Instituto Nacional de Investigação Agrária e Veterinária, I.P.

Project Arimnet-0005-2015 "Salinisation in irrigated areas: risk evaluation and prevention" SALTFREE

Deliverable 6.1

Guidelines for soil salinisation risk prevention and corrective management practices

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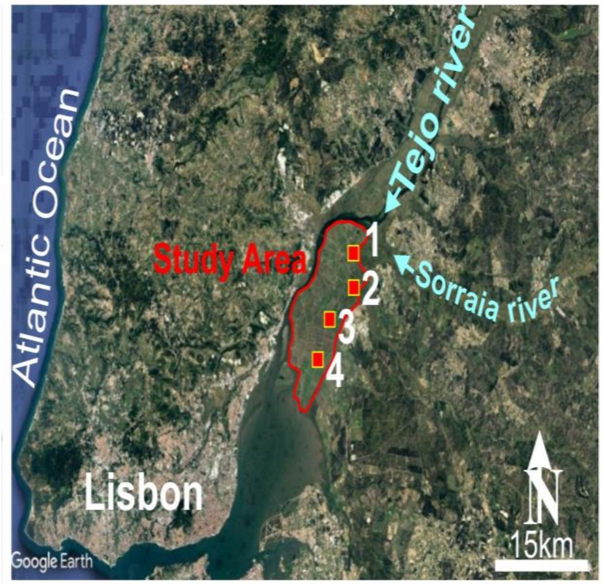

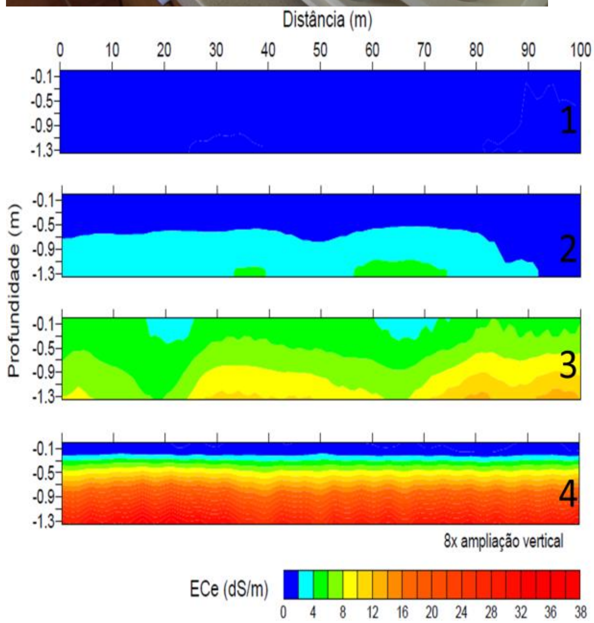

Outubro 2019

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1. Introduction

Salinisation is one of the soil degradation processes referred in the Thematic Strategy for Soil Protection (COM (2006) 231), which leads to an increase in the concentration of soluble salts in the soil and in soil solution, to harmful levels to plants. The accumulated salts include sodium (usually the most important) and Ca, Mg and K salts, especially in the form of chlorides, but also sulphates. In saline soils, crops are affected either by specific toxic effects or by the high osmotic potential of the soil solution, which reduces the soil water extraction capacity of the plants (Ayers and Westcot, 1985).

Sodicization is the process by which the Na^+ ion gains preponderance in the soil exchange complex, which can cause the loss of one or more soil functions. Sodium has a negative effect on soil properties and plant growth, promoting clay expansion and/or dispersion, altering soil pore geometry that, affects soil intrinsic permeability, water retention and crop productivity (Keren, 2000). Sodium dynamics is associated with the dynamics of other cations, namely calcium and magnesium.

Perspectives of climate change for the coming decades, including the increase in temperature and in the concentration of CO_2 in the atmosphere may also interfere with soil salinisation, as the use of water by plants is potentially influenced by high concentrations of CO_2 leading to lower conductance of leaf stomas and an increase in photosynthetic rates (Kirschbaum et al., 1996). Especially in the hotter and drier regions, soil water, associated with dissolved salts existing in the deep layers of the soil, will undergo a greater capillary ascending movement that may result in the accumulation of salts (salinisation) in the superficial layers of the soils.

In the Mediterranean region, land degradation associated with soil salinisation may worsen at increasing rates in the coming decades, owing to the expected increase in irrigated areas and the increasing scarcity of good quality waters, where the emergence of the need for preventive measures (Bowyer et al., 2009).

Soil salinisation/sodicization risks must be analyzed case by case because they depend on various factors including:

- the meteorological conditions;
- the calculation of crop evapotranspiration and the "normal" irrigation need;
- the irrigation efficiency. Low watering efficiencies are sometimes enough to meet the needs of the wash. For example, low wash fractions (<10%) are generally supplied by irrigation inefficiency;
- the electrical conductivity of the irrigation water;
- the type and properties of soil (e.g. texture, hydraulic conductivity, pH);
- the soil salinity (given by the saturation extract or alternative methodologies after calibration);
- the resistance of each crop to the salinity of the soil and irrigation water. Tables with crop resistance to salinity of either soil or irrigation water can be found at Ayers and Westcot (1985);
- the amount of rain during the autumn-winter period. In most cases the rain that occurred during that period was always enough to wash the salts.

Tailor made solutions must be provided for minimizing the risks in each case/scenario.

2. Nature and origin of soil salinisation

The accumulation of salts in the soil is due to the existence of a source of salts and to the insufficiency of precipitation and/or drainage that allow their leaching. Some of the causes are natural (**primary salinisation**) and others result from human induced processes (**secondary salinisation**). The most common natural causes of salinisation are the presence of sea water tables and/or the direct action of the tides in coastal regions and the presence of water tables rich in salts derived from the weathering of the rocks. The most common causes of man-induced salinisation are the use of inadequate irrigation and drainage practices, and the use of poor quality irrigation water

(Kibblewhite et al., 2008). The intensive use of fertilizers or correctives particularly under conditions of limited leaching, and the use of wastewater or saline products of industrial origin, could also be a problem.

