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Current research and research needs on irrigated soils

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SUMMARY - The maintenance of the quality of our soils and waters is an important requirement for the long term sustainability of irrigated agriculture. Our agricultural practices are therefore challenged to meet present and future needs without compromising our ability to sustain the earths renewable resources. The basis for the attainment of a sustainable irrigated agriculture is to reduce the use of off-farm inputs potentially harmful to the environment, to incorporate to a greater extent the productive use of the biological and genetic potential of plants, to improve the match between cropping patterns, productive potential and the land's physical limitations and to improve farm management and conservation of soil, water, energy and biological resources. The scope of this work is to highlight specific research needs aimed to protect soil and water degradation. These needs are exemplified by presenting the work performed in the Ebro river basin in relation to two key issues: water management for salinity control in return flows from irrigation and the analysis of factors affecting the structural stability of semi-arid soils under irrigation.

Key words: Soil quality, water quality, sustainable agriculture, agricultural management.

RESUME - Le maintien de la qualité de nos eaux et de nos sols est une condition importante pour la durabilité à long terme de l'agriculture irriguée. Nos pratiques agricoles sont donc mises en question lorsqu'il faut faire face aux besoins présents et futurs, sans mettre en compromis notre aptitude à conserver les ressources renouvelables de la terre. La base pour l'obtention d'une agriculture irriguée durable est de réduire l'utilisation des inputs externes potentiellement nuisibles à l'environnement, d'introduire dans une plus grande mesure l'utilisation productive du potentiel biologique et génétique des plantes, d'améliorer la combinaison entre les modèles de culture, le potentiel productif et les limitations physiques de la terre et d'améliorer la gestion agricole et la conservation du sol, de l'eau, de l'énergie et des ressources biologiques. La portée de ce travail est de mettre en relief les besoins de recherche spécifique tendant à protéger la dégradation du sol et de l'eau. Ces besoins sont illustrés dans la présentation du travail réalisé dans le Bassin de l'Ebre sur deux points clés : la gestion de l'eau pour le contrôle de la salinité dans les flux de retour de l'irrigation et l'analyse des facteurs qui affectent la stabilité structurale des sols semi-arides irrigués.

***Mots-clés**: Qualité du sol, qualité de l'eau, agriculture durable, gestion de l'agriculture.*

Introduction

History notes that irrigation was one of the first modifications of the natural environment undertaken by man. The development of many early civilizations was primarily due to the success of irrigation and its major impact on providing an increased and more stable supply of food and fibre.

The world's current 220 million hectares of irrigated land are estimated to cover about 18% of the total cultivated area and contribute about one third of the world's food production (Hoffman *et al.*, 1990). We can therefore conclude that the continuous expansion of irrigated agriculture has successfully contributed to world food and fibre production for thousands of years.

Increased pressure in natural resources suggest, however, that the benefits of irrigation can no longer be taken for granted. Population growth, intensified land use, environmental degradation and agricultural productivity are interrelated issues. Our land use practices are therefore challenged to meet present needs without compromising our ability to sustain the earths renewable resources and our capability to meet future needs.

To achieve sustainable irrigated agriculture, the world's agricultural productivity must be enhanced while its resource base is conserved (Table 1).

Table 1. Scope of sustainable irrigated agriculture (NRC, 1989 a).

SUSTAINABLE IRRIGATED AGRICULTURE
Attainment of a productive agriculture compatible with the conservation of earth's resources:
1. More thorough incorporation of natural processes.
2. Reduction in the use of off-farm inputs with the greatest potential of plants and animals.
3. Greater productive use of the biological and genetic potential of plants and animals.
4. Improvement of the match between cropping patterns/productive potential/ land's physical limitations.
5. Improved farm management and conservation of soil, water, energy and biological resources.

Research will be essential to this task in the following six areas (National Research Council, 1991): (1) Overcoming institutional constraints on resource conservation; (2) Enhancing soil biological processes; (3) Managing soil properties; (4) Improving water resource management; (5) Matching crops to environments; and (6) Effectively incorporating social and cultural dimensions into research.

In relation with the third objective, research is necessary in three fronts: First, techniques must be developed to intensify use of good quality lands while minimizing environmental degradation. Second, ways must be sought to enhance production and reduce degradation on lands previously viewed as 'marginal'. Thirdly, new emphasis must focus on restoring degraded lands (National Research Council, 1991).

