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"Soil degradation and crop production in the tropics"

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Soil Degradation and Climate-Induced Risks of Crop Production in the Tropics

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Abstract. Soil degradation and associated risks of crop production are generally stronger in tropical regions due to the climate and soil characteristics, but also due to inapropiate use and management of the natural resources imposed by population pressure and social & economic factors. This has led to a generalized non sustainable agricultural production, and to an increased inability to produce food for the growing population in many developing countries of the tropics. Not less important are the increase of risks of catastrophic floodings, sedimentations, landslides, mudflows. etc, and the effects on the global climatic changes. Most of the agricultural production in the tropics is still mainly based on rainfed crops, growing in seasonaly rainfed areas with semiarid to subhumid climates. These climates are characterized by continuous high evapotranspiration rates and a high variability and unreliability of rainfall, mostly concentrated in a few high intensive storms. Therefore, water is the main single limiting factor of crop production, and the main responsible of the high risks of crop production and soil degradation. These risks are further accentuated with the increasing physical and chemical degradation of soils. To decrease those risks there is required a better understanding and prediction of the efficient use of rainfall water, and its relationships to rainfall characteristics and soil properties. Rainfall records, together with adequate information on crops and hydraulic properties of soils, and their dynamic changes under different land use and management, may be integrated in simple water balance models, to assess the intensity, timing and probabilities of conditions affecting crop production and soil degradation. The generated information would be used in planning strategies on land use, and in the selection of water and soil conservation and management practices based on probabilities of success, levels of risk, and long term sustainability. The development and application of those models must take into consideration the limited availability of the required climate and soil data in many tropical regions, and the possibility to gather the missing information through direct measurements using simple and reliable field methodology instead of unreliable computer generated data. Examples of application of the proposed approach to different agroecological systems in tropical Latin America are presented.

Introduction. Soils and water are the most important resources for ensuring sustainability of food production. Reduction of the level of production risk is one of the basic objectives of sustainable land management (12). Production risk include adverse effects such as fall in production, fall in profits, and soil degradation, derived from unforeseen environmental changes. Much of the risk is related to climate. Subsistence farmers often develop and use cropping patterns that produce low, but dependable yields under situations of risk and uncertainty.

Poor soil and water management may cause severe land and soil degradation. Soil degradation has been defined as a decrease on the ability of the soil to perform its function as medium for plant growth, regulator of the water regime, and as environmental filter, due to natural and man-induced causes. Unfavourable alterations of the soil's physical, chemical and biological properties have a negative effect on plant productivity and environmental quality. The process of soil degradation starts with the degradation of soil structure, specially the functional attributes of soil pores to transmit and retain water, and to facilitate root growth (22). The deterioration of those attributes is manifested through interrelated problems of surface sealing, soil compaction, impeded root growth, poor drainage, frequent drought, excessive runoff, and accelerated erosion. Although land degradation problems are not confined to tropical regions, they are generally worse in those regions because of the prevailing climate and soil characteristics, and the increasing pressures brought about by population growth and lack of resources.

In spite of some technological advances in agricultural production, still millions of people in developing countries of tropical regions do not have enough to eat. There are a number of causes, but the main one is the fast reduction in the productive capacity of land and in the quantity and quality of water resources, by increasing rates of soil erosion and land degradation in general (16). Land degradation directly affects food supplies, diminishing crop yields and increasing risks of production.

According to some evaluations about 70% of the potentially cultivable lands in the World lies in tropical developing countries, and presently less than half of that land is used for agriculture (10). Only two or three decades ago it was assumed that there was plenty of potentially arable land in the tropics, specially in Africa and Latin America, from which to feed additional population. The real situation is that most of that land is marginal for agricultural use, or it is geographycally inaccesible. In other cases the economic resources for their development and the required inputs for sustained production are not available, with the result that some of the land already cultivated exceeds what is compatible with sustained agriculture (5). Previous projections of production potentials in the yet unexploited land resources of the tropics have also failed because the effects of soil degradation were not previewed (32). The result is that problems of sustainable crop production in the tropics have led to inability to produce enough food, and per capita food production is even lower that two decades ago in some tropical regions and countries (27)(37). It is considerd that land degradation, due to different processes of soil degradation, has become the main limitation for the expansion and intensification of agriculture in the whole world, especially in tropical regions, therefore limiting the possibilities to produce the food required for the increasing population (4)(11).

Increased food production in tropical regions can be achieved by expansion of land under cultivation, and increased yields or increased cropping intensities on land now being cultivated. Most of the new food production in the tropics during the last 30 years has been by expansion of agriculture, mainly through deforestation, in lands with semiarid to subhumid climates, where some of the more fertile soils are found. But the requirements to substitute degraded lands that have become non productive, and to provide food to the growing population, has led to accelerated deforestation, use for agriculture, and overexplotation of increasing fragile ecosystems and marginal lands in the humid, dry semiarid, and steep tropics. This leads to a fast reduction in chemical fertility and deterioration of the soil physical properties, with accelerated erosion in many cases, resulting in a rapid decline of productivity, loss of farmland, floodings, and silting of water reservoirs (18). Marginal lands are often the ones more used for traditional food crops in the tropics, because the relatively better agricultural lands are used for cash crops to export, with high level of costly inputs. The food crops for the local markets are generally not able to pay the cost of the required inputs for a sustainable production, due to the low prices the farmers get for these crops. In this way, small and poor farmers are many times forced to move into less productive marginal lands or uncut forests, promoting further deforestation and increased risks of soil degradation (55). Additionally, the increase of foreign debt of most of the developing countries in the tropics in the last decade, has led to further intensification and changes in use of land resources, to increase the export income.

As a result of soil degradation due to deforestation, overgrazing and innapropiate agricultural practices, close to 1% (7-8 Mha) of the land resource is lost every year in the tropics, which is not compensated by the production of new land (10-12 Mha) brought annualy into cultivation, resulting in a shrinkage of the productive potential of tropical lands. Technical limitations and socioeconomic constraints make more and more difficult and expensive the expansion of agricultural lands, woth increasing production and degradation risks due to poorer and more fragile soils, inadequate climate, and low availavility and high costs of required inputs. There has been increasing international concern about the continued and incresing destruction of tropical forests (10-12 Mha/year, half of them in Latin America), because of the effects on hydrological changes, and the potential effects on global climate. More recent, and less publicized, is the concern about the unsustainability of agriculture, due to the widespread problem of soil degradation, and the present and increasing possibilities of food deficits in developing countries of tropical regions. It is previewed that due to a population growth slightly higher than 2% per year, the demand for food and agricultural production will double in the next 20 years (10).

Presently, more than 85% of the agricultural land in the tropics is rainfed, with problems of uncertain or low rainfall in 37% of them. Although limitations from poor chemical fertility, common in many soil sin the tropics, may be relativelly easily corrected in some cases, the required lime and fertilizers are generally scarce and expensive in tropical developing countries, and the economic possibilities of the farmers to buy and use them is very limitted. Therefore, under those conditions chemical fertility may be a strong limitation to food crop production, but for large areas in the seasonally rainy tropics water continues to be the main single limiting factor for crop production. The posibilities to decrease risks and increase food production by increased use of irrigation, where water resources are available, is limited due to the high costs of development and maintenance, and the scarcity of resources. Most of the agricultural land presently being irrigated in the tropics is concentrated in Asia, with only 7% and 2% of the cropped land presently being irrigated in Latin America and Africa respectively. Almost 50% of that irrigated land is already affected by problems of salinization and sodification (30). Therefore, much of the additional agricultural production in the near future in the tropics, will have to be based on rainfed cropping.

Risks of Soil Degradation in the Tropics. In a large proportion, the soil degradation in the tropics is a result of inadequate use and management of land as a consequence of poverty, caused or increased by population growth and unfair distribution of land and resources among countries and within each country. The poor farmers are responsible for land degradation when they are obliged to do so to cover their food and fuel requirements to survive, but also large public and private land development projects, pursuing short term objectives, lead frequently to extensive soil degradation (37)(40). Severe soil erosion and degradation is also caused by overgrazing and improperly managed rangelands, especially in steep lands (33).
Risks of soil and environmental degradation are high in the tropics when already cultivated lands are overused due to population pressures and limited resources, or the agriculture is extended to marginal lands. These risks are further accentuated by the resource based and low input agriculture widely practiced in tthe tropics. Shifting cultivation based on long fallow periods, for was generally effective in the humid and subhumid tropics, with low inputs and low risks of subsistence food production, with the shortening of the fallow periods due to degradation. With the shortening of the fallow periods due to increased population and food needs, that system has become increasingly inefficient, leading to fast soil degradaton and production decline (21). Introduction of permanent farming and continuous cultivation in humid tropical regions has been only exceptionally succesful, requiring the use of large amounts of fertilizers and organic residues. The increasing large scale farms in the humid and subhumid tropics, with annual crops and mechanized practices, are often not sustainable unless there are used suitable crop rotations and management practices to minimize soil degradation. Large scale plantations with perennial crops (coffee, cocoa, rubber, tea, oil palm) may be highly sustainable

in the humid tropics, protecting the soil against leaching, compaction and erosion, if they are associated with agrophorestry systems, with carefull soil and vegetation management. Therefore, the possibilities of soil degradation, and not only the short term production, must be considered before any deforestation and change in use or intensity of cropping in tropical lands, in order to develop or adopt cropping systems to maintain and increase productivity. In many countries in the tropis, the application of conservation measures is limited by lack of integration between conservation and development, lack or no application of legislation, and shortage of basic information and of economic and prepared human resources.
The physical degradation of agricultural soils in the tropics is mainly due to deterioration of soil structure, with loss of porosity and of pore continuity, and different consequences, being erosion the most frequent. In surface soil it is manifested by the formation of seals and crusts, resulting in decreased water infiltration, waterlogging, increased runoff, poor seedling emergence, and increased erosion, depending on the particular situation. In deeper soil, it may result in general compaction, or in the development of shallow compacted pans, leading to decreased available water holding capacity, poor drainage, and aeration problems. Another important consequence is the reduction in plant root development and root depth. Therefore, the maintenance of good soil physical properties is very important, besides chemical fertility and crop varieties, to maintain soil productivity in the tropics (41). For many years the research on management of soil physical properties of tropical soils was, and still is in many tropical regions, neglected, assuming that most of them had only chemical fertility problems, and an inherent very stable structure.
Incorrect tillage and intensity, both in low input agriculture and in large scale mechanized farms in the tropics, may be one of the main causes of soil degradation. But tillage, the main management practice for surface soil, may also be an effective tool to alleviate some soil-related physical constraints to crop production, like compaction, low infiltration, and poor drainage. Appropiate tillage methods differ among soils, crops and climate, and the right cholice depend on a range of interacting factors (36).

Risks of Crop Production in the Tropics. It is generally assumed that climatic conditions in most of the tropics are suitable for growing a wide variety of crops through the year, but in many cases there are climatic constraints derived of unreability of rainfall in onset, duration, intensity and volume, and high concentration of a substantial part of the rainfall in a few intensive storms (15). This is further aggravated by soil related constraints (40). Although no valid general statements can be made about the production potential and limitations of the tropical soils, where all orders and extremes can be found (25), a large proportion have inherent limitations related to low fertility and high acidity, low available water-holding capacity, mechanical and chemical restrictions to root development, and low structural

bility of surface soil to raindrop impact. Different levels these constraints, and on the possibilities of using external uts by farmers, makes agriculture in the tropics more or less tainable, limiting crop and pasture production more in some ls, environments and socio-economic conditions than in others.
high variability of rainfall in the humid and subhumid pical regions, and inadequate amounts and irregular tribution of rainfall in the semiarid tropics, result in large iations in water supply to the crops during the growing season, h periods of excesses and deficits of available soil water, ch create a risky environment for plant growth (44).
ls may serve to buffer the erratic and variable supply of water rough rainfall, or to accentuate the conditions of moisture ess or deficit. With soils having a low chemical, and usually a r physical fertility, the levels of productivity are generally , and the risks of crop production very high. Periods of water icits may occur frequently even in subhumid tropical regions. refore, drought stress is an important climatic constraint to op production in large areas of tropical regions, being tributed to poor rainfall distribution, variable and inadequate infall amount, high evapotranspiration rates, low water holding pacity of the soil's root zone, and poor structural stability d high compactability of soils resulting in reduced infiltration tes and high runoff and erosion. In some cases, even short riods of waterlogging and of excesses of soil moisture may sult in strong reductions in plant growth, and even a total kill plants (31). Variability in net returns coming from a mbination of crop yields and purchased inputs, increase the risk losses, lessening the degree of security. That is why many rmers in the tropics are resistant to adopt new management actices or systems requiring more inputs, if more risky, even if ey are more profitable in average.
il and water conservation practices minimizing those climatic d soil constraints will contribute to improve crop growth and to duce production risks (31)(39)(42). On the other hand, cropping stems and land management practices leading to soil degradation, th further loss of soil chemical and physical fertility, may sult in a decreased productivity and increased production sks. Soil and water management systems must also be developed to store productivity of land already degraded, if that is still ssible.
e risks of soil degradation and drought, and the difficulties of veloping sustainable agricultural systems, increase with higher mperatures and lower precipitation, and in the soil orders more mmonly found in tropical regions (47). These effects are related the decomposition rates of soil organic matter, to the ssibilities to produce enough residues for mulch cover, to the apotranspiration rates in relation to the amount, distribution d uncertainty of rainfall, to the available water-holding pacity of the soil root zone, and to the fertility of subsurface il. There are some exceptions, especially in the humid tropics, ere the extremelly high rainfall may increase erosion and trient leaching and acidification in soils used for agriculture. ith similar soils and climate, the agriculture is more sensitive

to risks in crop production due to climatic variations and soi degradation in some regions and countries than in others Different factors, including low and unstable yields and foo production, limited economical resources to import food, etc increases the vulnerability of tropical developing countries t climatic variation.

Soil Degradation and Productivity in the Tropics. Soil erosion i one of the major threats to a sustainable agriculture in th tropics, because much of the rain occur during short intens storms. Erosion is particularly severe following deforestation, by the introduction of mechanized seasonal crops leaving the soi unprotected, overgrazing, improper maintenance of plantations etc. common in tropical regions. The susceptibility of soils o the tropics to surface erosion, is on the average not much highe than in other climatic regions, but the erosive power of rainfal is much higher (19). All erosion processes are active in th tropics. Mass movements and slip erosion are common in stee slopes. This process of erosion generally affects soils wit exceptional resistance to sheet erosion due to the excellen structural and hydraulic properties of the surface soil (38).
A given amount of soil loss by erosion generally causes a mor serious decline in crop production in the tropics than it does i temperate environments, due to shallower soil rooting depths nutrient concentration in the surface soil layer of the profile unfavourable subsoil properties, and higher water requirement fo the crop in tropical climates. Yields generally decline linearl with soil loss for soils with uniformly distributed nutrien reserves, and exponentially in texture contrast soils and in thos with nutrients concentrated in the upper layer, common in th tropics (48).
As the result of erosion, soil physical, chemical and biologica properties are changed, usually reducing the amount of water an nutrients available for crops to use, and leading to reduce yields and more risky production. As erosion brings subsoi horizons, richer in clay or more compacted, closer to the surface the risks of runoff and further erosion increases (23). I adittion to effects on productivity and crop production risks, i many tropical regions soil erosion and subsequent sedimentatio degrades hydrographic catchments, affecting negatively th production of hydroelectric power and irrigation of low land (33). Natural disasters (flooding, landslides) are also rooted i soil degradation and are affecting with growing incidence th developing tropical countries. In both cases, the decrease o risks of those problems depends on a appropiate land use an management planning for sustainable agricultural development. Thi requires an adequate identification and evaluation of th processes and of the relations cause - effects of the differen problems. For example, although a grassland or mulch cover may b very good to increase infiltration, reducing runoff and surfac erosion in moderate slopes of semiarid to subhumid tropics, it ma the reverse on steep lands with humid tropical climates and soil prone to lanslides and mass movements (38), where the tree roo shear strengh given by an appropiate forest cover may be importan

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prevent that form of erosion and main source of sediments in the tropical steep lands (14).
Soil compaction, mainly associated to agricultural mechanization, and to decrease in organic matter and in aggregate stability, is one of the leading processes of soil degradation in tropical regions, affecting directly crop growth, and increasing risks of crop production. These effects are mainly derived of reductions in water and nutrient absorption by roots, due to reduced aeration and reduced root growth (51). Indirectly, by decreasing soil permeability, soil compaction may affect risks of crop production and erosion by increasing water runoff in sloping land, or by enhancing waterlogging in flat lands.
The response to a given compactive force depends on the soil characteristics. Not all crops respond in the same way to a given compaction, and the response will also depend on the climate and soil moisture regimes during critical growing periods. In years when due to a good rainfall distribution during the growing season a favourable soil water environment is maintained, the differences of yields between soils with shallow compacted pans or not may be negligible.
It is not clear, because the available information is largely based on work under controlled and artificial conditions, wether under tropical conditions high soil temperatures may be an important and generalized negative factor for increasing risks of crop production. In any case, this hypothetical effect would be decreased with the same management practices to enhance soil and water conservation.