3. Salinity/sodicity indicators

3.1 The type of extract

The most reliable soluble salt determinations are carried out in aqueous extracts of the soil. The lower the soil/water ratio, the easier the separation of the extract is, but the less representative this is from the soil solution in contact with the roots of plants. The ideal extract would be obtained at soil water between field capacity and wilting point but, the difficulty of obtaining such extracts renders impracticable its use in routine analyzes (Richards, 1954).

The most frequently used extract in soil salinity studies is the **saturation extract obtained from a saturated soil paste** (Bresler et al., 1982), since it has the advantages of being an easy and reproducible preparation method, and is still relatively close to the range of field moisture contents, with which it has some relation, since in many soils **the water content of the saturated paste is approximately the double of field capacity and the quadruple of wilting point**. Thus, salinity measurements in saturation extract take into account the water retention properties of soil under field conditions and provide a realistic indication of the conditions under which the plants are subjected. However, sometimes 1:1, 1:2 or 1:5 extracts are used, but should be noted that not only the concentration but also the ionic composition of these extracts is affected by the soil/water ratio. The results of those extracts must be correlated with the saturation extract ones in order to allow the comparison of results.

3.2 The salinity indicators

The determinations on the saturation extract for soil salinity diagnosis involves the **electrical conductivity (EC_e)** and the determination of the ions Ca^{2+}, Mg^{2+}, K^+, Na^+, CO_3^{2-}, HCO_3^-, SO_4^{2-}, Cl^- and B.

Table 1 shows soil salinity classes as a function of the electrical conductivity of the soil saturated paste extract (EC_e), and the expected effects on crop yield (adapted from Richards, 1954).

Table 1. Soil salinity classes considering the electrical conductivity of the soil saturated paste extract (EC_e), and the expected effects on crop yield (adapted from Richards, 1954).

EC_e (dS m^{-1})	Class	Effect
0 - 2	Non saline	Negligible
2 – 4	Slightly saline	Yield reduction of very salt-sensitive crops
4 – 8	Moderately saline	Yield reduction of many crops
8 – 16	Strongly saline	Normal yields for salt-tolerant crops only
>16	Very strongly saline	Reasonable crop yield for very salt-tolerant crops only

EC_e shows a high positive correlation with the **total concentration of cations or anions (TDS)** and with the **osmotic potential** of the aqueous extracts of the soil. The following equations are often used:

$$\text{TDS (g L}^{-1}\text{)} = \mathit{0.64} \times EC_e \text{ (dS m}^{-1}\text{)}, \quad (1)$$

Where:

TDS is the total dissolved salts and ECe the electrical conductivity of the saturation extract.

$$\text{Total cations (mmol}_c \text{ L}^{-1}\text{)} = \mathit{10} \times EC_e \text{ (dS m}^{-1}\text{)}, \quad (2)$$

$$\text{Osmotic potential (MPa)} = -0{,}036 \times EC_e \text{ (dS m}^{-1}\text{)} \quad (3)$$

From this expression it can be deduced that a soil with an EC_e of about 20 dS m^{-1}, corresponding to a value of about 40 dS m^{-1} at field capacity (Richards, 1954), has practically no water available for the plants, as the osmotic potential of the water approaches 1.5 MPa (the potential considered equivalent to the permanent wilting point).

In addition to the determinations made in the saturation extract, the soil salinity diagnosis is usually completed with **pH, exchangeable cations and, cation exchange capacity (CTC)** determinations.

3.3 The sodicity indicators

The most relevant indicator for the diagnosis of soil sodicity is the **percentage of exchangeable sodium (ESP).** This indicator identifies the degree to which the exchange complex is saturated with sodium. ESP values greater than 15 are associated with severely deteriorated soil physical properties. It consists on the ratio between exchangeable Na^+ concentration, and the cation exchange capacity (CEC)::

$$\mathrm{ESP}\ (\%) = \frac{\left[\mathrm{Na}^{+}_{\mathrm{exchangeable}}\right]\ (\mathrm{cmol_c\ kg^{-1}})}{\mathrm{CTC}\ (\mathrm{cmol_c\ kg^{-1}})} \times 100. \qquad (4)$$

Where:

ES is the exchangeable sodium ($\mathrm{cmol_c\ kg^{-1}}$), and

CEC is the cation exchange capacity ($\mathrm{cmol_c\ kg^{-1}}$).

It should be noted that the degree of saturation of the exchange complex with sodium depends on the composition of the soil solution.

The **sodium adsorption rate (SAR)** is another indicator, more easily to determine. The SAR gives information on the comparative concentrations of Na^+, Ca^{2+}, and Mg^{2+} in soil solutions, usually in the saturated soil paste extract, or in irrigation water, allowing the measurement of soil sodicity. The SAR of a soil extract takes into consideration that the adverse effect of Na^+ is moderated by the presence of Ca^{2+} and Mg^{2+} (Weil and Brady, 2017). It is calculated from the following expression:

$$\mathrm{SAR}((\mathrm{mmol_c L^{-1}})^{0.5}) = \frac{[\mathrm{Na^+}]}{\sqrt{\frac{[\mathrm{Ca^{2+}}]+[\mathrm{Mg^{2+}}]}{2}}}, \qquad (5)$$

Where:

$[Na^+]$, $[Ca^{2+}]$ e $[Mg^{2+}]$ are the concentrations of dissolved cations in the saturated soil paste extract in milliequivalents per litre (meq L^{-1}) or in $mmol_c$ L^{-1}.