In summary, the maintenance of soil quality is an important requirement for the long term sustainability of the productive capacity on our croplands.

The objectives of this work are (1) to highlight some specific research needs aimed to protect soil quality and soil and water degradation in the context of irrigated agriculture and (2) to exemplify these needs using the Ebro River basin (Spain) as a case study.

Source control: research needs

Irrigated agriculture is increasingly viewed as an industry that creates environmental problems much like any other industry. In fact, irrigated agriculture is one of the major contributors to non-point source pollution for contaminants such as pesticides, nutrients, salts, trace elements and sediments (National Research Council, 1989 a).

Source control should be the fundamental approach to improving environmental performance. Source control can be achieved in two ways: (1) By reducing the total mass of fertilizers, pesticides and irrigation water through improved input management, and (2) By reducing loss of nutrients, pesticides and salts by controlling leaching and runoff, or by increasing plant uptake through changes in cropping systems or land uses.

The potential to reduce pesticide, nutrient and salt runoff and leaching losses is particularly great in irrigated agriculture through improved water distribution uniformity, irrigation scheduling using agroclimatic data, and use or management of the shallow groundwater.

Research on water management and, in general, on source control strategies is therefore critical for minimizing off-site negative impacts and the sustainability of irrigated agriculture.

Soil quality and soil degradation: research needs

Fig. 1 presents a schematic diagram of the main physical, chemical and biological processes of soil degradation (Lal and Stewart, 1990), and Table 2 gives a quantitative assessment of the world-land surface areas affected by human-induced soil degradation (USDA, 1992). These impressive figures indicate that fifteen percent of the total thirteen thousand million hectares of the earth's land surface has already been degraded by men's intensive agricultural activities.

Biological degradation

Biological degradation includes the reduction in organic matter content, decline in biomass carbon and decrease in activity and diversity of soil fauna.

Biological activities are associated with organic matter decomposition, nutrient cycling, the genesis of soil structure, degradation of pollutants and disease suppression (Lal and Stewart, 1990).

Degradation of these activities through erosion, compaction, organic matter depletion or toxic inputs results in negative changes in cropping system performance and therefore are key research issues.

Chemical degradation

Nutrient depletion, acidification/alkalinization, salinization and buildup of toxic chemicals resulting from human activities are very common soil chemical degradation processes.

Although loss of nutrients appears to be the most important chemical degradation process (Table 2), Szabolcs (1989) has made quite a different estimate of the worldwide salt-affected surface areas (including also non-irrigated land): about 340 million ha (23%) of cultivated lands are saline and another 560 million ha (37%) are sodic.

These figures indicate that, approximately, one-third of the developed agricultural lands in arid and semiarid regions reflect some degree of salinity accumulation. The salt-affected soils in the Mediterranean countries amount to some 16 million ha, with Egypt (7.4 m), Algeria (3.2 m) and Turkey (2.5 m) being the most affected.

For irrigated land, Szabolcs (1989) estimates that some ten million ha are abandoned yearly as a consequence of salinization, sodification and waterlogging. It is a consensus of specialists that, without proper soil and water (irrigation and drainage) management, on-site effects of salinization will continue to increase (Table 3).