Global Climate Changes and Risks of Crop Production in the Tropics. Increasing concentration of trace gases, mainly CO_2, in the atmosphere, are likely to produce a substantially warmer climate on the Earth, by what is known as greenhouse effect. If the present trend continue, it is previewed that a global warming of a few centigrades will have a profound effect on climate in the next century. The impact of this climate change is difficult to predict, but it will probably incresase evaporation rates and annual global rainfall.
Although the temperature changes previewed for the tropics are less pronounced than in temperate or cold regions, rainfall probably will increase in that region, while sub-tropical regions might become drier. The consequences for soils and the associated vegetation in tropical regions will be very complex and largely unpredictable (54). We may guess that increased levels of CO_2 in the atmosphere would promote plant growth, which together with higher rainfall would deplete soil nutrients faster, increasing the needs of fertilizers. In depresional sites or level soils, increased rainfall would cause prolonged waterlogging or water saturation, and temporary floodings. The increased intensities and continuity of rainfall events, and the increased total rainfall, would give rise to larger runoff and erosion on tropical cultivated sloping lands, and to increased risks of landslides, mass movements and mud-flows in steep lands (38). Problems of increased sedimentation in low lands, and the salinization of tropical coastal plains and river delatas may be also of great

importance (6).
To make soils in the tropics more resistant to the expected dire and indirect consequences of climate change, the soil manageme measures would have to concentrate in mitigating the effects high rainfall events, and drought. They should be directed to t maintenance of a complete and continuous soil cover, to minimi rainfall impact and non beneficial evaporation, assure go infiltration and aeration, and promote deep root penetration. any case, under the present and previewed future trends deforestation, and agricultural land use and development in t tropical regions, mainly derived of previewed population pressur and socio-economic factors, the changes in soils leading to the degradation by direct human action, and the on-site and off-si effects may be faster and more important than the expected futu climate-change induced effects. Besides, human induced so degradation indirectly contributes to accelerate such climat changes.
Soils can be the main source or the main sink of most greenhou gases, specially of CO_2. Soil degradation contributes directly an increase in atmospheric CO_2 through rapid decomposition of so organic matter, especially in tropical and subtropical climate As world contains aproximately three times more reserves organic C than all living things in it, that source of CO_2 potentially the most dangerous to global warming (1). Indirectl soil degradation and the resulting declining agricultur productivity, also contribute to the increase in atmospheric CC bringing new and more fragile lands under cultivation, wi deforestations, and burning of vegetation, in tropical region Only an annual deccrease of 0.15 % of soil organic C, or decrease of 5% in the C fixed by photosynthesis, will double t present annual rise of atmospheric CO_2 (13). This situation cou be reversed by reforestations, restoring the biologic productivity of degraded lands, controling soil degradation, increasing yields to produce more food from less land. To re that objective there are required appropiate policies of la development, and adequate land management systems and practice in the whole world, but especially in tropical regions.

Assessment of Soil Degradation and Risks of Crop Production in Tropics. The assessment and long term prediction of s degradation risks requires information, with quality and quant to guarantee the effectiveness and possibilities of aplication the outcome. The required information may be gathered throu different approaches, including observations of present trenc analyzing historical evidence of the site, comparing simi sites, and through theoretical projections, using dir measurements, statistical sampling, and predictive models. One of doing direct measurements is through trial and error fi experiments, but this approach is too slow and very expensive cover the whole range of posible combinations of factors (52).
In any case, for the assessment of soil degradation and consequences, there is required a complete or appropi characterization - physically, chemically and biologically - the soil resource, and of the climate, for a better understand

the agricultural management systems and their sustainability. It is required a better use of climate probabilities, and to rely upon averages, which have little meaning, particularly in the seasonally rainfed (semiarid and subhumid) tropical regions. The selected soil attributes (indicators) for sustainability or rate degradation analysis must include the ones determining the soil lities having more direct or indirect influence on the bility of the use being investigated (8), mainly productivity rainfed or irrigated crops, and hydrological regulation. The ection of the attributes, which may be measured, observed or imated, requires an understanding of cause-effect relationship ng them and soil qualities. It is preferable that the ributes used are readily observed or measured in the field, her than being dependent on laboratory and on complex cessing. There is a need to eliminate insignificant attributes or to the analysis, in order to minimize the cost and effort of luation.

tropical regions with seasonal rainfall distribution, the nfall pattern, with large variability from year to year, from ce to place, and within the same year at any one place, is the or factor determining crop yields and soil degradation. This iability has to be taken into consideration for planification selection of management and conservation practices to minimize ks. Therefore, the quantitative evaluation of crop-production ks, as influenced by soil degradation or soil conservation sures, as influenced by climate, has to be done on the basis of ld variability. Conclusions based on the results of one or two rs experiments can be misleading. Instead of using only slow expensive field experiments, they can also be estimated in a atively fast and cost-effective manner analyzing historical matic data and using computer simulation models. These models able, through various combinations of soil, crop, rainfall and agement practices, to predict crop success or risk, and to ntify optimum combinations, based on research findings of short n experiments in particular sites. In this way the selection of agement practices may be based on the probabilities of ferent rainfall patterns, and not on results of experiments ried on short time span with extreme or low probable climate ditions.

refore, under the high variability and uncertainty of tropical mate, rainfall data analysis, integrated with information from ls and crops are crucial for predictive purposes, on the luation of risks of crop production and of soil degradation ler different management systems and practices, and on icultural planning for a most efficient use of natural ources. A serious limitation for that is the lack or ufficiency of available climatic data in many tropical regions, re the records are generally too short or discontinuous, and m sparse recording sites. There have been developed spatial ther generators for daily weather sequences of given tropical ditions, trying to fill the gaps in space and time, but this not substitute the requirements on longer, better and more tinuous climatic data for reliable predictions and planning poses.

as moisture stress or excess for prolonged periods, during and after the establishment of the crop, are generally the most important cause of crop failure and production risks, the assessment of the soil moisture regime during the growing season, integrating climatic data with soil and land management information is very important. The concept of length of growing period (9), or period where the climatic constraints would permit growth of crops, is based on average values of amount and distribution of rainfall, evapotranspiration, and temperature, and on an assumed fixed (100mm) soil available water capacity. It is only useful for regional or global assessments of land suitability. The use of average values is an oversimplification, not useful to define the soil moisture regime in a particular situation, because it say nothing about the distribution and variability of rainfall during critical growth periods. The effective growing season is also a function of the soil available water-holding capacity, which depends on soil characteristics and root depth, very variable in the tropics. It is also necessary to take into consideration the way in which water can be stored in the soil for latter uptake by roots, which depends on rainfall and soil surface characteristics, affecting infiltration and runoff.

When variable rainfall is irregularly distributed, it is also very important to evaluate the amount of water roots can extract from the soil, known as available water-holding capacity. It is difficult, and subject to significant errors to calculate the amount of water roots can actually extract from soil, based only on laboratory measurements of water retention (44). If roots are not growing in some parts of the soil, depending on crop species and soil mechanical and chemical properties, no extraction is possible except for some amount of flow that sometimes will occur from wetter deeper soil where roots are not growing to upper drier soil with roots. This amount is less important when there is a sharp contrast between the two layers, and with high evapotranspiration and root absorption rates (26), the most common situation in tropical soils and climates. There is also a strong interaction between the pattern and rate of evaporation from the soil surface, affected by climate and soil cover, and the dynamics of water movement from deeper soil to the root zone (39). It is also common that those contrasting layers below the root depth have a low hydraulic conductivity, restricting the internal drainage of the soil profile. Under those conditions a significant amount of water, above the classical laboratory upper limit of available water, can be held at root depth for enough long period of time to be used by plants, or to create aeration problems. In humid tropical climates and steep slopes this situation may increase the risks of lanslides and mass movements.

Accurate evaluation and prediction of the soil water regime and water balance in general, also requires an estimate of the amount of rainfall water able to infiltrate. In many cases, and especially in tropical regions with most of the rainfall concentrated in a few high intensive storms, this is more important than the total amount of rainfall and the capacity of soil to store water in defining the best beginning and effective length of the growing season, and on the prediction of levels and risks of crop production. A large amount of rainfall is important, but it does not ussualy compensate for the lack of infiltration if the rainfall is not well distributed (31). The proportion of rainfall able to infiltrate depends mainly on the volume and intensity of rainfall, on the soil type, vegetation cover, slope, surface roughness, and initial water content of the surface soil. Some of these soil properties responsable of how much water infiltrates into the soil, especially the soil surface conditions, are subject to rapid dynamic changes by cultivation and effects of raindrop impact. These changes are also a consequence of soil degradation processes, including structure degradation in surface soil, and water erosion. That is why many infiltration equations, or statistical models that have been proposed to estimate water intake are often useless, or cannot be extrapolated outside the site and conditions where the experimental data for their development or test were taken. The use of indices or values obtained using direct measurements in the field or laboratory with rainfall simulators, have probved to be more useful for such purpose (29)(31)(32).

Not only temporal variability in rainfall, but also spacial variability has to be of concern in evaluating water available capacity, drainage and infiltration characteristics of the soil under field conditions. There has been a lot of work being done on statistical methods to deal with spatial variability, but in practice still the identification of such variability and decissions about sampling and measurements taking it into consideration, have to rely mainly on the experience of the technician to recognice it in the field, on the scale and precission of previous soil surveys, and on empirical field tests using simple equipment as penetrometers. The only practical approach at field scale will be to estimate the average or predominant water balance for a whole area, based on estimates at the same level of surface runoff, infiltration, evapotranspiration, soil-water storage and root depth.

Information about the time, length, probabilities and frequencies of the periods with critical soil moisture conditions, for single crops and cropping sequences, would be required for better planning of cropping cycles and for decissions about land use and management to increase production and minimize risks of crop failures and soil degradation, while maximizing rainfall use efficiency. For this, the dry or wet spells, based on the soil moisture conditions, must be interpreted according to treshold moisture values for the soils and crops under consideration, and their occurrence in different crop growing periods. The effect of soil physical properties, especially the ones affecting infiltration, water retention, drainage, and root development, is critical in the assessment of the soil moisture regime in relation to availability of water to the crop during the growing season. Chemical fertility is of obvious importance, but the natural or man induced defficiencies can often be easily rectified, whereas the reclamation of eroded and physically degraded soils in the tropics is a rather difficult and often uneconnomical task. An important factor in the widespread non reversible land degradation in many tropical regions has been the failure to recognize the importance of soil physical properties in maintaining the productivity of tropical soils (18).

Relationships between soil physical characteristics and soil hydrological properties are the beginning point to simulate or predict dynamic soil processes, including water supply, erosion hazard, etc. Standard soil profile descriptions in soil survey are more oriented toward taxonomic grouping, with observations and simple measurements of long lasting features. Most of the important soil physical characteristics required for the assessment of the soil moisture regime for crop growth, or of soil erosion, are overlooked at that point (17). Some times there are used pedotransfer functions to translate, through mostly empirical relationships, the basic information collected in soil survey into soil properties, to be used to deduce land qualities. This is only possible, if an appropiate set of accurate primary data is available, but in any case emphasis has to be placed upon measurement and estimation of soil-water properties, preferably in situ. Through simulation models it is possible that the measured or estimated intrinsic soil properties may be converted or interpreted in terms of dynamic soil qualities, as the soil water regime.

The techniques for measuring the soil hydraulic properties to model the soil water regime include from simple, straightforward field techniques (24), usually providing rough estimates of those properties, to rather complicated techniques for accurate time consuming measurements, requiring sophisticated skills and equipment. In general, but specially in the scarce resource developing countries of the tropics, the simple field techniques must be prefered (32), because of operational considerations, and because they are more able to be adapted to the required sample volume and spatial variation of soil hydraulic properties under field conditions. In soil survey, in addition to the usual recognition in the field of soil morphology, efforts shoud be made for a further physical characterization by applying simple field tests such as cone resistance, soil moisture, rooting patterns, infiltration, and water flow in the profile following infiltration. In general, it is required that soil surveys move from a purely qualitative description of soil to a more quantitative process-oriented approach.

Methods of predicting soil erosion have been and are widely used to identify excessive soil losses and to select the best erosion control practices. In tropical regions, direct measurements of soil erosion is not practical because erosion varies greatly in time and space (34). Therefore, the prediction of water erosion is generally done using mostly empirical, and much less process based methods and models, combining climate, soil, topography and management. Among the empirical models the one more widely used in the tropics to assess soil erosion problems for different land use systems has been the so-called Universal Soil Loss Equation (USLE), some times with adaptations to the tropical conditions based on results obtained in runoff plots and in rainfall simulation studies (7). This model, among other problems to be used for tropical soils and climates, does not predict adequately the effect of disastrous storms occurring frequently in the

...ions and causing most of the erosion. The erosion control ...tices have to take into consideration the probabilities of ...se events and their consequences. Process-based prediction ...ls based on equations that represent fundamental hydrological ... erosion processes, including rainfall, runoff and ...ltration, may be more usefull and reliable for tropical ...itions, if they are based on fundamental or critical ...lable, or easily measured information, and use probability of ... approaches. Up to now, these process-based models have ...ived little or no application in tropical regions (7).

...long term effect of erosion on-site is the loss of the soil's ...luctivity, with generally faster and stronger negative ...sequences in tropical regions. Although considerable data has ... obtained about soil loss from different soils and cropping ...ems in the tropics, very few assessments of the effects of ...se losses on soil productivity have been done. Some early ...oaches tried to relate crop yield to topsoil depth, affected ... soil erosion removal, but the relations were site and time ...ific, and only valid for each combination of climate and soil ...erties. Now, it has been proposed to quantify the long term ...ects of erosion on soil productivity, using parameters of ...ilable water capacity in the surface soil, and of pH, bulk ...sity and permeability of the subsoil, wiewing the soil as the ...ironment for root growth and water depletion. Projections about ... effects of erosion on crop productivity are difficult to ...idate. The difficulty to separate erosion from other ...radation processes, the short-term and site-specific nature of ...t erosion studies, and the inadequacy of available data base ...ired for asssessment in many tropical regions, are the main ...straints for those projections (28).

...ability or risks of soil compaction depend not only on the ... susceptibility, but on rainfall, soil moisture, and cultural ...tices. The effects of soil compaction on crop growth cannot be ...ed only in laboratory measurements, but on field measurements ... observations, including root development. Restricted root ...elopment due to limitations imposed by compaction, affects crop ...duction levels and risks because of reduced water availability, ... some times also reduced nutrient absorption.

... of Simulation Models for Risk Prediction in the Tropics. The ...reased requirements of more quantitative results in ...babilities and risks of soil degradation and crop production in ... tropics, often require the use of physically-based models, ...re the large number of important variables and their complex ...eractions can be integrated. Climate variability and the ...ociated high risks of crop yield and food production in many ...pical regions, requires strategies based on models using ... information on soils, climate and crops, for decision ...ing. Modern computer technology permits to store, process and ... a large amount of soil, climate and crop data. Although ...lation modeling is a rapid and cheap method of investigation, ...h is the main reason of their increased, and often ...iscriminated use, in the scarce resource tropical developing ...tries, it can not replace completelly field gathering of data

and field experiments, but it increases the efficiency of those two activities. The identification and selection of the main critical factors of soil, climate and crop, affecting risks of crop yield, soil degradation, and natural desasters, must be generally based on observations, experience and short-term field experiments.