A SAR value of 13, or >13, for the solution extracted from a saturated soil paste is approximately equivalent to an ESP value of 15, or >15, and the soil is termed sodic (Daliakopoulos et al., 2016). The relationship between ESP and SAR was first proposed by Richards (1954), and is given by:

$$ESP = \frac{100\ (-0{,}0126+0{,}01475\ SAR)}{1+\ (-0.0126+0.01475\ SAR)}. \qquad (6)$$

The evaluation of the risk of sodicization of the soil should take into account several aspects such as texture, clay mineral type, pH, SAR and electrolytic concentration of the soil solution, in addition to other parameters necessary to evaluate irrigation water quality.

Soil pH is also an indicator of its acidity or alkalinity, affecting directly nutrients availability to plant, and should be used in the diagnosis of the soil salinisation/sodicization.

3.4 Alternative methods

Geophysical methods such as electrical resistivity tomography (ERT) and electromagnetic induction (EMI) techniques are being used as a promising alternative to traditional techniques for soil salinity assessment as it allows to take non-invasive, reliable, rapid and repeatable measurements which can be used to cover large areas in less time and at a smaller cost. These techniques measure the apparent soil electrical conductivity (EC_a) which is primarily a function of soil salinity, soil texture, moisture content, and cation exchange capacity. However, in saline soils, soil salinity is generally the dominate factor responsible for the spatio-temporal variability of EC_a. Among geophysical methods, EMI techniques have been used increasingly to estimate soil salinity due to the fast and non-invasive nature of this method. EMI instruments measure EC_a, which represents a weighted integration of the soil electrical conductivity in a soil volume. Whereas EC_e determines EC of the solution extracted from soil, EC_a determines the EC of a volume of soil ("bulk soil EC"). Using a modelling procedure

EC_a data can be used to provide a volume specific distribution of the soil bulk electrical conductivity (σ).

This innovative method was tested by the SALTFREE partners to predict soil salinity over large areas. The following procedure were carried out in order to assess soil salinity in space and time from EMI measurements: (1) use of electromagnetic instrument to measure soil apparent electrical conductivity (EC_a, dS m^{-1}); (2) inversion of EC_a allowing the mapping of soil bulk electrical conductivity (σ, mS m^{-1}) distribution with depth – electromagnetic conductivity imaging (EMCI); (3) calibration process consisting of a linear regression between σ and electrical conductivity measured in the saturated soil paste extract (EC_e, dS m^{-1}) allowing to estimate EC_e from EMCI; and (4) conversion of EMCIs into salinity maps using the obtained calibration equation.

4. Classification of salt-affected soils

Using salinity/sodicity indicators referred above (**ECe, SAR, ESP and pH**), salt-affected soils are classified as **saline, saline-sodic and sodic**. Soils that are not greatly salt-affected are classed as normal (Weil and Brady, 2017). Table 2 shows the classes of salt-affected soils as a function of the several indicators.

Table 2. Classes of salt affected soils.

Soil type	Soil property			
	EC_e (dS m^{-1})	SAR	ESP (%)	pH
Normal Soil	<4	<13	<6	<8.5
Saline	>4	<13	<15	<8.5
Saline-sodic	>4	>13	>15	≤8.5
Sodic	<4	>13	>15	>8.5

4.1 Saline soils

The processes that result in the accumulation of soluble salts are referred as salinisation. The salts are mainly chlorides and sulfates of calcium, magnesium, potassium, and sodium. The concentration of these salts sufficient to interfere with plant growth is generally defined as that which produces an EC_e greater than 4 dS/m. However some sensitive plants are adversely affected when the EC_e is only about 2 dS/m (Weil and Brady, 2017; Richards, 1954). Although EC_e >4 dS/m, these soils present ESP and SAR values, in the saturation extract, less than 15 and 13, respectively. Thus the exchange complex of saline soils is dominated by calcium and magnesium, not sodium. The pH is usually below 8.5. Because soluble salts help prevent dispersion of soil colloids, plant growth on saline soils is not generally constraint by poor infiltration, aggregate stability, or aeration.

4.2 Saline-sodic soils

Soils that have both harmful levels of soluble salts (EC_e> 4 dS/m) and a high proportion of sodium ions (ESP>15 or SAR>13) are classified as saline-sodic soils. Plant growth in these soils can be adversely affected by both excess salts and excess sodium levels. Those soils present physical conditions intermediate between those of saline soils and those of sodic soils. The high concentration of soluble salts moderates the dispersing influence of sodium. The salts provide excess cations that are adsorbed to the negative charged colloidal particles reducing their tendency to repel each other, or to disperse. The salts, therefore, help the colloidal particles associated with each other in floccules and aggregates (Weil and Brady, 2017). Unfortunately, this situation is subjected to rather rapid change if the soluble salts are leached from the soil, especially if the SAR of the leaching waters (e.g. irrigation water) is high. In such a case, salinity will decrease, but ESP will increasing, and the saline-sodic soil will become a sodic soil.

4.3 Sodic soils

Sodic soils are, perhaps, the most troublesome of the salt-affected soils. While their levels of soluble salts are low (EC_e<4dS/m), they have relatively high levels of sodium on the exchange complex (ESP and SAR values are above 15 and 13, respectively). Their pH values generally exceed 8.5, rising to 10 or higher in some cases. These extreme pH values are largely due to the fact that sodium carbonate is much more soluble than calcium or magnesium carbonate and so maintains high concentrations of CO_3^{2-} and HCO_3^- in the soil solution. Plant grow on sodic soils is often constrained by specific toxicities of Na^+, OH^-, and HCO_3^- ions. However, the main reason for the poor plant growth is that few plants can tolerate the extremely poor soil physical conditions and slow permeability to water and air that accompany clay dispersion in sodic soils

5. Irrigation water quality

The characteristics of the irrigation water can have a major role in the appearance or increase of soil secondary salinisation problems. Because of that, it is very important to evaluate its quality. Some of the indicators, which are used to evaluate soil salinisation problems, are the same that are used to evaluate the irrigation water quality, namely, electrical conductivity, in this case, **water electrical conductivity (EC_w), TDS, SAR**, and some **specific ions that might cause toxicity to the crop**. Although the suitability of saline water for irrigation depends on different conditions of use, like crop, climate, soil, irrigation method and management practices, only very tolerant crops can have satisfactory yields if irrigated with waters that exceed about 10 dS/m in EC_w. In fact, few normally used irrigation waters exceed electrical conductivities of about 2 dS m^{-1} (Rhoades et al., 1992).