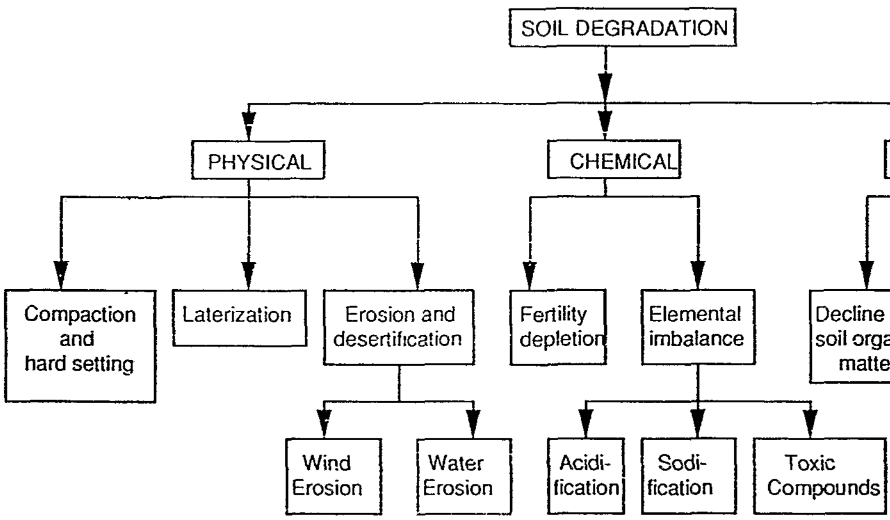

Fig. 1. Processes of soil degradation (adapted from Lal and Stewart, 1990).

Problem recognition in the last decade has sifted from on-site effects towards off-site effects from irrigation return flows or drainage waters high in salts, nutrients, pesticides and trace elements.

The irrigation-induced selenium contamination at Kesterson National Wildlife Refuge and the ongoing problems with trace elements in irrigation drainage throughout California's San Joaquin Valley (USA) illustrate the conflicts that can arise between the interests of agriculture and the environment (National Research Council, 1991 b).

We can therefore conclude that salinization is as old as irrigated agriculture, and that all areas irrigated in (semi) arid regions are subject to salinization if adequate drainage and leaching is not provided. Research efforts in this area are therefore essential for establishing sound management principles and practices aiming to control soil and water quality.

The work performed in the Ebro River basin is summarized in a later section as an example of some of these research needs.

Physical degradation

Erosion is the single largest threat to soil quality and represents the major agent of soil degradation worldwide (Table 2). Four to seven million ha is being removed from crop production annually because of soil erosion (Lal and Stewart, 1990).

Table 2 shows that water erosion and the consequent loss of topsoil is the most important soil degradation process. In erosion caused by rainfall or sprinkling water, raindrop impact energy is responsible for soil detachment, and overland flow for transport of these detached particles from interrill to rill areas.

These processes are intensified in situations were structural breakdown and soil dispersion are enhanced: low-salt waters, soils or waters high in sodium, soils low in organic matter and high in silt, and high intensity water applications (Hoffman *et al.*, 1990).

A wide array of chemical, physical and biological management options are available to reduce crusting and related problems: (1) Chemical amendments such as gypsum and phosphogypsum to increase electrical conductivity of irrigation water and decrease soil sodium content; (2) The use of polymers and related chemicals to aid in stabilizing soil structure; (3) Shallow tillage to disrupt crusts; (4) Addition of crop residue to increase organic matter, and (5) The use of early-cover crops and surface mulches to intercept raindrop and sprinkler drop impact energy (Table 4).

Aggregate instability, sealing and crusting of soils affect infiltration, time to ponding, raindrop detachment, overland flow and soil loss from erosion. In addition, they create crop production and irrigation management problems.

Although research efforts in this area have greatly increased in the last decade, more work is needed (1) to determine the principal factors affecting the water stability of structural entities in arid and semi-arid soils and (2) to establish reliable diagnostic procedures to both define the nature of the problem and to allow for definitive recommendations for solution.

The work performed in the Ebro River basin is summarized in the following section as an example of some of these research needs.

Table 2. Global human-induced soil degradation (millions of hectares)(adapted from USDA, 1992).

Type of degradation	Severity			
	Light-Moderate	Strong-Extreme	Total	%
Water				
Loss of topsoil	755.7	165.0	920.3	
Terrain deformation	114.2	58.8	173.3	
Total	869.9	223.8	1093.7	55.6
Wind				
Loss of topsoil	444.0	10.3	454.3	
Terrain deformation	68.1	14.4	82.5	
Overblowing	10.1	1.5	11.6	
Total	522.2	26.2	548.4	27.9
Chemical				
Loss of nutrients	115.5	19.8	135.3	
Salinization	55.2	21.1	76.3	
Pollution	21.2	0.5	21.7	
Acidification	4.4	1.3	5.7	
Total	196.3	42.7	239.0	12.2
Physical				
Compaction	56.9	11.3	68.2	
Waterlogging	9.7	0.8	10.5	
Subsidence org. soils	4.4	0.2	4.6	
Total	71.0	12.3	83.3	4.2
Grand total	1659.5	305.0	1964.5	

Table 3. On-site and off-site effects of salinity in irrigated agriculture.