Simulation models must be able to analyze in a quantitative way the interactions among land characteristics (soil attributes, climate, slope) to deduce land qualities (moisture availability, resistance to erosion) to be used as independent diagnostic criteria for risk of crop production, and risks and effects of soil degradation processes. These models must allow a detailed quantification of hydrologic prosesses for both actual and potential conditions, answering major questions about crop production and problems of degradation, related to different alternatives of soil management (3). In this way, modeling can be used to determine the most productive and/or least risky combination of management practices, for different combinations of soils, climates and crops. It can be also used to explore the possible effects on soil rehabilitation of different cropping and soil management practices (46). In tropical regions where water is available to supplement temporal deficits of rainfall, the model, using the same soil, climate and management information, may also give the amount of irrigation requirements in deffinite periods of the crop growing season. Combined with short term field experiments in particular sites, simulation modeling can provide a better understanding of results, enabling us to extrapolate them to a wider range of site conditions. This would require the collection of more and better quantitative soil physical data, not provided by the regular soil survey, both in the site of the experiment and on the sites where the results will be transferred.

Predictive simulation modeling can provide, if properly used, the scientific basis for evaluating the production and environmental impact of proposed land use changes, and the consequences of climatic variations in the tropics. Combining climatic data with soil data and land management information, these models would permit identify which crops can be grown in a particular area of the tropics, how the crop will perform, and to evaluate the level of risk under different land use and management (2). They would also permit the prediction of other problems of great social and economic importance in the steep and low lands of the tropics, like floodings, landslides, etc(56). When coupled with computer technology, geographic information systems, and expert systems, the simulation models may be very useful for design of sustainable management systems (53), with minimum risks of crop production and soil degradation, derived of variability on soils and climate.

Models must be based on well established cause-effect relationships for prediction, and validated for the conditions and purpose to be used. The guidelines must be flexible enough to be able to include the variety of soil-climate-cropping situations prevailing or possible in tropical regions, and to be constantly improved, as more is known about the influence of specific land characterisitics and qualities on crop yields and degradation processes. It is also necessary to keep in mind that good redictions by using models will be only possible if they are ased on good data from field observations and measurements, which any times are scarce in tropical regions (49), and not on enerated or assumed data. Modeling has permited the dentification of the most important inputs and has increased the equirement for more and accurate observations and measurements of oil properties under field conditions (50). Therefore, when ecessary, gathering of the missing data, and quality control of he available data. would be a prerequisite to use models. In any ase, models should only be used when the user has wide field xperience, so that unreasonable results can be detected and xplained.

The fundamental data required for models used in predicting crop erformance and soil degradation processes in the tropics, derived f the impact of land use and management practices in the soil ydrology, must include weather (mainly rainfall) variability in pace and time. and soil properties and their spacial variability. The data about soil properties generally required are those nfluencing water entry and retention in the soil, limits of water retention capacity of the soil, loss of water by evaporation, and environment for root growth. When there are not possibilities for the direct measurement of the soil attributes required to execute a simulation model, there have been proposed methods to approximate the needed soil properties from existing soil taxonomic data, but many times, when the correlations have not been obtained in situ, the possibilities of large errors in the output of the model are very high. The weather data required for the models are the ones influencing potential water supply to the crop and to runoff, and evapotranspiration. These includes daily values of rainfall, and monthly values of solar radiation and of maximum and minimum temperatures. When long term weather records, or daily rainfall, are not available, an alternative procedure is to use stochastic time-series modeling to generate a sequence of weather data, similar to historical sequences (45).

As an example of the proposed approach to evaluate and predict crop production and soil degradation risks, there are presented three isolated examples, showing different combinations of soil, climate, slope, cropping pattern and land management. The soil moisture regime, is calculated using an agroclimatic model (35)(38)(39), that simulates the evolution of the soil water balance with a time step of one day. The output of the model includes the soil moisture regime of the soil in a daily basis, including average soil moisture in the root zone, water losses by runoff and internal drainage, duration and intensity of waterlogging, and suplementary irrigation requirements. The soil moisture conditions, and waterlogging, may be interpreted in relation to drought and aeration problems along the growing periods of different crops.

The graphs in figures 1, 2 and 3 represent in a simple way some of the inputs and outputs of the model. The left vertical coordinate represents the mm of rainfall (Rain) (vertical bars) and of water stored (horizontal lines) at effective maximum root depth, at saturation (Satn), field capacity (F.Cap.), liquid limit (Liqu.Lim), 0,15 Mpa suction (WP), 1,5 Mpa suction (PWP), and mm

of actual soil moisture (Soil Moist.) (solid curved line) at root depth. The right vertical coordinate represents the total mm of runoff, drainage below the root depth (Int.Dr.) and waterlogging (W Logging). The horizontal coordinate are the days from sowing of the crop (Fig.1), of the first crop in the cropping sequence (Fig. 3), or of the period with higher rainfall concentration (Fig.2).

Figure 1 shows the risks of erosion and drought, due to surface sealing under raindrop impact on bare soil, and shallow root depth (10 cm) derived of previous soil erosion losses, in an Alfisol on gently sloping land (6% slope), and semiarid climate (900 mm/year of average rainfall) in the Central Eastern Plains of Venezuela. The land is used for continuous, high input mechanized cropping of rainfed grain sorghum, with crop residues mostly used for cattle feeding on place. The most striking effects observed in the graph, with rainfall data from a year with average rainfall (frequency of 5 years), are the high concentration of rainfall and runoff at the beginning of the growing period (12-20 days) of sorghum, with low soil protection, and therefore high risks of accelerated soil erosion with losses of surface soil, fertilizers and seedlings; and the very high risks of drought (SM < WP) during the critical flowering and grain filling stages of the crop after 60 days.

Figure 2 shows the risks of mass movements by landslides in a Ultisol on very steep slopes (30-100%), in the SW of the Venezuelan Andes, with sub-humid to humid tropical climate (1500-2000 mm/year of rainfall), during the wetter part of the rainy season of an exceptionally rainy year (frequency of ten years), where the natural forest is being changed to grassland, usually overgrazed, and to continuous subsistence, low input cropping, with cassava, sugar-cane, coffee, etc. The continuous rainfall during the 56-64 and 110-116 days of the main rainy season on a a soil already wet, results in very wet topsoil, above liquid limit and saturation, with possibilities of associated concentrated runoff during those periods, and high risks of lanslides. The topsoil (30 cm) consists of very stable microagregates, which are very sensitive to liquefaction when the soil remains very wet, due to the restricted drainage of the underlying argillic horizon.

Figure 3 show the risks of low yields and crop loss by waterlogging and drought, during critical growing periods on the cropping sequence corn-sesame, in a flat Inceptisol, under a subhumid climate (1400 mm/year of average rainfall), in the Western Plains of Venezuela. The land is continuously used for high input, mechanized, rainfed agriculture, where the repeated use of disk harrowing generally leads to the formation of shallow (15 cm) compacted pans. Due to surface sealing, and reduced internal drainage and root depth, in a year with rainfall close to average (frequency of three years), the risks of waterlogging at the beginning of the growing period of corn (upper graph), and of drought in the 2nd half of the growing period of sesame (lower graph) are very high.

The same way, we might simulate the effects on those risks, of management practices providing surface cover, surface drainage, and breaking or preventing the formation of compacted pans, for various crops and cropping patterns, on wetter and drier years.

Fig. 1: Soil Moisture Regime (CHAGUARAMAS)
1 June-20 Sept.(Sorghum.10cm Root Depth)
(6% Slope. Bare. Average Rainfall)

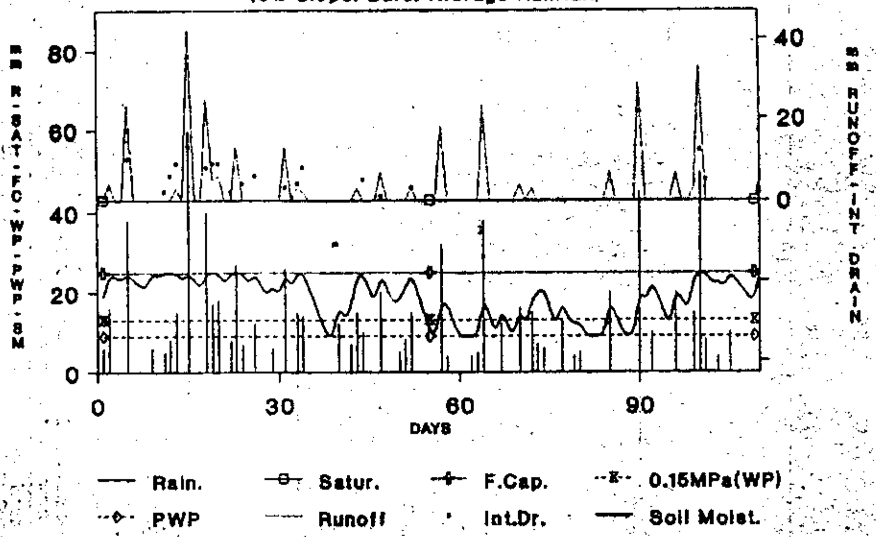


Fig. 2: Soil Moisture Regime (PREGONERO)
1 May.-28 Oct. (Grass. 30cm Root Depth)
(30-100% Slopes. High Rainfall)

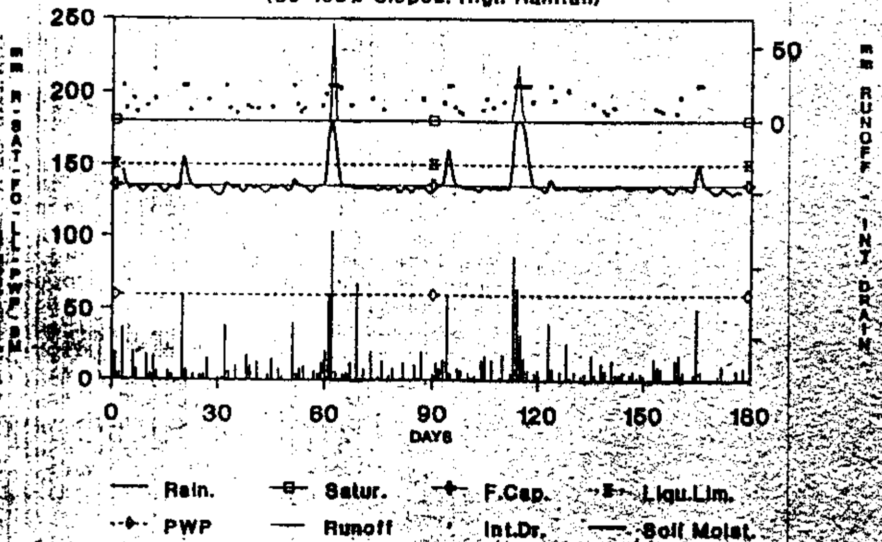
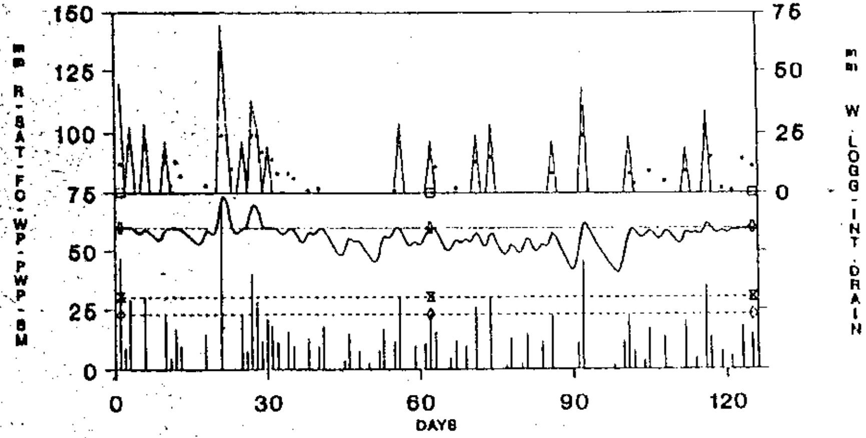
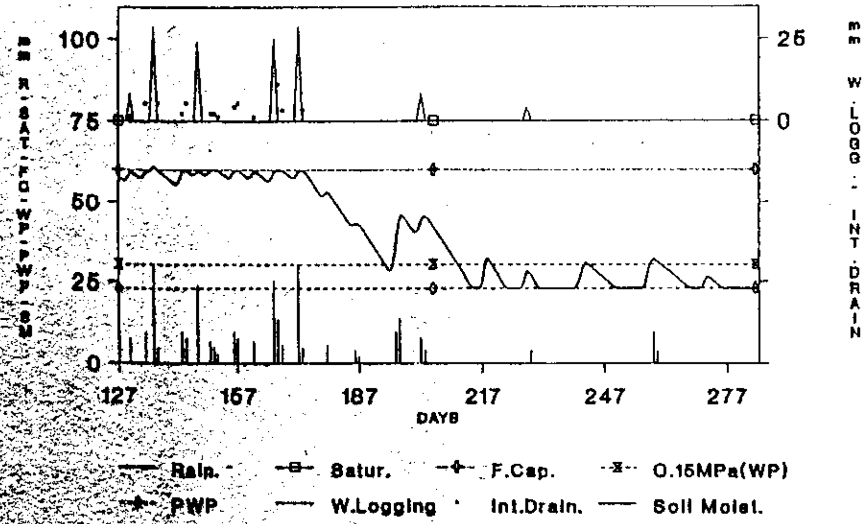


Fig. 3: Soil Moisture Regime (TUREN)
15 May-20 Sept.(Corn. 15 cm Root Depth)
(No slope. Bare. Average rainfall)