It is consensual the use of the FAO water-quality guidelines for irrigation, reported by Ayers and Westcot (1985), which considers three levels of restriction to the use of an irrigation water: none, slight to moderate, and severe (Table 3). The potential irrigation problems addressed are: (i) Salinity, assessed from EC_w; (ii) Infiltration rate of water in the soil, assessed using EC_w and SAR together; (iii) Specific ion toxicity by sodium, chloride or Boron (B), when sensitive crops are being irrigated; (iv) Miscellaneous effects on sensitive crops, regarding NO_3^- and bicarbonate (HCO_3^-) concentrations, and pH. This water-quality guidelines for irrigation, proposed by Ayers and Westcot (1985), systematized and updated work previously developed by US Salinity Laboratory Staff (1954), Wilcox (1955), Maas and Hoffman (1977), Rhoades (1977).

These guidelines emphasize the long-term influence of water quality on crop production, soil conditions and farm management, considering, not only the water salt content, evaluated by EC_w, but also the combined effect of EC_w and SAR. In fact, the higher the irrigating water salt content (high EC_w values), the worse is its quality, leading to a high input of salts, and to restriction of water availability to the plants.

However, for the same SAR, the water that poses higher restriction to their use would be the one with the lower EC_w, once a higher salt content in the irrigation water compensates, to some extent, the increase in sodium hazard. So, in fact, water with a low salt content may worsen soil physical problems (Weil and Brady, 2017).

Table 3. FAO guidelines for interpretation of water quality for irrigation (adapted from Ayers and Westcot, 1985)

Potential irrigation problem	**Units**	**Degree of restriction on use**		
		None [1)]	**Slight to moderate** [2)]	**Severe** [3)]
Salinity [4)]				
EC_w	dS m^{-1}	< 0.7	0.7 – 3.0	> 3.0
Infiltration [5)] [6)]				
SAR 0 – 3 and EC_w	dS m^{-1}	> 0.7	0.7 – 0.2	< 0.2
SAR 3 – 6 and EC_w		> 1.2	1.2 – 0.3	< 0.3
SAR 6 – 12and EC_w		> 1.9	1.9 – 0.5	< 0.5
SAR 12 – 20 and EC_w		> 2.9	2.9 – 1.3	< 1.3
SAR 20 – 40 and EC_w		> 5.0	5.0 – 2.9	< 2.9
Specific ion toxicity [7)]				
Sodium (Na)				
Surface irrigation	SAR	< 3	3 – 9	> 9
Sprinkler irrigation	meq L^{-1}	< 3	> 3	-
Chloride (Cl)				
Surface irrigation	meq L^{-1}	< 4	4 – 10	> 10
Sprinkler irrigation	meq L^{-1}	< 3	> 3	
Miscellaneous effects[8)]				
Nitrate (NO_3)	mg L^{-1}	< 5	5 – 30	> 30
pH	-	Normal range: 6.5 – 8.4		

[1)] None - no soil or cropping problems are experienced. [2)] Slight to moderate - gradually increasing care in selection of crop and management alternatives is required if full yield potential is to be achieved. [3)] Severe – there will be soil and cropping problems or reduced yields, but even with cropping management designed especially to cope with poor quality water, a high level of management skill is essential for acceptable production. [4)] Affects crop water availability; [5)] Affects infiltration rate of water into the soil. [6)] Evaluated using EC_w and SAR together; [7)] Affects sensitive crops; [8)] Affects susceptible crops.

6. Recovery of salt-affected soils

The recovery of salt-affected soils generally involves two processes: the leaching of soluble salts (saline soils) and the replacement of exchangeable Na^{+} by exchangeable Ca^{2+} (saline-sodic and sodic soils). The leaching of soluble salts is usually accompanied by the leaching of nutrients such as nitrates, and measures to restore soil fertility may be necessary. While in the arid regions leaching requires the use of irrigation, in the semi-arid regions rain usually provides leaching of the soil.

6.1 Leaching requirements

According to leaching theory, to control the salinisation in a given period of time, it is necessary to add to the amount of water needed for the crops an amount of additional water given, for example, by the following equation (Van der Molen, 1973):

$$LR = (ETc - P)\frac{EC_i}{f\left(EC_{FC} - EC_i\right)} = (ETc - P)\frac{EC_i}{f\left(2\,EC_e - EC_i\right)} \quad (7)$$

Where:

LR is the leaching requirement needed to control salts within the tolerance of the crop, mm (as totals over the period considered),

ETc is the crop evapotranspiration in the period considered (mm),

P is the amount of rain in the period considered (mm):

EC_i is the electrical conductivity of the irrigation water (dS m^{-1}),

EC_{FC} is the electrical conductivity of the soil solution at the field capacity (dS m^{-1}),

EC_e is the average electrical conductivity tolerated by the crop as measured on a soil saturation extract. (dS m^{-1}) (Table 4),

f is the factor that represents the leaching efficiency, which depends on the type of soil (texture) and the irrigation method used.