1. On-site effects:
- 30% of irrigated land in arid/semi-arid areas is salt-affected.
- Mediterranean countries: 16 million ha of salt-affected soils.
- 10 million ha of irrigated land are abandoned yearly.
- Without proper soil, irrigation and drainage management, on-site effects of salinization will continue to increase.
2. Off-sites effects:
- Irrigation return flows high in salts, nutrients, sediments, pesticides and trace elements.

Table 4. Problems and management options in relation with soil physical degradation in irrigated agriculture.

1. Relevant problem for:
- Low-salt waters.
- Soils/waters high in sodium.
- Soils low in organic matter and high in silt.
- High intensity water applications.
2. Chemical, physical and biological management options:
- Gypsum, Phosphogypsum, Pyrites, Polymers.
- Shallow tillage to disrupt crusts.
- Addition of crop residue: increase organic matter.
- Use of early-cover crops/surface mulches: interception of rain/sprinkler drop impact energy.

The Ebro River basin as a case study

This section presents the results of two research projects performed in the Ebro River basin in relation with two key issues previously highlighted: (1) Water management for salinity control in irrigation return flows, and (2) structural stability of semi-arid soils under irrigation.

Irrigation return flow hydrosalinity model

The 85,000 km^2 Ebro River basin lies in the semi-arid northeastern area of Spain and has more than 700,000 ha of irrigated land. Approximately 310,000 ha of the cultivated soils are salt-affected, most of them containing sparingly soluble gypsum and limestone in addition to the dissolved mineral salts. The chemical weathering, leaching and drainage of these salt sources are enhanced when cropland is irrigated, affecting to the quality of the receiving water bodies.

The Ebro River discharges 6.7 million ton of salt into the Mediterranean Sea annually, and the established salinity trends towards the middle reaches of the river show annual total dissolved solids (TDS) increases of 10 to 15 mg/l (Aragüés and Alberto, 1983). The salinity-flow relationships and salinity trends in four stations of the river were explained by Quílez *et al.* (1992). Using the methodology of the transfer function-noise models, they concluded that in two of the stations there was a significant increase in salinity ($P<0.05$) during the studied period, most probably due to an increase in the consumptive use of water in the basin.

From these studies, it was anticipated that as new irrigation projects develop in the salt-affected areas of the Ebro River basin, the irrigation return flows and the salinity loading of the rivers will increase.

For these reasons, we modified and applied an irrigation project hydrosalinity model capable of predicting the volume and salinity (EC) of these return flows (Aragüés *et al.*, 1985; Faci *et al.*, 1985; Aragüés *et al.*, 1990). The detailed studies performed in the Violada irrigation district showed that the calculated values for volume, concentration and salt load of the calibrated model were within 2% of the measured values. The calibrated model was verified with data from two other hydrological years, showing that model predictions were within 13% of the observed values (Table 5).

Table 5. Results of the Conceptual Irrigation Return Flow Model for Violada irrigation district: calibration and verification (Aragüés *et al.*, 1990).

	Calibration			Verification nº 1			Verification nº 2		
Parameter	Meas.	Calc.	Diff.	Meas.	Calc.	Diff.	Meas.	Calc.	Diff.
Volume (10^4 m^3)	3164	3107	-1.8%	3643	3552	-2.5%	4307	4282	-0.6%
TDS (mg/l)	2273	2273	0.0%	2054	2330	13.4%	1843	2071	12.4%
Salt mass (t)	71910	70615	-1.8%	74850	82782	10.6%	79391	88656	11.7%

The modelling results demonstrate that the modified model could accurately simulate the average volume of water and salinity of irrigation return flows in areas with non saline to saline soils where gypsum is the main source of salinity, and that it is a reliable tool for evaluating alternative salinity control practices.

The sensitivity analysis of the model proved that the key management strategy to minimize salt loading in irrigation return flows from the Violada irrigation district is to decrease applied irrigation water and, thus, reduce subsurface drainage water.

Model projections assuming that salt control practices resulted in a hypothetical reduction of 20% in diverted irrigation water indicate that, although the final salinity of soil water increased slightly due to an increase of the evapotranspiration concentration factor, the decrease in the amount of water percolating beyond the root zone and the corresponding decrease in the mass of dissolved gypsum reduced salt mass emissions by 28% (Table 6).