21 Sept-28 Feb.(Sesame.15 cm.Root Depth)
(No Slope; Bare; Average Rainfall)



General Conclusions. The actual and potential damage to soil and
environment by agricultural developments in the tropics is
generally more dangerous than in other climatic regions of the
world. Due to increased demand of food by the fastly growing
population, or to urgent requirements to increase export income,
the traditional low input shifting cultivation in the tropics
based on long fallow periods is intensified or changed to
continuous cultivation, and the cultivated land is expanded
through deforestation and development of new land mostly in
fragile ecosystems. In both cases, the degradation of the soil's
life support processes is accelerated, reaching in many cases the
point of no return.
The major constraint for sustained rainfed agricultural production
in the tropics is the variability in the supply of soil water to
plants, due to the variability, uncertainty, unreability and
pattern of rainfall, and the variable and dynamic soil properties
limitting the infiltration of rainfall water, and root
development. With high potential evapo-tranpiration rates the
result are unreliable soil moisture availability during critical
growing periods, leading to low yields and high production risks.
These problems are being intensified when also due to the climatic
and soil characteristics, the soil is degraded by erosion, loss of
structure and decline in chemical fertility.
The objective of agriculture and land management systems in the
tropics must be to achieve a high and stable production, with low
probabilities of risk, and desirable yields, while causing a
minimum degradation of the soil quality. Conservation practices
have to be designed to compensate for non-uniformities, excesses
or inadequacies, in amount and distribution of rainfall, and to
reduce risks of crop failure, and stabilize crop yields at
economic levels. Low input systems, like traditional shifting
cultivation, cannot solve any more the problems of food deficit
for the increasing population in most of the tropical developing
countries. A large portion of the food required for the near
future in the tropics will have to come from intensification and
improving the crop production in the present agricultural lands,
making more effective use of water and fertilizers, and using
practices that minimize risks of production and of soil
degradation. The most effective way to control erosion, and
increase crop yield in the tropical semiarid to subhumid tropics,
is through better rainfall water management. Practices that reduce
water related constraints (excesses or deficits) that limit crop
production, and minimize runoff losses, result in more efficient
use of rain water for crop production, while reducing erosion. To
reach those objectives, the management efforts have to be mainly
directed to maintain or to increase the soil, by giving the physical and
water-holding capacity of the available
chemical conditions for a non restrictive root development,
together with providing sufficient protection and stabilization of
the surface soil to prevent strong reductions in infiltrability by
sealing effects. With higher crop yields, also higher crop
residues levels can be managed to further increase water
conservation, reducing the level of risk of crop production and of
soil degradation. In another words, this means using a sustainable

land management. The new areas to be developed are situated in
more adverse environments, where production risks will be higher
due to increasing hazards such as droughts, floods, erosion,
compaction, etc, unless drastic measures are undertaken to combat
the causes and effects of land misuse.
Improved systems for the conjunctive use of the inherently
unpredictable rainfall and suplementary irrigation for crop
production in the semiarid and subhumid tropics, may be an
important factor for a greater use efficiency of both water
resources, increasing and stabilizing, with decreased risks,
future agricultural activities on those areas. In regions or areas
with high population pressure, it may be the only way to reach
sustainability.
In some tropical regions the previous traditional strategy for
sustainable agriculture through soil modifications (fertilizers,
tillage, irrigation) to suit the needs of annual crops for food
production, will have to be substituted by crop (mainly perennial
crops) adaptation to adverse conditions and low input.
Agricultural systems based on perennial crops, including trees
(coffee, tea, rubber, oil palm, cocoa) and grasses, alone or in
combination with annual crops, have been, and may be the best
solution for proper and efficient use and management of soil and
water resources, while keeping relatively high productivity, in
many tropical areas where sustainability of production of annual
crops would be not possible or too costly.
In tropical areas where soil resources for expansion of
agricultural production are limited in extension and quality for
cropping, efforts have to be also directed to the rehabilitation
of already degraded lands. It is necessary to investigate the
extent to which the degradation-induced productivity loss is
reversible, and if it is more cost effective to intensify
production on already cultivated lands of higher quality than to
invest in rehabilitation.
The development and selection of agrotechnology for a better
management of soil and water resources, to optimize productivity
and to decrease levels of risk of crop production and of
degradation of soil and water resources to a minimum in tropical
regions, requires a better understanding of the efficient use of
water and its relationship to soil properties. This understanding
is also required for the study of possibilities and development of
technologies for the rehabilitation of already degraded lands.
Historical climatic records, including statistics of past events
and trends, together with adequate information on crops and on the
hydraulic properties of soils and their dynamics under different
land use and management, may be integrated in simple water balance
models, and used to assess the intensity, timing and probabilities
of unfavourable soil moisture conditions, and other environmental
factors affecting crop production and soil degradation in
particular area. When these assessments are analyzed in
conjunction with other social, economical and environmental
issues, they may provide a very meaningful information on risk
levels, and possible consequences of drought, waterlogging,
surface erosion, floodings, sedimentation, landslides, etc, in
different tropical regions. This information can be used in

nning strategies about agricultural or other uses of land, and select water and soil conservation and management practices and pping systems based on probabilities of success, level of sks, and log term sustainability. Once the strategies based on dictions are adopted, monitoring, using real information and predictions of high uncertainty in tropical climates, is uired for rapid adjustments of soil, water and crop management ctices designed for sustainable agricultural production.

climate aand soil data required for the proposed assessments risks of crop production and soil degradation, and to evaluate entially useful sustainable land management practices, are erally not sufficient, both in quantity and quality, in many pical regions of the world. Under those circunstances, use of hly detailed models, which require more and better climate and data than available, is worthless, and may lead to dangerous stakes in land use and management decissions. The increased use information technology such as geographic information systems, of simulation modelling procedures, generally need more and tter climate and soil data to be properly applied. Even the sibility of using "pedotransfer functions" to infer the available soil parameters which are needed for simulation, uire of accurate primary soil data to relate with.

conclusion, land use and soil management practices in the opics, have to be based on the principles of soil and water servation, with the partial objectives of preventing or nimizing degradation of soils and environment and rehabilitating ready degraded lands, while increasing productivity. The fective design, selection and implementation of technologies to ach those objectives require of more and better information out climate and soil resources in the tropics. Considerable fort must be directed to the development and selection of equate and applicable field and laboratory methodology, to ther the minimum required data set, where this is not available. pecially needed are better and simpler methods to monitor portant hydraulic properties of soils, and their dynamics, on a eld scale, for both diagnostic and prediction purposes. The erall objective must be the improvement of food production in stainable systems, with the minimum inputs and levels of risks. the rapidly increasing population and social needs in many opical regions, this would be only possible transforming the evailing low-input subsistence agriculture in marginal, very eep and fragile tropical ecosystems, into sustainable and tensive commercial farming in the more rich and stable, flat or ntly sloping lands. This will require of important cio-economic changes and control of population growth in many veloping tropical countries, with the solidarity and cooperation the international community.

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Faunal activities and soil processes : Adaptive strateg that determine ecosystem function

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Knowledge of (faunal) effects will no become of utmost importance in the near when man will distinguish that soils have rich in life for his survival (Bal,

Introduction. Soils host an extremely high diversity of organisms. In one hectare of tem forest, several hundred species of soil invertebrates may coexist (Lavelle and Spain, 1994). been -and it still is- an enormous task for zoologists to identify and classify all these sp However, the perception of the functional importance of soil invertebrates is as old as the interc their classification. Aristoteles called earthworms "the intestine of the earth" and Darwin was th of a long lineage of zoologists that have been fascinated by the unwearying and multiform activ earthworms.His book "The formation of vegetable mould through the action of worms observations on their habits" (1881) and the work of Müller on humus forms (1884) are still fa products of an active scientific community which inspire the creation of soil ecology (Bal, 198 the same time, Dokuchaev (1883) formulated the basic concepts of pedology, but soil biolog pedology largely ignored each other for several decades while they devoted considerable effo soil classification and the separate elucidation of basic soil processes.

In the 1970's, the International Biological Programme (IBP) produced a large amou quantitative data on the abundance of soil invertebrates and their participation in energy flux different ecosystems (see e.g., Petersen and Luxton, 1982). It was concluded that their direct e on the release of CO_2 from soils was limited to a few percent of the total, microorganisms bei far the major decomposers. During the following decade, considerable efforts were devoted t description and quantification of the direct and indirect effects of soil invertebrates on the r processes that determine soil function, i.e., regulation of microbial activities, the dynamics o organic matter and nutrient cycling, and the formation and maintenance of the physical structure e.g., Lavelle, 1978; Barois, 1987; Coleman, 1985; Anderson and Ineson, 1982 ; Eschenbre 1986; Martin, 1990; Andren et al., 1990; Blanchart, 1991). Experiments in small laboratory cha called microcosms, and field observations and experimentation, mainly developed over short periods, gave a large amount of results, sometimes quite contradictory (Anderson, 1987). The e of soil invertebrate activities on plant growth have been considered in a number of studies, as a n to ultimately test their effects on fertility (e.g., Stockdill, 1959, 1982; Setälä and Huhta, 1991; S et al., 1992; Okello-Oloya and Spain, 1986 ; Pashanasi et al., 1992).

These experiments have demonstrated that 1). in small laboratory designs, soil invertebrates have effects which are largely disproportionate to their abundance and biomass, especially on s term processes, e.g., the release of mineral-N and P from decomposing litter, or aggregation of 2). in field conditions, the addition of these short-time effects may not have significant effect larger scale of time and space since climate, soil characteristics or the chemical composition of or matter may have a larger impact in determinating soil processes than invertebrate activities.

Soil degradation and desertification in Mediterranean environments
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SOIL SALINIZATION AND LAND DESERTIFICATION

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SUMMARY

The salinization, or development of salt affected soils (saline and sodic),is a degradation process usually leading to desertification of lands. In general, in salt affected soils the water defficits make the survival of natural vegetation and crops difficult or impossible. These moisture deficits are due to the difficulties for the plants to use the water stored in the soil ("saline soils"), or to the difficulties for root development and for water infiltration into the soil ("sodic soils"). Although those processes may occur, and have ocurred under natural conditions, , they become accelerated, leading to secondary salinization, when, mainly in arid and semiarid environments, the soil water regime is drastically changed with the introduction of irrigation and/or drainage.

In many countries the irrigation has become a very important component of food production, sometimes the most important. The area with irrigation in the World has increased from 50 Mha in the year 1900 to 100 Mha in 1950, and to 250 Mha today. To this phenomena has also contributed the decrease of productivity and the increasing risks of dryland agricultural production on lands already affected by other degradation processes, mainly water erosion. The yearly loss of productivity, and desertification of irrigated lands, amounts to 1.5 Mha around the World, but the salinity problems, in different degrees, presently affect almost 50% of all the irrigated land. Although the affected areas by salinity are much less than the ones affected by other degradation processes like erosion, the social, economical and environmental effects are of the same magnitude, as a consequence of the high value and productivity of irrigated lands, and their coincidence with areas of large urban and industrial developments. In arid and semiarid climates, the scarcity and erraticity of rainfall, together with the high evapo-transpiration rates, makes the water and salt balances favourable for the processes of soil salinization, specially under poor drainage conditions. These are the predominant conditions in the plains, valleys, deltas and coastal plains of the Mediterranean Region where irrigation has been introduced, because the soils and climate are favourable for a continued agricultural production of high productivity, if the soil moisture and salinity are well controlled.

The problems of secondary salinization are a consequence of non adequate water management by irrigation and drainage, under a particular set of conditions, including climate, crops, soils, fertilization, grounwater depth, water quality, and irrigation system. Therefore, the possibilities to preview the best conditions and alternatives of irrigation water management to prevent, control and decrease the problem of salinity, will depend on the understanding and modelling of the interactions of those factors for each set of conditions. This becomes more important when the limited water resources of good quality are preferentialy used to satisfy the urban and industrial requirements, and when the quality of surface and ground waters used for other purposes may be affected by the drainage effluents from irrigated lands. In this paper there is presented an improved version of a model developed by the author, which may be useful, among other things, to preview the best alternatives for the use and management of the available soils and waters, preventing the process of desertification by secondary salinization.

1. Introduction

Salinization, or development of salt affected soils, is one of the processes of soil degradation leading to land desertification. The salt accumulation may lead to a partial or complete loss of the soil capacity to provide the required amounts of water to plants, changing fertile lands to "deserts". Frequently, the salinization processes creates a practically irreversible chemical or physical internal soil degradation.

Worldwide more than 10% of lands are affected by some type and level of salinization, with 350 Mha already completelly "desertified". Although the salt affected soils may be found in almost any climate, they are more common in arid and semiarid climates, and in flat and low lands. It is considered that about 25 Mha of lands have been salinized through human intervention since the development of irrigated agriculture thousands of years ago (Szabolcs, 1989; WRI-IIED-UNEP, 1988).

The salinity problems appear as a consequence of salt acummulation in zones and depths where the soil moisture regime is characterized by strong losses of water by evaporation and transpiration, and by reduced leaching of the remaining salts. Although these processes of salinization may progressively develop under natural conditions where a combination of aridity and restricted drainage exists, they may only be accelerated when the soil moisture regime is drastically changed with the introduction of irrigation, without appropiate drainage conditions.

2. Salinization and irrigated agriculture

Irrigation of agricultural lands has been considered for several milenia the most effective way to increase and regulate the crop production, specially in arid and semiarid zones. Frequently those benefits have not been sustainable mainly due to soil salinization. This is known from the ancient times, and it has been said that the salinization of large irrigated areas in the Mesopotamian Plain conduced to drastic decreases in food production, and was one of the main causes of the fall of the Sumerian civilization almost

5000 years ago. Both then and nowadays, the salinization of agricultural lands is a co sequence of an inadequate combination of irrigation water management, and drainag conditions.

Salts, in variable amounts, are always present in irrigation waters. The input of sal through irrigation may reach more than 10 Mg/ha in one year. Most of them remain i the soil when the water is lost by evapo-transpiration. When those salts are not leach to the subsoil and lost through internal drainage, they will accumulate in the surface so reaching levels which may affect the plant growth. When the required leaching is not pr vided by the excess of rainwater, common situation in arid and semiarid climates, it required to apply an excess of irrigation water for such purpose. If those excesses water are not taken away by the natural or artificial drainage systems, probably the le ched salts will come back to re-salinize the surface soil.

From the previous arguments it may be deduced that the introduction of irrigation i arid, semiarid, and ocassionally subhumid zones, will lead to soil salinization problem unless there are provided adequate drainage conditions. The drainage practices to contr salinity problems in irrigated areas were practically unknown until the beginning of th century, and only after 1945-50 they had a scientific base (Boumans, 1987). The conce of leaching requirement, or leaching required to control salinity under tolerable limi (expressed as a % of the irrigation water applied), was introduced only in 19 (USDA, 1954). The application of all these recent advances have allowed in many cas to control salinization, and even to recover areas already affected by salts, finishing wi the old axiom that irrigation would lead in any case to soil salinization.

Although the development of irrigated agriculture has been associated to the dev lopment of great ancient civilizations, its rapid expansion to large areas has been only recent times. From about 8 Mha of land with irrigation in the whole World in 1800, t irrigated area was extended to 50 Mha in 1900, ant to almost 250 Mha at present, wi projects to expand it to 350-400 Mha in the next twenty years. Presently, 80-1000 milli people in the World have activities related to irrigated agriculture, which produces ab 35 % of the food in only 18 % of the cropped area (Szabolcs, 1989; WRI-IIE UNEP, 1988). The main factors responsible for such accelerated growth of irrigated ag culture are:

1) The need to intensify the agricultural use of lands for satisfying the increasi food requirements of people.
2) More than 75% of the World agricultural lands are in arid, semiarid and subh mid zones, where the scarcity and erraticity of rainfall leads to very poor a risky production of rainfed crops.
3) The more or less irreversible loss of productivity in large areas of rainfed ag cultural lands affected by some other processes of soil degradation, mainly wa erosion.

In many cases, the irrigated agriculture developed in the lower and flatter lands valleys and watersheds, makes use of soils formed on sediments originated from past a present processes of erosion in the higher and steeper lands of the watershed. It also us surface and ground waters feeded by runoff losses from those degraded lands, due to their low rainwater intake rates and reduced moisture retention capacity.

Regretfully, the fast development of irrigated agriculture has been, and still is, associated to an increase in soil degradation by salinization processes. This happens despite our generally good knowledge about how to predict, control, and revert such processes. The precise evaluation of salt affected areas of human origin is sometimes difficult (ISRIC-UNEP,1990), because the problems of salinization develops progressivelly, and sometimes they are only visually apparent when they have reached conditions difficult to recover. It is known that every year about 1.5 Mha of irrigated land lose 25-50% of their productivity due to salinity; and that 50% of the whole irrigated area in the World suffer losses of productivity due to salinization processes. Taking into consideration the great investments required for the development of irrigated agriculture, and their high contribution to the World food production, we may conclude about the great importance of land degradation by soil salinization from the economical, social and environmental point of views; and about the urgent requirements to prevent and control the processes leading to such degradation.

3. Salinization in the mediterranean region

In the predominant semiarid mediterranean climate rainfall is impredictable, and with great variation from one year to another. Therefore, the probabilities of low yields, and the risks of complete losses, of rainfed crops is very high. In addition to that, the high erosivity of rainfall, together with poor soil cover and inadequate land use and management, have led to advanced land degradation by water erosion in the predominantly hilly topography of the region (Chisci,1990), decreasing the potential for producing rainfed crops. This, added to the increasing markets for some agricultural products requiring irrigation, explains why the irrigated area in the Mediterranean Europe has increased three times since the beginning of the century.

The development of irrigation has been mainly in flat alluvial lands, bottom of valleys, and coastal plains and deltas, generally with slopes less than 5%. Those areas, under the predominant mediterranean climate, are frequently affected by floodings and sedimentation. In those lands, with low risks of erosion (Rubio and Sanroque,1990), the main potential problem of desertification is soil salinization, due to the combination of climate, drainage, quality and management of the irrigation waters.