Tentatively, the following *f* values may be used:

Silty loam, sandy loam	f = 0.5 - 0.6
Silty clay loam, sandy clay loam, loam	f = 0.4 - 0.5
clay	f = 0.2 – 0.3

Another equation for determining the leaching requirements of soil salts is that reported by Richards (1954):

$$LR = \frac{EC_i}{5EC_e - EC_i} \quad (8)$$

Where:

LR is the leaching requirement needed to control salts within the tolerance of the crop,

EC_i is the electrical conductivity of the irrigation water (dS m^{-1}),

EC_e is the average soil electrical conductivity tolerated by the crop as measured on a soil saturation extract. (dS m^{-1}) (Table 4). It is recommended a *ECe* value that can be expected to result in at least a 90 percent or greater yield be used in the calculation. For water in the moderate to high salinity range (>1.5 dS/m), it might be better to use the EC_e value for maximum yield potential (100 percent) since salinity control is critical to obtaining good yields (Ayers and Westcot, 1985).

The total annual depth of water that needs to be applied to meet both the crop demand and leaching requirement can be estimated from following equation:

$$aw = \frac{ETc}{1-LR} \quad (9)$$

Where:

aw depth of applied water (mm/year),

ET_c is the total annual crop water demand (mm/year)

LR is the leaching requirement

Table 4. Crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (EC_w) or soil salinity (EC_e)[1] Yield potential[2] (Ayers and Westcot, 1985)

FIELD CROPS	100%		90%		75%		50%		0% "maximum"[3]	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Barley *(Hordeum vulgare)*[4]	8.0	5.3	10	6.7	13	8.7	18	12	28	19
Cotton *(Gossypium hirsutum)*	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Sugarbeet *(Beta vulgaris)*[5]	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16

Sorghum *(Sorghum bicolor)*	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7	13	8.7
Wheat *(Triticum aestivum)*[4],[6]	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Wheat, durum *(Triticum turgidum)*	5.7	3.8	7.6	5.0	10	6.9	15	10	24	16
Soybean *(Glycine max)*	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0	10	6.7
Cowpea *(Vigna unguiculata)*	4.9	3.3	5.7	3.8	7.0	4.7	9.1	6.0	13	8.8
Groundnut (Peanut) *(Arachis hypogaea)*	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice (paddy) *(Oriza sativa)*	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Sugarcane *(Saccharum officinarum)*	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12
Corn (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Flax *(Linum usitatissimum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Broadbean *(Vicia faba)*	1.5	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12	8.0
Bean *(Phaseolus vulgaris)*	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
VEGETABLE CROPS										
Squash, zucchini (courgette) *(Cucurbita pepo melopepo)*	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Beet, red *(Beta vulgaris)*[5]	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15	10
Squash, scallop *(Cucurbita pepo melopepo)*	3.2	2.1	3.8	2.6	4.8	3.2	6.3	4.2	9.4	6.3
Broccoli *(Brassica oleracea botrytis)*	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14	9.1
Tomato *(Lycopersicon esculentum)*	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13	8.4
Cucumber *(Cucumis sativus)*	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10	6.8
Spinach *(Spinacia oleracea)*	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15	10
Celery *(Apium graveolens)*	1.8	1.2	3.4	2.3	5.8	3.9	9.9	6.6	18	12
Cabbage *(Brassica oleracea capitata)*	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12	8.1
Potato *(Solanum tuberosum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Corn, sweet (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Sweet potato *(Ipomoea*	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11	7.1

batatas)										
Pepper *(Capsicum annuum)*	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Lettuce *(Lactuca sativa)*	1.3	0.9	2.1	1.4	3.2	2.1	5.1	3.4	9.0	6.0
Radish *(Raphanus sativus)*	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	8.9	5.9
Onion *(Allium cepa)*	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.4	5.0
Carrot *(Daucus carota)*	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.0	8.1	5.4
Bean *(Phaseolus vulgaris)*	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Turnip *(Brassica rapa)*	0.9	0.6	2.0	1.3	3.7	2.5	6.5	4.3	12	8.0
Wheatgrass, tall *(Agropyron elongatum)*	7.5	5.0	9.9	6.6	13	9.0	19	13	31	21
Wheatgrass, fairway crested *(Agropyron cristatum)*	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22	15
Bermuda grass *(Cynodon dactylon)*[7]	6.9	4.6	8.5	5.6	11	7.2	15	9.8	23	15
Barley (forage) *(Hordeum vulgare)*[4]	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20	13
Ryegrass, perennial *(Lolium perenne)*	5.6	3.7	6.9	4.6	8.9	5.9	12	8.1	19	13
Trefoil, narrowleaf birdsfoot[8] *(Lotus corniculatus tenuifolium)*	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15	10
Harding grass *(Phalaris tuberosa)*	4.6	3.1	5.9	3.9	7.9	5.3	11	7.4	18	12
Fescue, tall *(Festuca elatior)*	3.9	2.6	5.5	3.6	7.8	5.2	12	7.8	20	13
Wheatgrass, standard crested *(Agropyron sibiricum)*	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28	19
Vetch, common *(Vicia angustifolia)*	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12	8.1
Sudan grass *(Sorghum sudanense)*	2.8	1.9	5.1	3.4	8.6	5.7	14	9.6	26	17
Wildrye, beardless *(Elymus triticoides)*	2.7	1.8	4.4	2.9	6.9	4.6	11	7.4	19	13
Cowpea (forage) *(Vigna unguiculata)*	2.5	1.7	3.4	2.3	4.8	3.2	7.1	4.8	12	7.8
Trefoil, big *(Lotus uliginosus)*	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.6	5.0
Sesbania *(Sesbania*	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17	11