Finally, another management alternative could be the reuse of return flows for irrigation purposes. These effluents are moderately saline (EC of 2-3 dS/m) and rich in gypsum in the Violada district. The model predicts that, after the first reuse, subsurface drainage waters become nearly saturated with gypsum, and that subsequent reuses negligibly affect the concentration of these waters (Fig. 2). Thus, assuming that 25% of the applied irrigation water is reused drainage water, the subsequent mass emission of salts will decrease by 30% without on-site negative effects.

Table 6. Model predictions for hypothetical 20% reductions in diverted irrigation water for Violada irrigation district (Aragüés *et al.*, 1990).

Parameter	Measured	Calculated	Difference (%)
Diverted irrigation water (m)	1.13	0.91	-20
Leaching below root zone (m)	0.74	0.53	-28
Salt pickup-salt deposition (t/ha)	0.42	0.33	-21
Gypsum salt mass (t/ha)	25.0	19.6	-22
Surface irrigation return flow (m)	0.91	0.69	-24
TDS surface IRF (mg/l)	2326	2244	-3.5
Salt mass IRF (t/ha)	21.2	15.4	-28
Leaching fraction	0.45	0.37	-18
ET concentration factor	1.13	1.92	+12
Eater application efficiency	0.45	0.53	+18

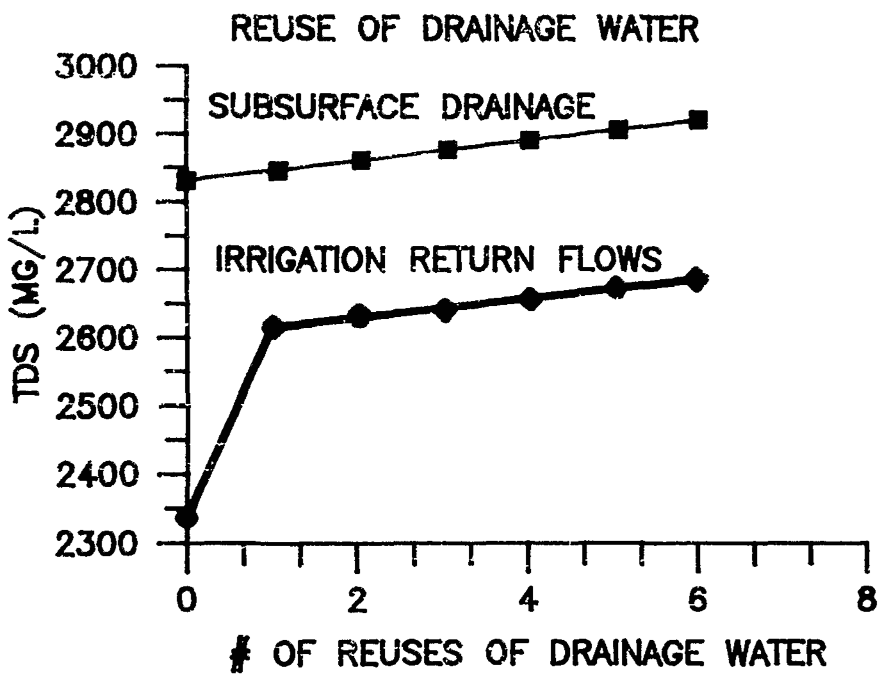

Fig. 2. Effect of six consecutive reuses of drainage water for irrigation on salinity (Total Dissolved Solids: TDS) of subsurface drainage water and surface irrigation return flow (Aragüés *et al.*, 1990).

Structural stability of irrigated soils

The large irrigation districts located in the left bank of the Ebro River receive low-salinity waters (EC =0.3 dS/m) from the Pyrenees. These waters, applied with sprinkler irrigation systems to soils low in organic matter and high in silt, cause water penetration problems, waterlogging, runoff and erosion (Aragüés, 1986). This is therefore an important area of research, as some 100,000 ha of land will be irrigated in the future with sprinkler systems using these low-salinity waters.