The needs to increase the areas with agriculture under irrigation, and the increasing problems of salinization in irrigated lands, in most of the mediterranean countries, has been already recognized (Albaladejo,1990; Chisci, 1990; Generalitat Valenciana,1987; Pereira et al,1987; Yassoglou,1990). Irrigation developments have not only reduced the production risks due to moisture deficits, but have also allowed cropping in the summer months, and the introduction of perennial fruit crops. With the high sun radiation in the Mediterranean Region, the irrigated crops are usually highly productive, if there are maintained adequate water and salt balances in the soil. The area under irrigation is already in some mediterranean countries more than 1/4 of the total cropped area. About 25%

of the 6 Mha of irrigated lands in the Mediterranean Europe are desertified by moderate and severe degrees of salinity (WRI-IIDE-UNEP,1988). Compared with this, 39% of the 76 Mha with dryland agricultural production (40 Mha with crops), are desertified mainly due to water erosion. The last twenty years, the irrigated area has been continuously increasing, while the area with rainfed agriculture has decreased almost 20%.

Frequently the areas with irrigated agriculture are located close to zones with high urban and industrial developments, which demand and consume most of the scarce water of good quality. For irrigation of crops there are sometimes only left waters of poor quality, mainly saline groundwaters and partially treated urban and industrial effluents. The over pumping of groundwaters in coastal plains frequently leads to intrusion of sea water in the aquifer, gradually increasing the salinity of the pumped water (Generalitat Valenciana,1987) . Similar results are obtained when the over explotation of aquifers brings to the pumping level deeper and more saline groundwater.

The excess of water required to leach salts from the soil, to reclaim or to prevent salinization, may cause other environmental problems derived of the disposal and further use of that water. The problem is agravated because those leachates may contain not only salts, bur also residues of fertilizers and pesticides, which are generally used in large amounts in the intensive irrigated agriculture. They may contaminate surface or ground waters to be use for human, industrial, or agricultural purposes. In those cases, the practices and systems of drainage and irrigation must pursue a maximum efficiency in the use of irrigation water, reducing the possibility of losses and contamination of other waters, but keeping at the same time the salts at depths not reached by the crop roots. This has to be sometimes combined with systems for disposal of drainage waters before they mix with others.

Desertification of lands by soil salinization in the Mediterranean Region may be worsening at increasing rates in the next decades, due to the previewed increase in irrigated areas, and to the increasing scarcity of good quality waters, unless some preventive actions are urgently taken. The problem may be aggravated due to the global climatic changes, previewed for the near future. It has been speculated that in the Mediterranean Europe those climatic changes would double the salt affected areas in the next 50 years, mainly in the same zones where salinity is already a problem (Szabolcs,1990). This would be caused by an increase in the aridity index, affecting the moisture regime and salt balance in the soil, with less leaching and more salinization. The increase in aridity would also force an increase in the irrigated areas, and the use of waters of poorer quality. Another previewed effect on the salinization of lands would be due to the rise of sea level, by flooding the low lands in deltas, and by increasing the intrusion of saline water in coastal aquifers.

Another reasonings, preview some positive effects of the future global climatic changes on the crop growth and productivity, due to the increase of CO_2 in the atmosphere (Goudrian and Unsworth,1990). Under greenhouse conditions it has been proved that higher levels of CO_2 increases its assimilation by plants, even in conditions of moderate soil moisture stress, due to low moisture (matric stress) and/or salinity (osmotic stress). This would happen because the CO_2 and the transpired water follow the same physical pathway through the stomata. The final result is an increase in the efficiency of water use, mainly due to a decrease in the transpiration rates (C4 plants), or to a stimulation in the rate of CO_2 assimilation (C3 plants). These effects would indirectly increase the availability of photosinthetic products for osmotic adjustments required to keep cell turgor in more saline soils. Nowadays, some of these effects are obtained with the increasing use of greenhouses for different crops in the Mediterranean Region.

It may be concluded, that although at present time the area desertified by human induced (secondary) salinization in the Mediterranean Region is less than the affected by other degradation processes like erosion, the importance of both problems, from the economical, social and environmental points of view are comparable. This is due to the higher value and productivity of the affected irrigated lands, and their location generally in areas with high urban and industrial developments, competing with agriculture for the use of the scarce available water resources.

4. Saline and sodic soils. Characteristics and effects

In general, all soils with problems directly or indirectly derived from the amounts and kind of salts in solution are referred as "salt-affectd soils". The resulting problems may be very different, depending on the geochemical processes involved in the development of salinization. This applies both to the salinization developed through natural processes (primary salinization), and to the salinization induced by human intervention (secondary salinization). In both cases, the main responsible factors are the concentration and the relative composition of salts in the surface and ground waters, and the changes they may suffer in soil solution. These changes are dependent on the soil moisture regime, which is a consequence of the drainage and climate conditions. Drainage is the result of the hydraulic properties of the soil profile, of the groundwater depth, and of the landscape position. Rainfall and evapo-transpiration are the main climatic factors to be considered. The development of secondary salinization, in different soils and climates, is generally caused by drastic changes in the soil moisture regime due to the introduction of irrigation with drainage restrictions.

Both in surface and groundwaters, and in soil solution, most of the salts are a combination of the cations Ca^{++}, Mg^{++} and Na^{+}, and of the anions HCO_3^-, Cl^- and $SO_4^{=}$. In some highly fertilized soils, the anion NO_3^- may also accumulate in soil solution. The main natural source of the predominant salts is the weathering of minerals in the earth crust, the rainfall in coastal areas, and the dissolution of fossil salts in some geological formations of marine origin. The human intervention brings additional salts to the soils through irrigation water, residual waters, and fertilization. The differences in amounts and kind of salts accumulated in soil solution result in "salt-affected soils" of varied chemical, physical and physico-chemical properties, having different management requirements for their prevention, use and reclamation.

Based on the main effects on soils and crops we may classify the "salt-affectd soils" in "saline soils" and "sodic soils". Traditionally the "sodic soils" have been called "alkali soils", although these include only the sodic soils with presence and accumulation of

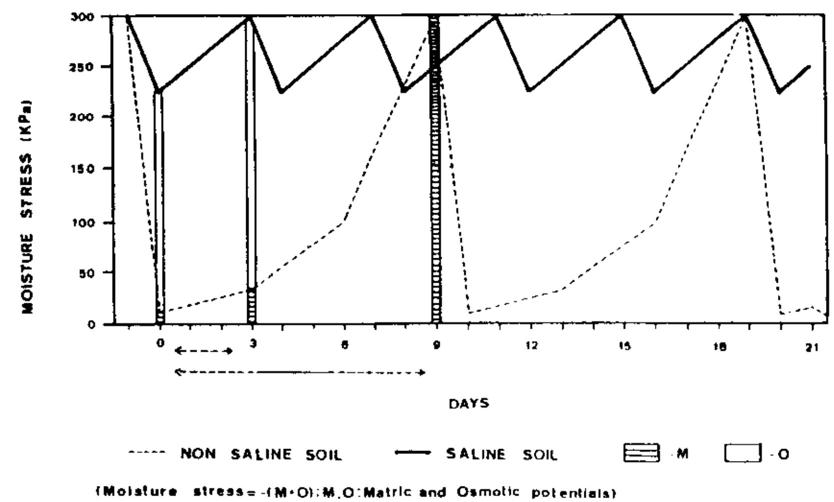

Figure 1. Frequency of irrigation in a non saline soil, and in a saline soil (EC:5 dS/m in Sat.Extr.) for a limitting soil moisture stress of 300 Kpascals.

Na bicarbonates and carbonates and pH higher than 8.5-9.0. There are other soils wit properties of sodic soils with lower pH and lower relative levels of Na than the alka soils (Pla,1988).

The "saline soils" are those where the salt content and osmotic pressure of the so solution do not allow the absorption by the crop of a great portion of the soil water, an do not show any direct effect on the soil physical properties. The main consequence i the partial or complete reduction in plant growth due to physiological water defficits. Fo practical purposes, the salt concentration is expressed in terms of electrical conduct vity (units of dS/m:deciSiemen/meter at 25oC) in soil saturation extract (USDA,1954 One dS/m is aproximatelly equivalent to a salt concentration in solution of 10 meq./lite and to an osmotic pressure of 36 KPascals.

It is well known that the soil moisture stress for plants is composed by the matri stress, which increases when the soil moisture decreases, and the osmotic stress, whic increases when the salinity in soil solution increases. Both stresses are more or less add tive. Therefore, one approach to reduce the effects of salinity would be to maintain th matric stress as low as possible, through frequent or continuous irrigation (see fig. 1 Another approach would be to plant salt-tolerant crops, which are able to grow and pro duce economical yields even at high soil moisture stresses, through adjustments in the transpiration rates or in the osmotic pressure in their cells.

As a consequence of the selective accumulation of some specific electrolites in so solution, in some occasions, specific nutritional or toxic effects are associated or prece de the more general osmotic stress effects. This is the case with some sensitive crop when chloride, sodium, and sometimes boron, reach critical levels in soil solution. I

Conditions					
IRRIGATION WATER					
Concentration:	(High)		(Medium)		(Low)
(EC):	> 2 dS/m		1-2 dS/m		< 1 dS/m
Compositon:	Cl>S>B Na>=CA		S>=Cl>B CA>Na	B>=S>Cl CA>=Na	B>S>Cl B>CA Na>=CA
DRAINAGE	(Variable)		(Very restricted)		(Restricted)
Soil Perm. (I):	1-50 mm/hour		< 1 mm/hour		< 5 mm/hour
Groundwat. level:	< 1.5 m		< 0.5 m		< 1.0 m
CLIMATE	(Ar. DSAr.)		(Ar. DSAr.)	(DSAr. -SH.)	(Ar. -HSAr.)
IMA (P/ETP):	< 0.5		< 0.5	0.5 - 1.0	< 0.8
LGP (P > (ETP/")):	< 120 days		< 120 days	120-270 days	<180 days
Resulting problem					
SOIL SOLUTION	(Very saline)		(Mod. saline)	(Sligh. saline)	(Var. sal.)
Concentration (EC):	> 8 dS/m		> 4 dS/m	< 4 dS/m	> 2 dS/m
Composition:	Cl>>S>>B Na>CA (A)	Cl>=S>>B Na>=CA (B)	S>Cl>B Na>CA (C)	(*) S>=B>Cl Na>>CA (D)	B>=S>Cl Na>>CA (E)
pH	< 8.5		< 8.5	>7.5	> 8.5
PRECIPITATED SALTS:	CAC, CaS		CAC, CaS	CAC	CAC
EXPECTED POTENCIAL KIND OF PROBLEM:	"SALINITY"			"SODICITY"	

Cl, S, B. Na, Ca, CA: Chlorides, sulfates, bicarbonates, Na, Ca, and Ca+Mg respectivelly, in water or soil saturation extract. CAC, CaS: Ca+Mg Carbonates and Ca Sulfate, respectivelly, precipitated in the soil. EC: Electrical Conductivity. I: Minimum Water Intate Rate. IMA: Index of Moisture Availability = Rainfall/Potencial Evapo-Transpiration (P/ETP) in the whole year. LGP: Length of Growing Period = Days with rainfall higher than 1/2 of the potencial evapo-transpiration, and average daily temperatures higher than 5°C. Arid Climate (Ar): LGP =-74 days; Cry Semi Arid (DSAr.): LGP 75-119 days; Humid Semi Arid (HSAr.): LGP 120-179 days; Sub-Humid (SH.): LGP 180-270 days. (*) Permanent groundwater level, or presence of strata impeding or restricting the internal drainage. (*) Change of composition under anaerobic conditions ("$Na^+ + SO_4^= + 2C + 2H_2O = S= + 2NaHCO_3$).

Table 1. Conditions for the potential development of soil salinity or sodicity under irrigation.

occasions, the concentration of elements like selenium in some grasses, may affect the health of cattle eating them.

Frequently, the salinity effects on plants are only visible after the crop yields have been strongly decreased. This gradual effect of salinity on yield may be calculated (Mass and Hoffman,1977):

$$Y/Ymax.= 1\text{-}b\ (ECSE\text{-}ECSE\ max.)$$

where: Y:Actual yield; Ymax.:Yield in non-saline soil; ECmax.:Electrical conductivity in soil saturation extract when Y starts decreasing:intercept in the y axis of the straight line

relating Y/Ymax. and ECSE; b:slope of the Y/Ymax. vs ECSE line, characteristic t each combination of crop, climate and irrigation management.

Development of "saline" soils is more common in arid and dry semiarid climat with LGP<120 days(see table 1). The methods for prevention or reclamation of th soils are based on the leaching of the excess of accumulated salts, taking maximu advantage of temporary (seasonal) surplusses of rain water, and applying more irrigati water than the crop requirements. Depending on the circunstances, this leaching m only pursue the displacement of salts to depths in the soil profile not reached by cr roots, or their deffinitive displacement by deep drainage. The first alternative requires a carefull control in the management of irrigation water and of the groundwater level. some ocassions the leaching of "saline" soils may result in the development of "sodi soils, as a consequence of the salt composition in the original soil or in the water used l leaching, and also due to the particular soil mineralogy. In these cases, the reclamati of saline soils must follow some of the practices recommended for reclaiming sodic soi

The "sodic soils" include those where the accumulation of high Na levels, sometim with Mg, both in solution and exchangeable, in relation to the levels of Ca+Mg and to salinity, leads to deleterious effects on their physical properties. The main consequenc are drastic reductions, both in the saturated hydraulic conductivity of the soil and in tl surface water intake rate. In practice it has been proved very convenient to express tl "sodification" levels in terms of "sodium adsorption ratio" (SAR) in the soil saturati extract (SE) (USDA,1954):

$$SARSE = NaSE/(CaSE+MgSE)1/2$$

where Na, Ca and Mg are the concentrations of those elements in the saturati extract (SE) in milimols/liter.

The effects on soil physical properties are in some cases mainly due to the dispersi of clay and silt particles in the surface soil. This produce inmediate surface sealing, an with time may lead to the complete and irreversible plugging of pores by the dispers particles in a soil layer close to the surface, which becomes almost impermeable to wat and extremely compacted and hard when it dries out. These effects are more common i soils with high contents of silt and/or low swelling clay (hydrated micas, caolinite which may be dispersed at relativelly low levels (5% or less) of exchangeable Na if th total salinity in soil solution is maintained very low (Pla,1988).

In other cases, the harmful effects on soil physical properties also includes the blo king of pores by reversible swelling of clays under wet conditions. This generally requ res of higher levels (10-15%) of exchangeable Na, and of swelling clays, and generall comes together with high soil pH and accumulation of salts (Na bicarbonates and carbo nates) of alkaline hydrolisis. These soils have been also called "alkali soils", and som times "black-alkali soils" due to the dispersion and surface deposition of black organi matter. When the surface soil dries out and the swelling effect disappear, they generall develop deep cracks and a prismatic or columnar structure. Higher salinity levels in th soil solution, or in the percolating solution, decrease the dispersion and swelling effect

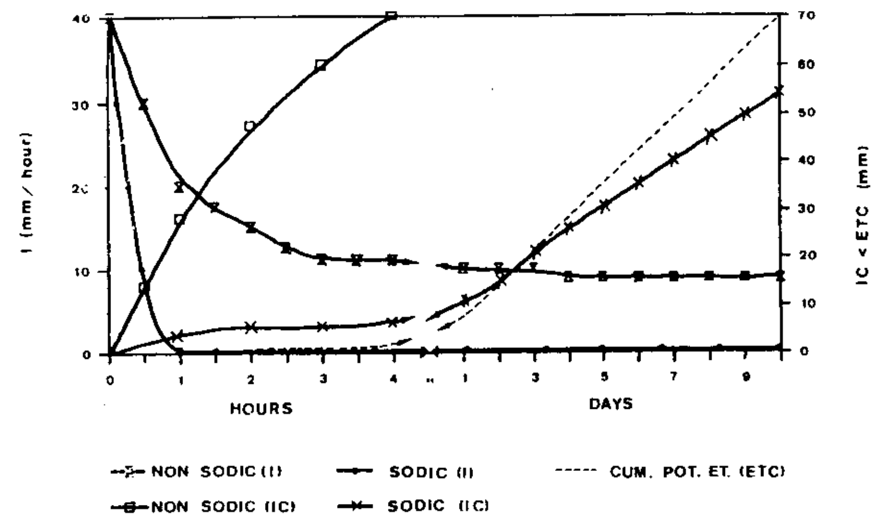

Figure 2. Water intake (Rate:I; cumulative:IC) in a non sodic soil and in a sodic soil, and cumulative potential evapotranspiration (ETC).

of Na . The critical levels of salinity and Na leading to sodicity effects, mainly depend on the content and nature of clays in the soil, and on the kind of predominating effects (dispersion or swelling).