exaltata)										
Sphaerophysa *(Sphaerophysa salsula)*	2.2	1.5	3.6	2.4	5.8	3.8	9.3	6.2	16	11
Alfalfa *(Medicago sativa)*	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16	10
Lovegrass *(Eragrostis sp.)*[9]	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14	9.3
Corn (forage) (maize) *(Zea mays)*	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15	10
Clover, berseem *(Trifolium alexandrinum)*	1.5	1.0	3.2	2.2	5.9	3.9	10	6.8	19	13
Orchard grass *(Dactylis glomerata)*	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18	12
Foxtail, meadow *(Alopecurus pratensis)*	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Clover, red *(Trifolium pratense)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, alsike *(Trifolium hybridum)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, ladino *(Trifolium repens)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, strawberry *(Trifolium fragiferum)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
FRUIT CROPS[10]										
Date palm *(phoenix dactylifera)*	4.0	2.7	6.8	4.5	11	7.3	18	12	32	21
Grapefruit *(Citrus paradisi)*[11]	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0	5.4
Orange *(Citrus sinensis)*	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0	5.3
Peach *(Prunus persica)*	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot *(Prunus armeniaca)*[11]	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape *(Vitus sp.)*[11]	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Almond *(Prunus dulcis)*[11]	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.8	6.8	4.5
Plum, prune *(Prunus domestica)*[11]	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Blackberry *(Rubus sp.)*	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Boysenberry *(Rubus ursinus)*	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Strawberry *(Fragaria sp.)*	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4	2.7

[1] Adapted from Maas and Hoffman (1977) and Maas (1984). These data should only serve as a guide to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions and cultural practices. In

gypsiferous soils, plants will tolerate about 2 dS/m higher soil salinity (ECe) than indicated but the water salinity (ECw) will remain the same as shown in this table.

[2] ECe means average root zone salinity as measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS/m) at 25°C. ECw means electrical conductivity of the irrigation water in deciSiemens per metre (dS/m). The relationship between soil salinity and water salinity (ECe = 1.5 ECw) assumes a 15–20 percent leaching fraction and a 40-30-20-10 percent water use pattern for the upper to lower quarters of the root zone. These assumptions were used in developing the guidelines in Table 1.

[3] The zero yield potential or maximum ECe indicates the theoretical soil salinity (ECe) atwhich crop growth ceases.

[4] Barley and wheat are less tolerant during germination and seeding stage; ECe should not exceed 4–5 dS/m in the upper soil during this period.

[5] Beets are more sensitive during germination; ECe should not exceed 3 dS/m in the seeding area for garden beets and sugar beets.

[6] Semi-dwarf, short cultivars may be less tolerant.

[7] Tolerance given is an average of several varieties; Suwannee and Coastal Bermuda grass are about 20 percent more tolerant, while Common and Greenfield Bermuda grass are about 20percent less tolerant.

[8] Broadleaf Birdsfoot Trefoil seems less tolerant than Narrowleaf Birdsfoot Trefoil.

[9] Tolerance given is an average for Boer, Wilman, Sand and Weeping Lovegrass; Lehman Lovegrass seems about 50 percent more tolerant.

[10] These data are applicable when rootstocks are used that do not accumulate Na^+ and Cl^- rapidly or when these ions do not predominate in the soil. If either ions do, refer to the toxicity discussion in Section 4.

[11] Tolerance evaluation is based on tree growth and not on yield.

6.2 Replacement of exchangeable Na+ by exchangeable Ca2+

Saline-sodic or sodic soils sometimes have to take special measures to prevent deterioration of the soil structure during leaching. Such measures generally consist of the addition of a calcium corrective (for example gypsum) to the soil or irrigation water, unless it contains enough calcium to replace Na^+ adsorbed in the exchange complex. The amount of gypsum required can be determined very roughly in the laboratory by treating a soil sample with a saturated gypsum solution and by measuring the amount of Ca^{2+} ions required to replace other exchange cations (except Mg^{2+}). It can also be deduced from the knowledge of CTC and ESP, using the following expression:

$$Q_z = \frac{(ESP - ESP_f)}{100} . CTC . Y_z \quad (10)$$

where:

Q_z is the amount of gypsum needed per hectare to restore the structure to a z cm-thick layer,

ESP is the exchangeable sodium percentage,

ESP_f is the exchangeable sodium percentage which is considered to be admissible at the end, *CTC* is the cation exchange capacity (cmolc kg-1),

Y_z is the amount of gypsum required per hectare to replace 1 $cmol_c$ of exchangeable Na^+ per kg of dry soil (at 105 ° C), in a layer of thickness z (cm) and with a certain bulk density. For a soil with a mean bulk density of 1.3 $g.cm^{-3}$, the theoretical value of Y_z is 3.4 t/ha of gypsum for a 30 cm layer (Weil and Brady, 2017) or about 1.2 t/ha for a 10 cm layer.

6.3 Predicting the effect of irrigation water quality on soils and crops

Models that describe and quantify the physical, chemical and biological processes of the soil, as they can integrate various processes, are very useful tools for optimizing agricultural practices such as irrigation and fertilization and defining environmental sustainability policies. Modeling soil water flows and transport of major ions in and below the root zone will help to predict groundwater quality by implementing better irrigation and fertilization techniques, and quantifying the risks of salinisation/sodization.

There are two distinct approaches to simulate the electrical conductivity of the soil solution (EC_{sw}). Most of the available models simulate EC_{sw} as a non-reactive solute, namely as a tracer without adsorption capacity to the solid phase of the soil. Only a few ones are also able to simulate EC_{sw} from the sum of the cations present in the soil solution (Šimůnek et al., 1996). The modeling of soluble cations requires a more complex approach where interaction between the different cations and competition for exchange bonds must be taken into account. An example of a mechanism used to describe the exchange processes between solid and liquid soil phases is the Gapon equations (White and Zelazny, 1986). These equations allow modeling the increase of Na^+ concentration in the soil solid phase and the transfer of exchangeable cations (Na^+, Ca^{2+}, Mg^{2+} and K^+) between the solid to the liquid soil phase. The models HYDRUS-1D (Šimůnek *et al.*, 2008) with the module UNSATCHEM (Šimůnek et al., 1996) and ,HYDRUS-2D (Šimůnek et al., 2006) are between the most used models to reproduce the measured values, and proved to be a good tool to evaluate saline water management and the effect of irrigation water quality on soil and crop development (Gonçalves *et al.*, 2006; Ramos *et al.*, 2011; Ramos *et al.*, 2012).