The flocculation values (FV) of various soils of the Ebro River basin are determined for a range of salinities (EC) and sodicities (SAR) of the applied waters with a relatively simple laboratory test. Soil dispersion is estimated by measuring the optical density of the supernatant solutions after sedimentation of the soil samples equilibrated with the corresponding electrolytes (Aragüés and Amézketa, 1991 a). The dispersion test is reliable and capable of predicting the dispersive behaviour of these soils (Fig. 3).

The effect of EC and SAR of irrigation waters on the hydraulic conductivity (HC) of saline-sodic soils is also evaluated in laboratory soil columns (Aragüés and Amézketa, 1991 b). The results show that (1) HC is reduced to negligible values with deionized water; (2) Effluent dispersion increases up to sixty times when reducing the EC from 5 to 0.01 dS/m; and (3) Very small fractions of dispersible clay (< 2% of total soil clay) induce large reductions in HC (Fig. 4).

The parameters obtained in the Dispersion Test were compared with the reductions in HC obtained during the leaching process of these saline-sodic soils. The results obtained indicate that, although in some cases there is a relation between them, there are other variables that affect the HC reductions, such as slaking of soil particles promoted by a osmotic explosion effect (Amézketa, 1992).

Finally, several rain simulator studies were performed for the evaluation of the effect of EC, SAR and kinetic energy of sprinkling waters on soil infiltration rate (IR). Results show that the best management practices are mulching or early ground cover by plants to avoid the kinetic energy effect and surface application of gypsum and phosphogypsum to prevent soil dispersion and crust formation (Ortíz de Zárate, 1992)(Fig. 5).

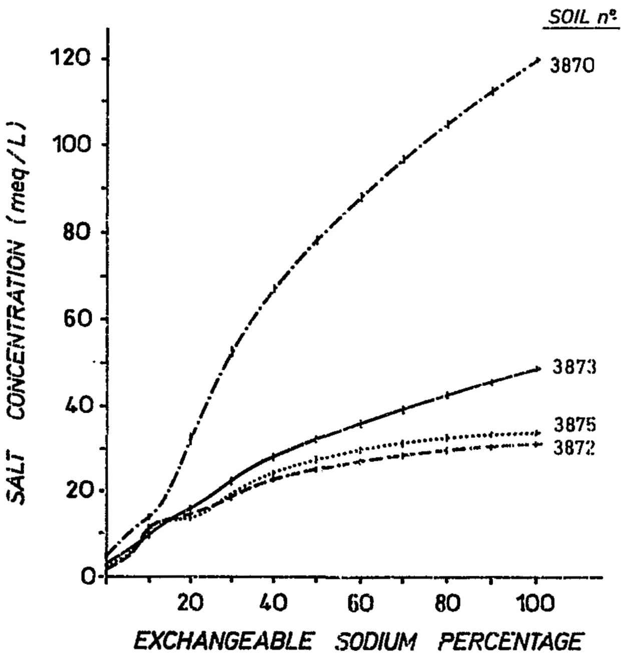

Fig. 3. Stability diagrams of four soils of the Ebro river basin: the region above the threshold curve of each soil represents flocculation state, and the region below it represents dispersion state.