The main negative effects of sodic soils on crops are due to the decreased infiltration and storage of water in the soil, to the increase of soil moisture at wiltting point, to poor and shallow root development, and to extended periods of defficient soil aeration. All these effects usually conduce to restrictions in water and nutrient supply to the crop. In some cases the maximum possible soil water intake is less than the accumulated potential evapo-transpiration of plants (Fig.2), making impossible even their survival. Some additional effects are due to poor root development or high pH, creating different nutritional problems. It is also common that many sodic soils, sooner or later become saline, because the very low soil permeability do not allow effective leaching of the salts continuously incorporated by the irrigation water. Therefore, the use of sodic soils is usually restricted to crops like rice or some grasses, which are able to grow under almost continuous flooding conditions. Their reclamation, and also their prevention in many cases, require the use of chemical ammendments before leaching. Those ammendments are mainly acid salts of Ca like gypsum, or acid products, and may be added to the irrigation waters or directly to the surface soil. The Ca from the applied product, or the Ca from the carbonates precipitated in the soil and dissolved by the acid, replace the exchangeable Na, which has to be afterwards leached from the soil solution. For leaching to be effective, there is required to improve the water intake and percolation rates in the soil profile to values higher than evaporation rates.

It may be concluded that there are not precise limits of salts and sodium to classi salt-affected soils (saline or sodic), and that the limits proposed in the past (USDA,195 may be only used as a general reference, and never to guide specific irrigation manag ment, or reclamation practices. The critical values may be very variable depending on tl particular combination of soil, climate, crop and management. The same variability exi in the possibilities of prevention and reclamation of saline or sodic soils. Table 1 show the main general conditions which may lead to the development of different kinds of sal ne and sodic soils. Additionally, some more specific conditions previous to irrigation (P and Florentino,1983), like presence of fossil salts at shallow depths in the soil profile, shallow saline groundwaters, may also influence the kind and degree of soil salinizatio Figures 3a-3e represent profiles of the different salt-affected soils developed with irrig tion under the conditions shown in table 1.

5. Predictive model for soil salinization

The problems of secondary salinization, leading to saline or sodic soils, are mainl due to poor water management (irrigation and drainage) in relation to a particular con bination of climate, soil, crop, fertilization practices, groundwater level and salinity, qu lity of irrigation water, and irrigation system. Today there are known methods and tecl nical possibilities to reclaim salt-affected soils, but in general they are too costly. Whe socioeconomic problems justify the reclamation, still we may have difficulties to do i derived from the scarcity of water of good quality for leaching, or from potential pr blems of contamination of surface and ground waters used for irrigation or for domest and industrial purposes. All these situations are very common in the arid and semiar zones under irrigation in the Mediterranean Region. Therefore, it would be more conve nient and economical to pre-stablish, through appropiate predictive models, which woul be the best alternatives for irrigation water management to prevent salinization problen for each combination of climate, soil and available - quantity and quality - irrigatio water. This would still be more important if there is a high competition for the use scarce resources of good quality water, when the quality of the available water is poo or when it is necessary to reduce the effluents of drainage water to a minimum.

To predict salinization problems the main pre-requisite is to identify the source salts, and to characterize the main factors determining the regime of water and salts i the soil. This is not easy, because the hydrological and chemical conditions involved i the process of salinization are usually very complicated. Therefore, we have to simplif some of them, to be able to develop models that can be put into practice.

Without adequate leaching and drainage it is not possible to control soil salinizatio under irrigation. That is why we base our prediction model in the so called "leachin fraction" (L), which integrates in one figure the actual or required water and salt balan ces. The leaching fraction is defined as the fraction of infiltrated water which eventuall is lost as internal drainage water after flowing through the soil below the root zone. It wa originally introduced in 1954 (USDA,1954), as a quantitative expression of the leachin required to control soil salinity below some critical level. Although the concept remain

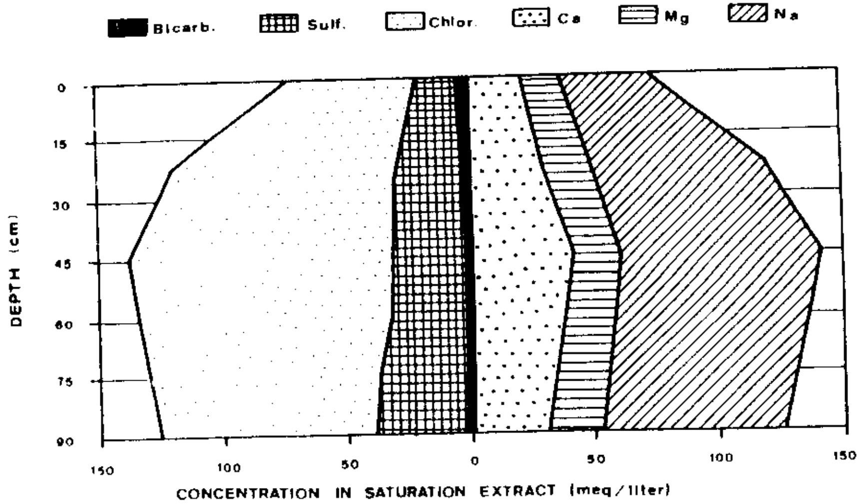

Figure 3a. Saline soil profile (A). (Predominant salt: Na chloride)

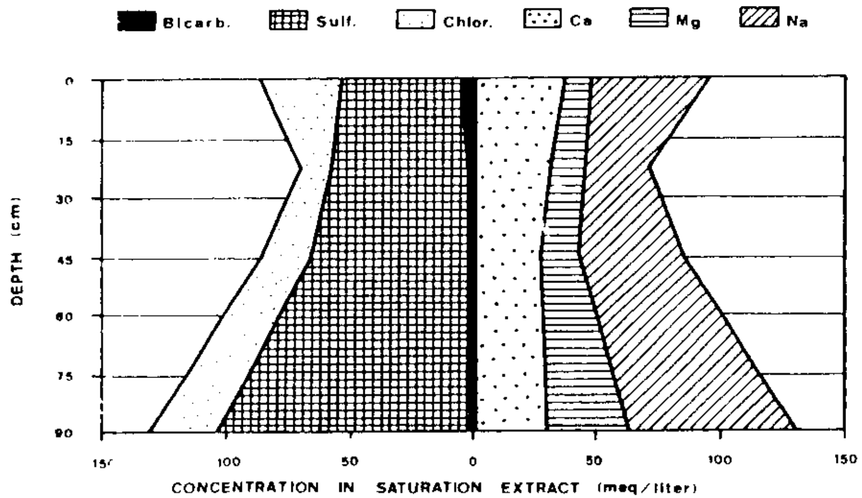

Figure 3b. Saline soil profile (B). (Predominant salts: Na and Ca sulfates)

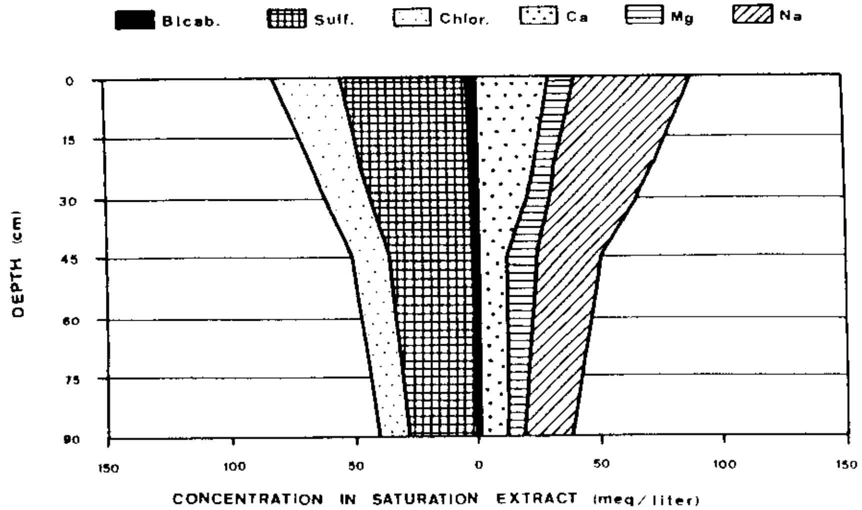

Figure 3c. Saline soil profile (C). (Predominant salt: Na sulfate)

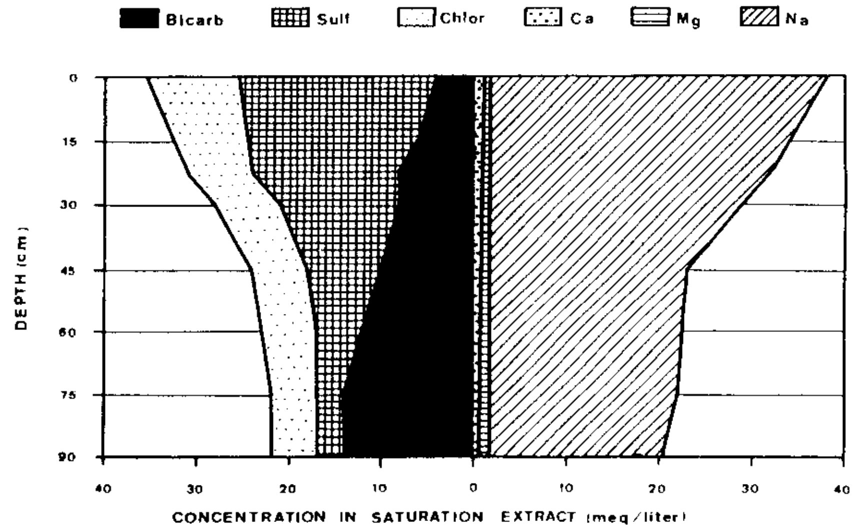

Figure 3d. Sodic soil profile (D). (Predominant salts: Na sulfate and Na bicarbonate)

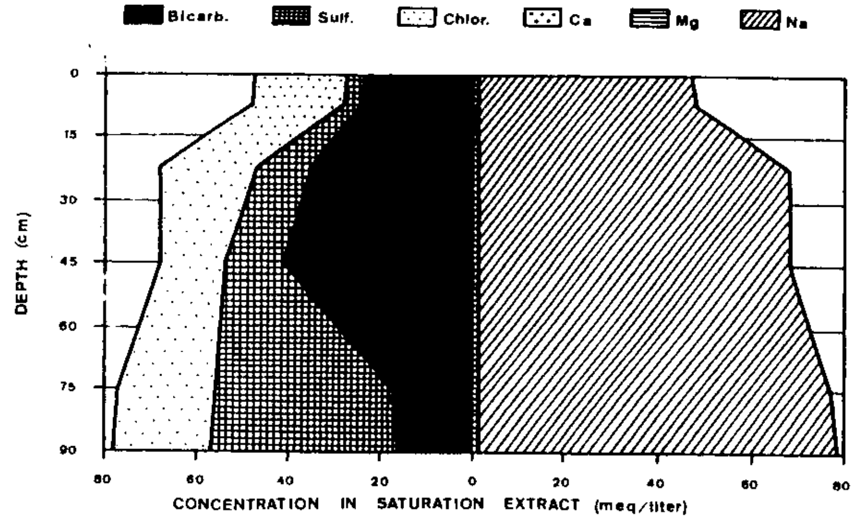

Figure 3e. Sodic soil profile (E). (Predominant salt: Na bicarbonate)

essentially the same, its calculation has become more precise through the years (FAO,1976; Pla,1968,1983,1988; Pla and Dappo,1974; Rhoades,1968,1984), and has been extended to the prediction of soil sodicity. These improvements have been possible thanks to a better knowledge of the relations among irrigation, drainage and salinity, taking into consideration in some cases the previewed precipitation or dissolution of salts in the soil profile, and the possibilities of sodification, besides salinization. This allows a more accurate calculation and planning of the irrigation and drainage requirements and practices.

The equations for the calculation of L presented in table 2, are the product of succesive approximations (Pla,1968,1983,1988; Pla and Dappo,1974) based on accumulated experiences and validations, in different agroecological zones, during the last 25 years. In this ocassion we introduce new independent balances of Ca and Mg, in order to preview some specific cases where the accumulation of Mg salts may be a critical factor. All calculations are based on an independent balance of the more common elements in irrigation waters and in soil solution, taking into consideration the possibilities of salt precipitation or dissolution under the prevailing conditions in irrigated soils. To do that, there are used as limiting conditions both the critical salinity levels for different crops and climates, and the critical sodium levels for different soils and concurrent salinity levels.

The proposed model first leads to preview the conditions for development of "salinity" or "sodicity". This prediction is very important, because the requirements for management or reclamation of those two kinds of salt-affected soils are very different. The

WHEN: B <= (Ca+Mg)

$$LF(ST) = (Na+Ca+Mg)/STSE; \quad LF(Na) = (2\,Na^2)/(SARSE^2 \cdot (Ca+Mg))$$

$$NaSE = Na/LF;\ CaSE = Ca/LF;\ MgSE = Mg/LF;\ ClSE = Cl/LF$$

If: 10 LF < B and 30 LF >= CaS
(Precipitation of Ca and Mg carbonates)

$$LF(ST) = (Na+Ca+Mg-B)/(STSE-10)$$

$$LF(Na) = \frac{((SARSE^2 (Ca+Mg-B)^2)+(80\,Na^2))^{1/2}}{20\,SARSE} - \frac{(Ca+Mg-B)}{20}$$

$$NaSE = Na/LF;\ CaSE = \frac{10(Ca+Mg-MgB)}{(Ca+Mg)} + \frac{(CaS+CaCl)}{LF};\ MgSE = STSE-(NaSE+CaSE)$$

$$ClSE = Cl/LF; \quad (Ca+Mg)Cp = (Ca+Mg) - LF(CaSE+MgSE)$$

If: 10 LF < B and 30 LF < CaS
(Precipitation of Ca carbonates and sulphates)

$$LF(ST) = (Na+Mg+CaCl)/(STSE-40)$$

$$LF(Na) = \frac{((SARSE^2 (Mg+CaCl)^2)+(320\,Na^2))^{1/2}}{80\,SARSE} - \frac{(Mg+CaCl)}{80}$$

$$NaSE = Na/LF;\ CaSE = 40+(CaCl/LF);\ MgSE = Mg/LF;\ ClSE = Cl/LF$$

$$CaCp = B - 10\,LF; \quad CaSp = CaS - 30\,LF$$

If: 10 LF >= B and 30 LF < CaS
(Precipitation of Ca sulphate)

$$LF(ST) = (Na+Ca+Mg-CaS)/(STSE-30)$$

$$LF(Na) = \frac{((SARSE^2 (Ca+Mg-CaS)^2)+(240\,Na^2))^{1/2}}{60\,SARSE} - \frac{(Ca+Mg-CaS)}{60}$$

$$NaSE = Na/LF;\ CaSE = 30+((Ca-CaS)/LF);\ MgSE = Mg/LF;\ ClSE = Cl/LF$$

$$CaSp = CaS - 30\,LF$$

WHEN: B > Ca+Mg
(Presence of Na bicarbonate and precipitation of Ca and Mg carbonates)

$$LF(ST) = Na/(STSE-Ca-Mg); \quad LF(Na) = Na/(SARSE \cdot ((Ca+Mg)/2)^{1/2})$$

$$NaSE = Na/LF;\ CaSE = Ca;\ MgSE = Mg;\ ClSE = Cl/LF;\ NaBSE = NaB/LF$$

$$(Ca+Mg)Cp = (Ca+Mg) \cdot (1-LF)$$

Ca, Mg, Na, B, S, Cl, MgB (B-Ca-NaB), NaB (B-Ca-Mg), CaS (Ca-B-CaCl) and CaCl (Ca-B-S) : Ca, Mg, Na, Bicarbonates, Sulfates, Chlorides, Mg Bicarbonate, Na Bicarbonate, Ca Sulfate and Ca Chloride in meq/liter in irrigation water, respectively; L : Leaching fraction; LF : Effective leaching fraction (F<=1); STSE, NaSE, CaSE, MgSE, ClSE, NaBSE, SARSE: Salinity (total), Na, Ca, Mg, Chlorides and Na Bicarbonate (meq/liter), and Sodium Adsorption Ratio ($SAR = Na/((Ca+Mg)/2)^{1/2}$) in $(mmols/liter)^{1/2}$, in saturation extract (SE),resp.; (Ca+Mg)Cp, CaCp and CaSp : (Ca+Mg) Carbonates, Ca Carbonate and Ca Sulfate, resp.,precipitated(+) or dissolved(-) in the soil,in meq/liter of irrig. water.