7. Management practices to prevent/reduce salinisation:

- monitoring and control irrigation water quality, for example, to close the floodgates when irrigation water, from a river, has an electrical conductivity greater than 1 dS/m
- adequate irrigation method according to irrigation water quality and the detrimental effects that both water and method of application can have on crop growth and yields. Surface systems are well adapted for leaching due to their lower inefficiency but are less appropriate for irrigation of less tolerant crops due to the increased water and salinity stresses that may rise in-between irrigation events. On the other hand, drip irrigation is appropriate for salt sensitive crops since small and frequent irrigation depths are used, but salts need to be prevented from returning into the wetted bulb
- irrigation scheduling should be able to fulfill crop water requirements and to help promoting salt leaching from the root zone. For surface irrigation, large depths and reduced number of events can eliminate salinity-build-up in the root zone and assure optimal crop production conditions if the fields are properly level and water and salt distribution are uniformly applied. For drip irrigation, small and frequent events can maintain maximum leaching in the root zone. However, on-farm management should be specific for each field conditions as small irrigation intervals can induce water uptake from shallow soil layers, increasing evaporation losses from soil surface and increasing salt load of soils. On the other hand, large irrigation intervals can enhance water uptake from deeper layers, enhancing salt movement to the soil surface if the groundwater is saline.
- fields properly level in order to ensure a regular distribution of water,
- irrigation depths according to soil properties (soil texture, available water capacity, hydraulic conductivity) and climate and crop demand,
- control of the use of fertilizers or amendments (particularly under conditions of limited leaching)
- meeting the leaching requirements. Under conditions of salinisation risk, leaching requirements should complement crop water needs in order to control the salt balance in the root zone.
- Suplementary irrigation events
- maintenance of drainage ditches
- Irrigation with multi-salinity waters. As fresh water supplies are not always available to fulfill crop water requirements, saline waters are often seen as a valuable alternative resource. Saline irrigation waters can be applied either separately, in a cyclic way, or mixed/blended together with fresh waters. When cyclic strategies are considered, fresh waters are applied to the most sensitive crop growth stages (germination and seedling) while saline waters can be allocated when the crop can tolerate higher salinity levels. When blending strategies are adopted, two or more waters sources are mixed together to reach a targeted salinity for a particular crop, and depend on the crop salt tolerance, the soil type and climate, and the long-term management plan for irrigation and crop production. Blending also requires additional infrastructures (dilution network, storage reservoirs) to allow the control mixing of two (or more) water sources.

Cyclic strategies are known to lead to higher yields than when blending is involved but all are associated to a risk of crop failure that needs to be properly managed.

- Salinisation studies must be supported by models for soil water dynamics and solute transport that, after calibration/validation with field data, become very useful tools for predicting different scenarios of irrigation water quality, climate, crops and soil.
- Chemical remediation of sodic soils. In sodic and saline-sodic soils, the sodicity can be reduced through chemical amendments. In the case of saline-sodic soils, the sodicity levels have to be reduced first, adopting strategies for leaching the excess salts in a second step. In the chemical reclamation of sodicity, Ca (calcium) is released by the chemicals amendments and is exchanged with the Na in the soil's exchange complex, the soluble Na can then be leached from the soil profile. Chemical amendments also increase the soil salinity level, mitigating or even preventing soil crusting. The most widely used chemical amendments are gypsum and gypsum-like by products. In general, these products are applied on the soil surface for soil crusting prevention or incorporated into the soil for sodic soil remediation. The doses depend on the soil and amendment characteristics. As general rule, the theoretical amount of gypsum required per hectare to replace 1 $cmol_c$ of exchangeable Na per kg of dry soil in a layer of 30 cm and with a mean soil bulk density of 1.3 $g{\cdot}cm^{-3}$, is 3.4 $t{\cdot}ha^{-1}$. Enough amount of water is also needed for gypsum dissolution. As a general rule, 1 m^3 of water is needed to dissolve 7 $t{\cdot}ha^{-1}$ of gypsum.
- Phyto and bioremediation of sodic soils. Phytoremediation works through a similar mechanism to that of chemical amelioration by making Ca available to replace Na in the soil's exchange complex. In this case, a source of Ca is necessary, which typically is the calcite existing in soils. The role of the plants in this process is to increase the CO_2 in the root zone, which enhances the dissolution of calcite. The increase of CO_2 in the root zone can be further helped by the activity of bacteria.
- awareness campaigns for better irrigation and fertilization practices and for the consequences of soil degradation processes like salinisation

8. Cases studied: Preventive e corrective practices

8.1 Portugal

The Portuguese experimental fields where set in Lezíria Grande of Vila Franca de Xira (LGVFX) that is an important agricultural system of alluvial-estuarine origin located northeast of Lisbon, where soil faces risk of salinisation due to its marine origin, irrigation practices, tidal influence from the proximity of Tagus estuary, and projected evolution of climate. In fact, soil salinity in the region manifests a north-south gradient, being this a predisposition for the distribution of land use types.