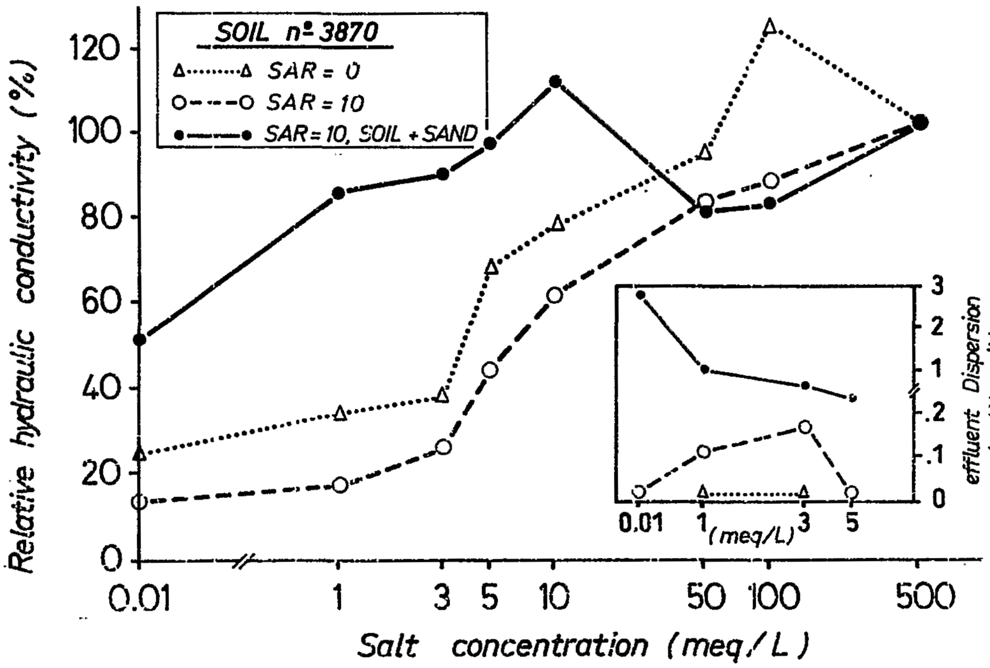

Fig. 4. Relative hydraulic conductivity and effluent dispersion of soil column and a soil:sand (1:2 w/w) column equilibrated with electrolytes of different salt concentrations and sodium adsorption ratios (SAR).

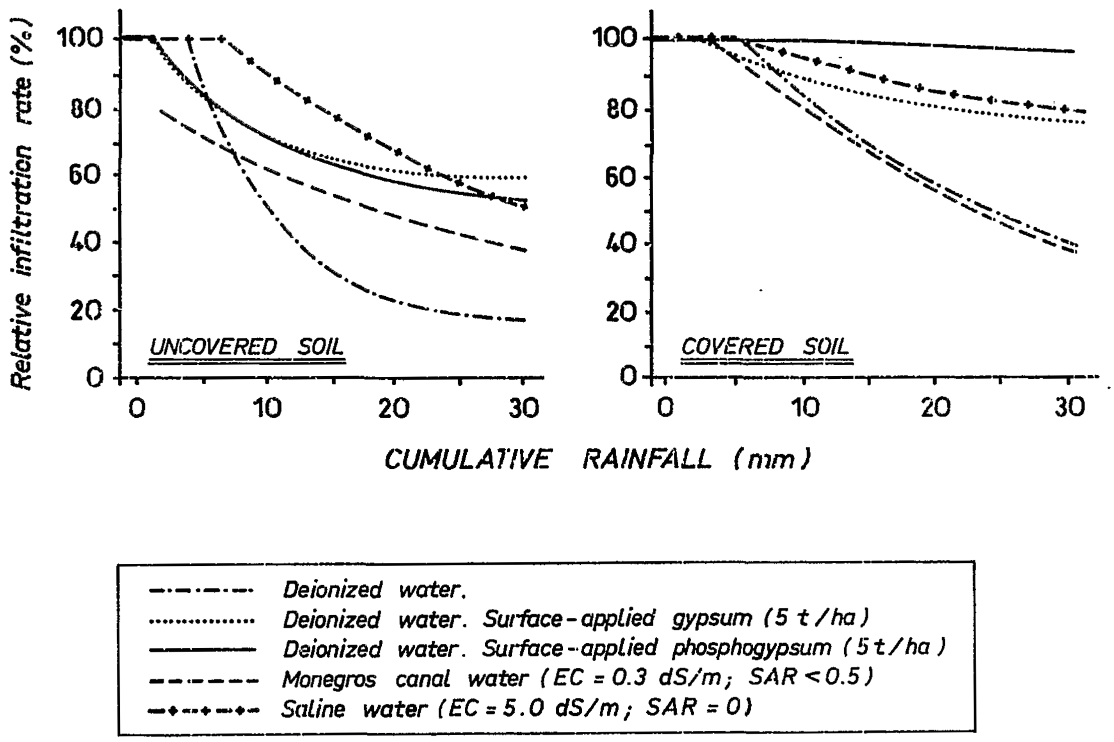

Fig. 5. Sprinkler irrigation simulation experiments: Effects of electrolyte concentration, gypsum and phosphogypsum application, and covered and uncovered soil on Infiltration rate of a soil of the Monegros II irrigation district (Ebro river basin, Spain).

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