Table 2. Equations to calculate the effective leaching fraction (LF), and the concentration and composition of salts in soil solution or precipitated in the soil, for different equilibrium expected values of total salinity (TS) and of sodium adsorption ratio (SAR) in saturation extract (SE), and for different concentrations and compositions of salts in irrigation waters.

independent balance of the different ions permits to predict the accumulation in soil solution of some elements like Cl-, Na+, etc. which may be toxic to some crops before the development of general problems of salinity or sodicity. With the same approach it is possible to preview the conditions leading to more precipitation or dissolution of salts of limited solubility (Ca and Mg carbonates, and Ca sulfate), and the effects of this on the leaching requirements to control salinity and sodicity in the soil root zone. This has also a high practical importance to define the conditions for the application of the concept of "reduced leaching" (Rhoades et al,1974), when it is important to decrease to a minimum the volume of drainage efluents, without reaching critical salinity levels in the root zone. Additionally, with the model it is possible to predict the characteristics of the drainage waters, and the possibilities and conditions for their further use in irrigation (Rhoades et al,1988), or for other purposes.

Using the calculated values of L, based on the different critical salinity and sodicity levels for crops, soils and drainage waters, it is possible to deduce the irrigation (hR) and drainage (hD) requirements in relation to the water requirements of a crop (hET) in a particular climate:

$$hR/hET = 1/(1-L) \quad hD/hET = L/(1-L)$$

Figure 4 shows how the requirements of irrigation water, and the volume of drainage water increase with increasing values of the leaching fraction. The "effective leaching fraction" (LF) may be calculated from L, using a factor (F) for leaching efficiency. In practice we define this factor as the relation between the salt or sodium concentrations in the soil saturation extract - used to fix the critical levels - and their concentratiom in the drainage effluents (Pla, 1983). The value of F is generally less than one, because the leaching water do not usually move uniformly through the soil mass, compared to the uniform mixing of soil and water in the saturated paste. The lower values of F are generally found in highly structured clay soils, specially if large cracks develop on drying, and irrigation is applied at large intervals. The higher values of F, close to one, are common in sandy or silty soils, with poor structural development, and when there are used high frequency or continuous irrigation systems.

The requirements of irrigation management (Pla,1988), are mainly derived of the relations between duration (tR) and frequency (tBR) of irrigation, and may be calculated from the values of leaching fraction (L) and intake rate (I) of irrigation water. The decission about using conventional, high frequency, or continuous (flooding or drip irrigation) irrigation systems will be based on that value. Figure 5 shows the relations between tR/tBR and L for different I/hET ratios. It may be appreciated that high values of tR/tBR may be a consequence of high L. This happens when the salinity of irrigation water is high and/or the crop tolerance to salts is low, but also when the I/hET values are very low, as it happens when there are sodicity effects. When the calculated values of L or tR/tBR are higher than one it means that the given conditions are impossible to reach.

In our model, the salt balance for the calculation of L is based on average equilibrium values of salinity or sodicity to be reached in the root zone. There would be some possi-

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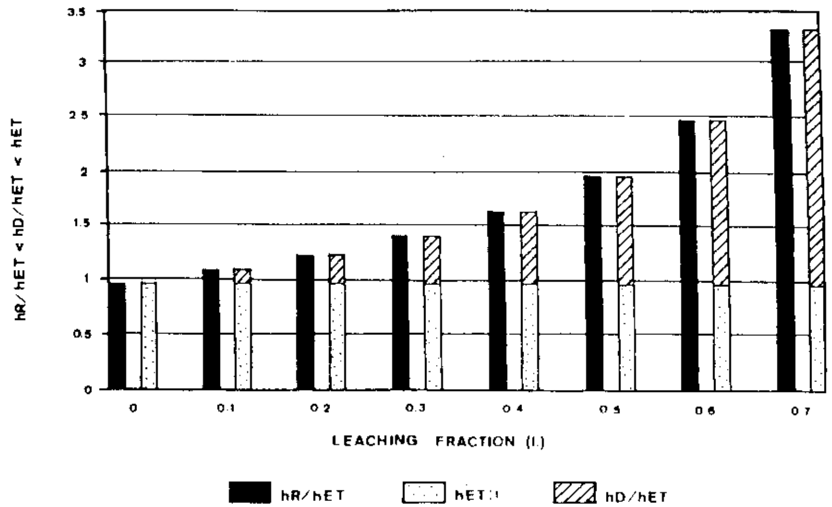

Figure 4. Irrigation (hR) and drainage (hD) requirements in relation to evapo transpiration rates (hET) for different leaching fractions (L).

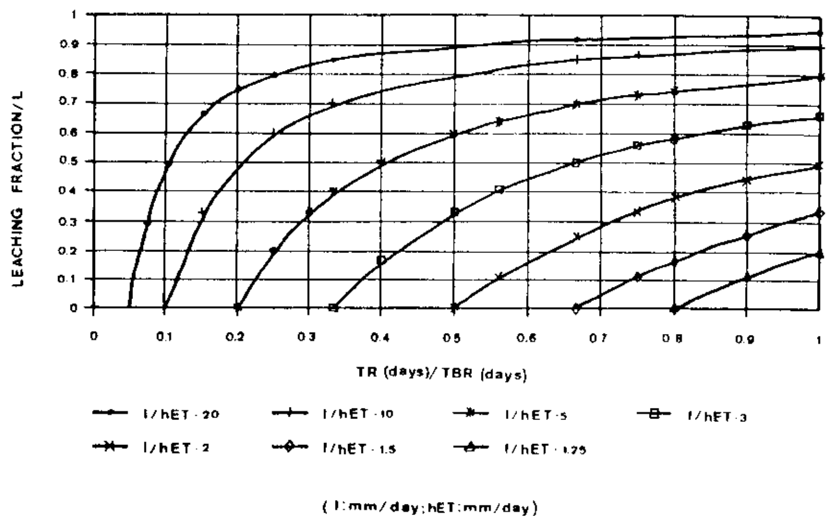

Figure 5. Requirements of irrigation management (duration/frequency:TR/TBR) for different combinations of leaching fractions:L (crop, soil), water intake rates:I (soil), and evapo-transpiration rates:hET (climate, crop)

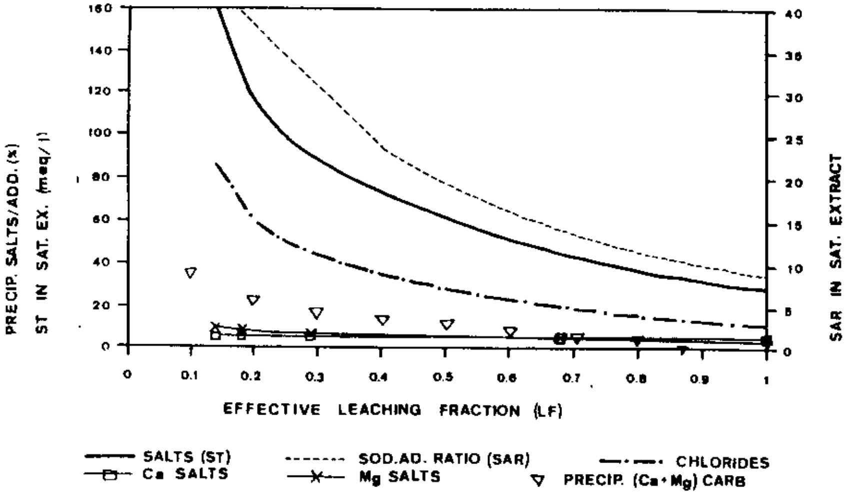

Figure 6a. Equilibrium levels of salts and sodium in soil solution for different effective leaching fractions. (Water I)

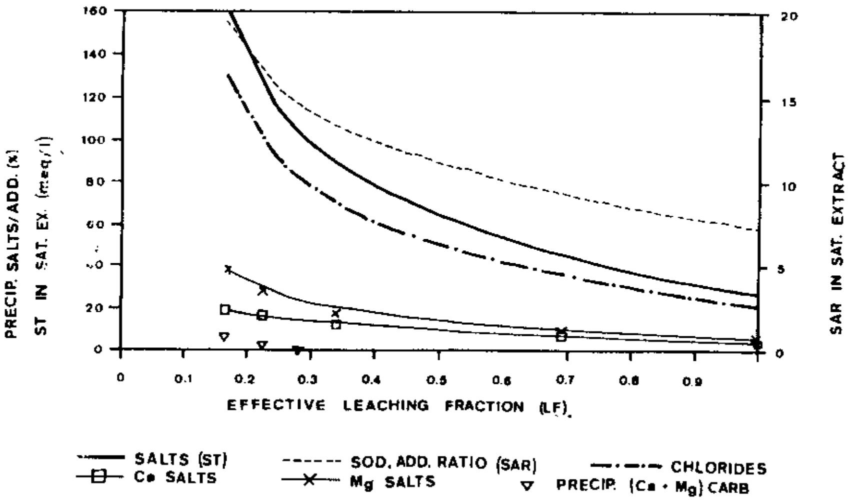

Figure 6b. Equilibrium levels of salts and sodium in soil solution for different effective leaching fractions. (Water II)

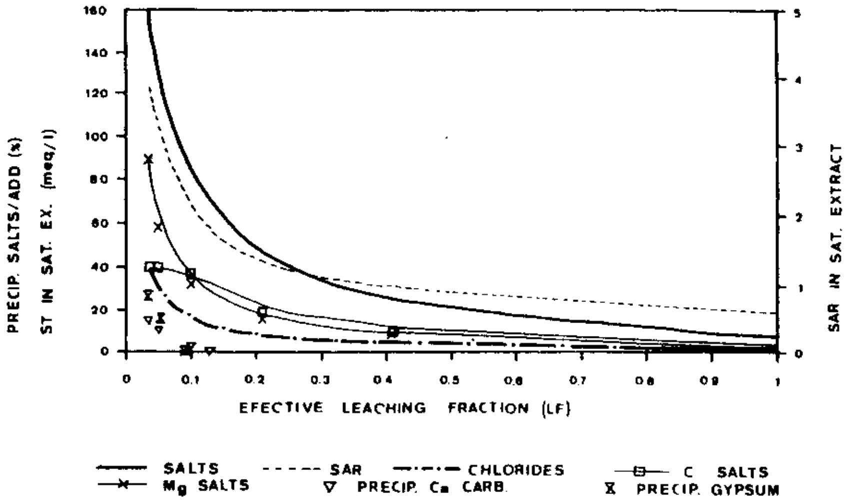

Figure 6c. Equilibrium levels of salts and sodium in soil solution for different effective leaching fractions. (Water III)

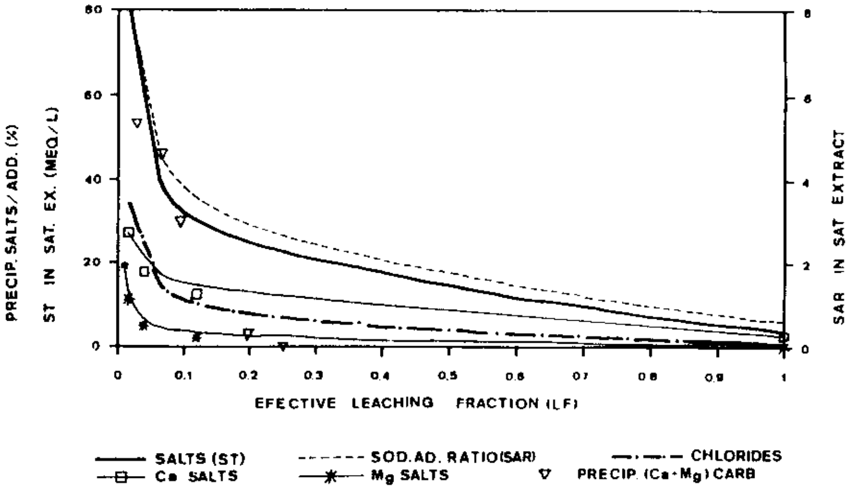

Figure 6d. Equilibrium levels of salts and sodium in soil solution for different effective leaching fractions. (Water IV)

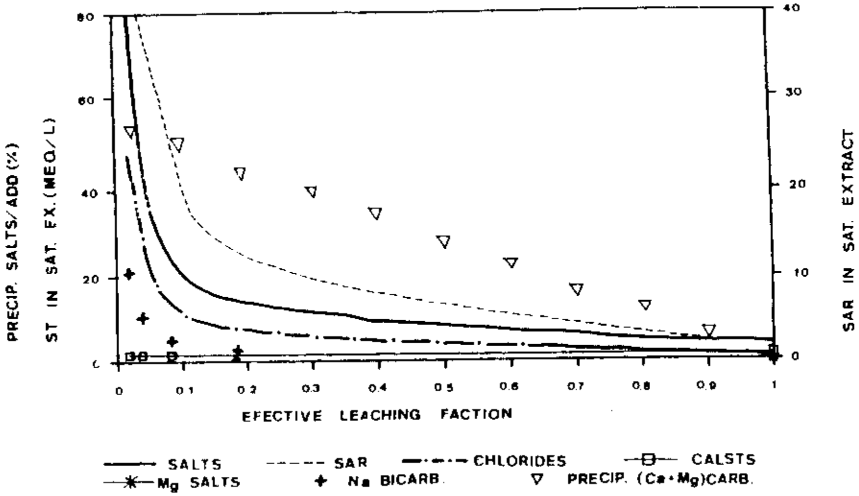

Figure 6e. Equilibrium levels of salts and sodium in soil solution for different effective leaching fractions. (Water V)

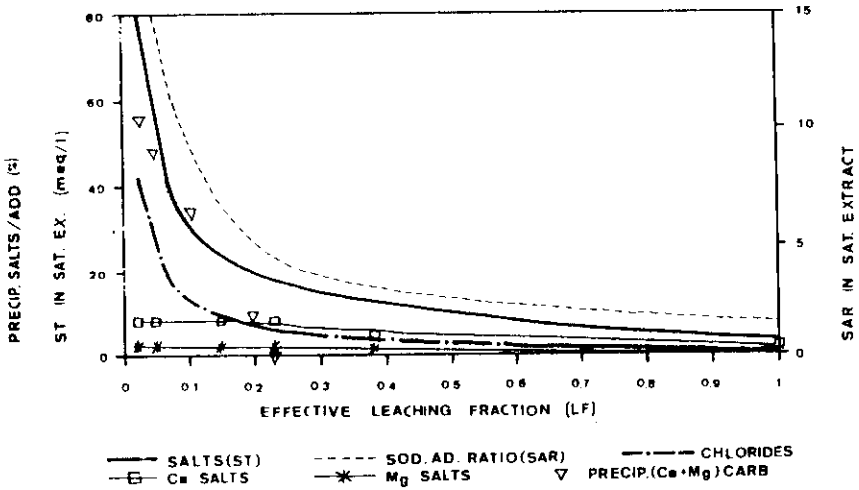

Figure 6f. Equilibrium levels of salts and sodium in soil solution for different effective leaching fractions. (Water Vg)

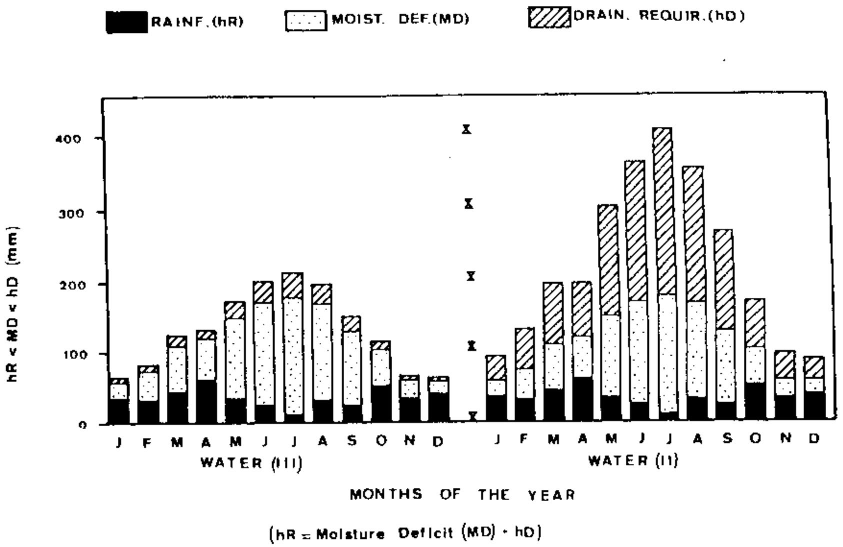

Figure 7. Irrigation (hR) and drainage requirements (hD) for salinity control (EC<8 dS/m in sat. extr.) using waters II and III (see table 3 and figures 6b and 6c), in the surface 50 cm of a medium texture soil, under a dry semi-arid climate.