The experimental fields were chosen to contemplate soils with different degrees of salinity, cultures and irrigation methods, representatives of LGVFX irrigation district. Four areas were selected:

Location 1 - tomato irrigated with drip irrigation and annual ryegrass (soil with very low salinity) named Montalvo;

Locations 2 and 3 - maize irrigated by a center pivot and in winter: annual ryegrass and a mixture of annual ryegrass, cloverleaf and lucerne (two areas with soils with moderate salinity) named Corte Lobo and Ermida, respectively;

Location 4 - permanent pasture, without irrigation (soil with very high salinity) named Polvarista. The irrigation water has a good quality (EC < 0.5 dS m^{-1}).

Field campaigns, in a total of six using both geophysical methods and soil sampling, were realised from May 2017 to October 2018.

In the case of the 4 locations studied in Portugal **the main preventive or reclamation management practices, in the respective production systems, are proposed below**:

Location 1 – irrigated field with tomato and winter cover of ryegrass

This location is non-saline and non-sodic along the entire profile, namely has low soluble salt concentration (EC_e < 2 dS m^{-1}), low soluble Na concentration (SAR < 13 $(mmol_c\ L^{-1})^{0.5}$), and exchangeable Na concentration (ESP < 15%). This location did not presented soil salinity issues during the time period of the SALTFREE project. However, considering that it is located in a region of alluvial and marine origin of the soil, has a shallow saline water table, and faces the risk of degradation of the irrigation water quality, especially in drought years, some concerns arise and the following preventive measures are proposed:

- Regarding irrigation practices, the fertigation should be carefully monitored in order to avoid unbalances in salts occurring in the soil and especially in the root zone. The management practice of applying higher amount of irrigation water to promote salt leaching can be also used if the quality of irrigation water decreases, as it may occur in a scenario of climate change with reduced rainfall and scarcity of good quality water. If the quality of the irrigation water does not decrease, irrigation can be performed without considering the leaching fraction to avoid the rise of the shallow saline ground water that exists at approximately 1.3 m depth.
- The crop rotation with the winter cover is a good practice to keep the soil structure, and prevent the development of salt-related problems.

Location 2 – irrigated field with maize and winter cover of ryegrass

This location is mainly non-saline and non-sodic at the topsoil and subsurface. In the upper subsoil, i.e., below 60 cm depth, is sodic. In detail, salinity levels were uniformly non-saline, with low soluble salt concentration (EC_e < 2 dS m^{-1}), low soluble Na concentration (SAR generally < 13 $mmol_c$ $L^{-1})^{0.5}$ along the entire profile, but high exchangeable Na concentration (ESP > 15%) from 60 cm depth. Sodic soils can face structural degradation, due to clay dispersion and slow permeability to water and air, which might be complex to remediate. The following management practices should be considered:

- Regarding the sodicity and the agricultural use of this soil, the root zone for irrigated maize is above the sodic soil layer. However the degradation of layers below can result in a decrease of permeability and promote salts accumulation in the root zone, and consequent productivity loss. A practice that can be used to promote infiltration is tillage that is being already used by the farmer at this location.
- The remediation of the sodicity issue depends on the soil composition in relation to the availability of carbonates. In the case of this soil, no carbonates were detected and therefore gypsum can be added in order to provide calcium to exchange with the sodium in the soil's exchangeable complex.
- The crop rotation with the winter cover is a good practice to keep the soil structure, and prevent the development of salt-related problems.
- Regarding irrigation practices, the fertigation should be carefully monitored in order to avoid unbalances in salts occurring in the soil. The study of the irrigation-induced risks of soil salinisation in this location revealed that when the electrical conductivity of the irrigation water increased, salts accumulate in the root zone to levels above the threshold tolerated by the maize crop. The management practice of applying higher amount of irrigation water to promote salt leaching from the root zone must be used carefully due to the presence of the sodic layer immediately above the root zone which can promote salts accumulation. Another approach can be to apply enough irrigation water to fulfil crop water requirements to keep the sodicity issues of that soil layer outside the root zone, practice that is already being used by the farmer.

Location 3 – irrigated field with maize and winter cover with a mixture of annual ryegrass, cloverleaf and lucerne

This location is mainly saline-sodic along the entire profile, with both salinity and sodicity increasing with depth. The salinity levels in the first layers might start to limit the productivity of maize. Considering the present situation, the following management practices should be considered:

- Considering the sodicity, as no carbonates were detected in the soil, gypsum can be added in order to provide calcium to exchange with the sodium in the soil's exchangeable complex.
- After the sodium concentration is reduced, the salinity reduction can be promoted by leaching the soil salts, which could be possible with the rain water.
- The remediation could be carried out during one wet season and the need for further remediation should be analysed. After the remediation period, the crop rotation with the winter cover is a good practice to keep the soil structure and prevent the development of salt-related problems.
- The addition of chemical fertilizers should also be carefully monitored in order to avoid unbalances in salts occurring in the soil.

Location 4 – rainfed spontaneous pasture.

This location is mainly non-saline and non-sodic at the topsoil and mainly saline-sodic in the subsurface. The climate change simulations show that in the future climate scenarios the salinity levels increase along the entire soil profile and the water content of the topsoil will decrease. This can lead to a decline in the pasture in case the plants do not tolerate the increased salinity associated with a reduction in water content. In these conditions the following management strategies should be considered:

- Maintaining natural vegetation at the location is necessary in order to preserve the soil structure, promoting leaching of the salts with the rain water, and avoiding erosion. This process is likely to be responsible for the good quality of the topsoil at this location.
- In order to maintain the plant growth it is necessary to analyse the salinity tolerance of the plants in the pasture and eventually study new species that could adapt to the changing salinity. Species with deep roots could also help to reduce the sodicity and improve permeability in layers below the topsoil.
- In addition to the higher salinity tolerance, the pasture species also have to be able to face a lower water content level in the topsoil.
- The challenges demanded for this new species for the permanent pasture are high and require a study of species that are well-adapt to other locations with similar conditions, and that can be introduced to the pasture and integrate the soil seeds bank to sustain the spontaneous pasture.

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