WATER	Source	EC dS/m	meq./liter Ca^{++}	Mg^{++}	Na^{+}	HCO_3^-	$SO_4^=$	Cl^-	SAR
I	Well	2.7	5.6	3.9	19.5	8.7	7.5	11.7	8.9
II	Well	3.1	4.3	6.2	17.0	2.8	3.2	21.5	7.4
III	River	0.61	4.0	3.1	1.1	1.3	5.3	1.4	0.6
IV	Channel	0.28	2.8	0.2	0.7	2.2	0.3	0.5	0.6
V	Well	0.35	1.4	0.5	1.5	2.3	0.3	0.9	1.5
Vg	*	0.38	1.8	0.5	1.5	2.3	0.7	0.9	1.4

* Water V with ammendment of 35 g. of gypsum per cubic meter of water, just enough to eliminate the excess of bicarbonates over Ca+Mg

Table 3. Composition and concentration of salts in some selected surface and ground waters used for irrigation in the Mediterranean Region.

bilities to reduce temporarily the calculated values of L and hD, when through irrigation or sowing systems and practices, the excess of salts remaining in the soil profile are maintained away from the zone or depth with higher root development. Figures 6a-6f show some of the results of applying the proposed model to some selected waters (Table 3) being used for irrigation in the Mediterranean Region (FAO,1976; Giraldez y Cruz,1973; Martinez,1978). The water II represents a typical example of groundwater salinized by sea water intrusion. Water Vg is the same water V with addition of an ammendment of 35 g/m3 of gypsum (Pla,1969) in order to reduce its potential sodicity effects on the soil. The graphs show the levels of salinity, sodicity, chlorides, and of Ca and Mg salts to be reached in soil solution for each effective leaching fraction (LF). There is also shown the % of salts added with irrigation water, that will precipitate in the soil as Ca and Mg carbonates and as Ca sulfate, at each LF value. The great differences among waters may be appreciated. Therefore, the individual analysis of each case in relation to particular conditions of climate, soils, crops, available water, possibilities and problems of drainage, etc. would lead to different conclusions about the more convenient alternatives of irrigation management.

As an example, figure 7 shows what would be the monthly irrigation and drainage requirements to control salinity in the surface 50cm of a medium texture soil, in a dry semiarid mediterranean climate. Those requirements were calculated both for the water III, slightly saline, and with a high tendency to precipitate carbonates and gypsum (see figure 6c) at medium soil salinity levels; and for water II, highly salinized by see water intrusion in the aquifer. Under the selected average conditions, the rainfall water would only help to reduce the needs of irrigation water to cover crop and drainage requirements, but it would not provide by itself any water surplusses for effective leaching of salts in any month of the year. The strong differences among the two irrigation waters demonstrate how important is to preview those effects, in order to take beforehand the right decissions for the use and management of water from coastal aquifers, to prevent their salinization.

6. Conclusions

The desertification of lands by soil salinization processes, which is already affecting large areas in the whole World, naturally or through the human influence, is specially a growing problem in large arid to semiarid areas of the Mediterranean Region. The problem has a tendency to become worse derived from the pressure to extend irrigated areas, due to the great limitations and risks of dryland agricultural production under the predominant climatic conditions in most of the region. The scarcity of water resources of good quality in the region, and the competing use of them for urban and industrial purposes, is leading to the increased use for irrigation of more saline waters, sometimes as a consequence of the over-explotation and salinization of aquifers, and in some others due to the use of more or less pre-treated residual waters. In ocassions the drainage effluents from an irrigated area are, or have to be used again, directly or mixed with other surface or ground waters, for irrigation or other purposes, including human consumption.

To minimize the contaminating effects of those drainage effluents, many times charged with salts, but also with residues of fertilizers and pesticides, used in large amounts in the very intensive irrigated agriculture, it is important to be able to precisely calculate the minimum drainage requirements to reduce those efluents, without reaching critical soil salinity levels.

Generally, the reclamation of salt-affected soils is difficult and very expensive. This is still more complicated when the sources of good quality waters are scarce, and there are possibilities of contamination of waters required for other uses. Therefore, the prevention of soil salinization may be preferred to reclamation. The proposed predictive model, has proved to be reasonably good to predict the type and approximate levels of soil salinization problems, that would develop under different combinations of the main hydrological and chemical factors and processes involved. It may also be used to calculate the requirements, and to deduce the best alternative practices, for irrigation and drainage, not only to prevent soil salinization and sodification, but also to control some other related environmental problems. In order to facilitate the use of the model, and to allow a faster analysis of all alternatives and their probable effects, it has been developed a PC computer program based on it.

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I -3 Soil degradation processes and methodology to evaluate relevant parameters

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SOIL DEGRADATION PROCESSES AND METHODOLOGY TO EVALUATE RELEVANT PARAMETERS

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INTRODUCTORY REMARKS

Soil degradation refers to the reduction in soil quality in relation to crop productivity. It is a complex process in which several factors, natural and human induced, contribute to the loss of productive capacity. Although it is a site specific problem, the effects of soil degradation processes extend beyond the original site and represent a considerable cost to society.

The various forms of soil degradation, mainly derived of the use and management given to the land, have become the major constraint for further expansion and intensification of agriculture in the whole World, and specially in tropical and subtropical regions. One of the most widespread and harmful soil degradation processes, with faster rates in the increasingly mechanized cropping systems, is physical degradation, mainly manifested through problems of compaction, sealing and crusting, and water and wind erosion. Although the main forms and processes of soil physical degradation are relatively well known, *there are only very general estimates of the actual and potentially affected areas, of the rates and risks of degradation processes, and of the accompanying losses of productivity*. Therefore, ***it is required to develop and test new methodologies, at both laboratory and field levels, to evaluate the actual problems and to assess the vulnerability of soils to physical degradation under different climates, topography, and management practices.***

Crop yield and sustained productivity have been the measurements commonly used to assess land use limitations and effects of soil degradation, but more quantitative characterization and prediction of the affected soil physical properties are required. The experimental analysis of the dynamics of soil degradation processes and their effect on crop productivity can be carried out through the instalation of experimental plots, but on the other end, for diagnostic purposes, the availability of specific data on semipermanent soil characteristics may be used to infer the relevant soil physical properties using statistical models. Methods should be developed for use by soil surveyors in doing the required observations and descriptions of soil horizons. Although modern indirect techniques like remote sensing, computerized data processing, and simulation models, may help in the required evaluations, they will always require of accurate direct measurements. Given the large spatial and temporal variability in most of the soil physical properties, there will be required many replicate measurements, with the least possible variability due to the measuring procedure or device itself.

METHODOLOGICAL PROBLEMS TO EVALUATE SOIL PHYSICAL DEGRADATION

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INTRODUCTION

Soil degradation is a complex process in which several factors contribute to the reduction of its productive capacity. It represents the most serious limitation for the production of the future food requirements of mankind (Brady, 1986). Previous projections of production potentials in the yet unexploited World land reserves in the tropics generally have failed because the effects of soil degradation were ignored. Some of the effects of soil degradation on crop production have been partially masked through improved technological imputs, with increases in environmental problems and costs of production.

The processes of soil physical degradation are mainly manifested through problems of compaction, sealing and crusting, and water and wind erosion. It has been questioned (Dudal, 1979) if the information given by the traditional soil surveys and classification systems is suficient to make interpretations which have adequate predictive value in relation to soil physical degradation processes. Methodology for an appropiate quantitative characterization and prediction of the affected soil physical properties, is required to evaluate the actual problems, and to assess the vulnerability of soils to different processes of degradation. The measurementes will generally require many replications, both in space and time, due to the common large spatial and temporal variability (Warrick and Nielsen, 1980) in soil physical properties. Geostatistical interpolation of these soil physical variables (van Beurden and Riezebos, 1988) may be therefore a better alternative, than conventional methods, for mapping degradation hazards.

The methods to assess soil degradation have been clasified (FAO, 1979) as direct observations and measurements, remote sensing techniques, mathematical models, and parametric methods.

PROCESSES OF SOIL PHYSICAL DEGRADATION

Soil compaction has been identified as one of the leading causes of soil physical degradation threatening future crop productivity World-wide, because it has the potential to affect crop growth and production directly, and also indirectly increasing the danger of soil erosion, water-logging, and/or water runoff. Excessive compaction is probably more extensive than ever before because of increasing use of heavy tillage and harvesting machinery, and also because of more intensive soil use. Additionally, large areas of soils in tropical rainforests have been reported damaged by compaction due to careless mechanical land clearing procedures.

Compaction implies a decrease in volume, or increase in density, as a soil response to external forces. Therefore, the primary effect of soil compaction is to reduce pore volume and to cause a redistribution amongst pore size groupings. These changes will affect, to a greater or lesser extent, air capacity and gaseous exchange, water retention, hydraulic conductivity, soil strength, and mechanical impedance to root growth. Indirectly, it will also affect many soil chemical and biological processes. For each crop, growing stage, soil, and climatic regime, there is an optimum level of compaction for maximum crop yield.

The degree of compaction or compactness, useful to diagnose root impedance, may be characterized by several parameters, measured with different, non standardised, procedures, such as:

Strength - Penetration resistance - Penetrometers

Porosity - Bulk density
- Soil cores
- Field excavations
- Surface gamma-neutron gauge

Size, number, distribution and continuity of pores
<u>Direct measurements</u>
- Thin sections with dye tracers
- Mercury intrusion porimeter
- Scanning electron microscopy
- Gamma-ray computed tomography

<u>Indirect measurements</u>
- Water flow
- Chemical transport

Observation of rooting patterns

Sampling of roots

The susceptibility to compaction or compactability will be useful to identify and characterize soils susceptible to strength problems, in order to anticipate the required management and potential rooting restrictions. It depends on soil type, moisture content, and initial compactness, and is frequently determined in the laboratory by several, non standardised methods, as

Uniaxial compresion tests

Empirical models, based on soil characteristics, to predict bulk density (Larson et al, 1986)

Indices of aggregate stability, derived from laboratory measurements

Regresion equations or theoretical models, with an empirical approach, to estimate the change in bulk density and water content, have been recently proposed (McBride, 1989) for soil compactability assessment.

When exposed surface soil aggregates are disintegrated under the impact of raindrops, the dispersed finer fractions of soil material are redeposited on the soil surface in a

denser arrangement, or move downward with percolating water to fill the soil pores, forming what is called a seal. This more or less compacted surface layer may drastically reduce water infiltration (sealing effect), causing water-logging, or runoff in sloped areas. The subsequent drying phase results on crust formation, which may offer mechanical resistance to seedling emergence. As a consequence, a degraded surface soil, with low stability to the process of sealing, not only reduces soil water storage by reducing water infiltration, but may also increase, specially in combination with high intensity rainfall, the rate of erosion, through increased runoff. Poor yields may result, both by poor crop stands due to reduced emergence of seedlings, or due to shortage of water held in the soil, and/or limited aeration. Besides structural seals and crusts formed as a result of water drop impact, there are depositional ones, formed by transport and deposition of fine particles by surface flow. Due to the degradation process of sealing, soil surface conditions are frequently more important than underlying soil permeability for infiltration of water from short-term concentrated rainfall events.

Simulation of soil sealing and crusting is generally done with the use of rainfall simulators, to study their effects on infiltration, runoff, and seedling emergence, both at laboratory and field levels. From these values there have been developed indices of sealing (Pla, 1985) and crusting. The differences in sealing and crusting susceptibility among soils, may also be evaluated this way. Crust strength in relation to emergence of seedlings has been estimated with the modulus of rupture test, and with mechanical probes and penetrometers. Subsequent micromorphological studies, using thin sections and scanning electron micrographs, may help to a better understanding of the processes of seal and crust formation.

Removal of topsoil, whether by erosion or by levelling or terrace construction, is a process of soil physical degradation generally resulting in reduced crop productivity. Loss of plant nutrients, reduced water holding capacity, and lower stability of surface soil structure, are the main causes. Soil erodibility is a quantitative measure of the inherent susceptibility to erosion by water or wind. The main approaches for the determination of soil erodibility by water are:

Long term measurements of soil loss under natural rainfall

Soil loss measurements under simulated rainfall

Use of predictive regression equations based on easily measured soil parameters

The best laboratory based indices are the ones that give more weight to dynamic soil properties relevant to the erosion process, like the soil's resistance to raindrop impact and surface flow. Empirical erodibility values, to be used in the so called Universal Soil Loss Equation (USLE)

(Wischmeier and Smith, 1978), have generaly been derived from the results of the three approaches. Recently, more process-based models are being developed to improve the empirical USLE model, providing a more quantitative understanding of soil susceptibility to erosion.

METODOLOGICAL PROBLEMS AND REQUIREMENTS

One of the present methodological problems to assess soil degradation processes is that still many soil physical properties associated with the development or recovery of degradation are imprecisely defined and not completely understood. Therefore, they cannot be properly quantified, and much less used for precise calculations and predictions.

Most of the methods presently available to measure soil physical parameters, related to the effect of degradation processes on root development, are not fully adequate for such purpose, because they were initially developed for engineering tests. Therefore, direct observations of the patterns of root development should be the focus of most studies, together with the measured indirect indicators of soil quality. Moreover, the measurements of soil physical properties and observations of root patterns have little value unless the impact of those conditions on the yield of the crop can be determined.

The methods and techniques applicable for predicting soil physical behaviour under field conditions should allow simple and direct measurements based on comprehensive physical relations, and should take into consideration the dynamic aspect of the soil physical properties, specially the ones depending on soil structure. These properties should be also quantified in terms of the dynamic action of root growth. The forces applied in the laboratory may attempt to simulate those found in the field under natural or cropped conditions. However, with the appropiate calibration and validation under field conditions, the laboratory methods may provide very useful information for diagnostic purposes, and for guiding management practices to prevent degradation processes. In any case, the choice of conditions for the measurement of soil physical properties under laboratory or field conditions will be largely determined by the purpose of the test. A full standardisation of the methodology is not possible, because the method used should be in any case relevant to the objectives of the study.

Although some basic studies of soil physical properties associated with the processes and effects of degradation make use of sophisticated means, there is an urgent need for more rapid, simple, and inexpensive field and laboratory methods and tools, so that many replicate measurements can be made on each soil unit and management conditions, taking into consideration the strong spatial variability of soil physical properties. Considering that the root system only occupies a very small fraction of the soil volume, the size of the samples has also to take into account such variability. Because of the strong dependence of most soil physical properties on soil water content, it is essential that under field conditions, accurate measurements and records of moisture be made at the same time.

Simulation models may be very useful to predict long term effects of degradation processes, which would be imposible to obtain by monitoring due to economical and practical limitations. They are used both to provide information about the expected effects of new soil management practices, and for rational planning of short-term field experiments. The feasibility and validity of computer-simulation models for defining soil-water regimes and associated qualities such as moisture deficits, aeration status, and workability, has been demostrated in several studies (Pla, 1988; Wösten and Bouma, 1985; Jacobsen and Dexter, 1987). They incorporate measured physical properties and rooting depths, for different climates and soil physical conditions, representative, or product of different soil management practices and degradation processes.

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