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

EJP SOIL
European Joint Programme

PhD course: “Soil Management for Sustainable Agriculture”

Soil Salinization and Alkalization

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REPÚBLICA PORTUGUESA | AGRICULTURA E ALIMENTAÇÃO

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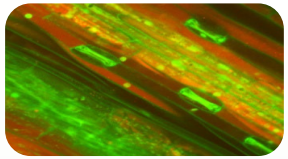
UNIPA, 26th October 2022







1. Introduction

2. Salt-affected soils

2.1. Saline soils

2.2. Sodic and saline-sodic soils

2.3. Alkaline soils

2.4. Classification of salt-affected soils

2.5. Measurement

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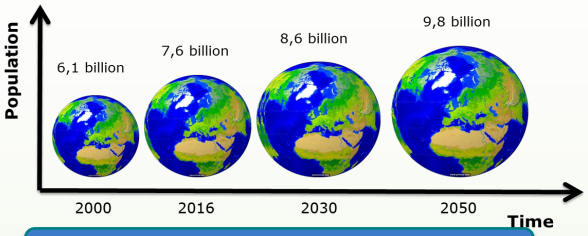
Pressures on soils



Increasing population

Diets change

Migration

Loss of biodiversity

Cities expand

Food insecurity

Pollution

Climate change

Poverty

Pandemic

FAO-ITPS, 2020

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3 main challenges of agriculture (OCDE, 2019):

Feed a growing population, provide livelihoods for farmers and protect the environment.

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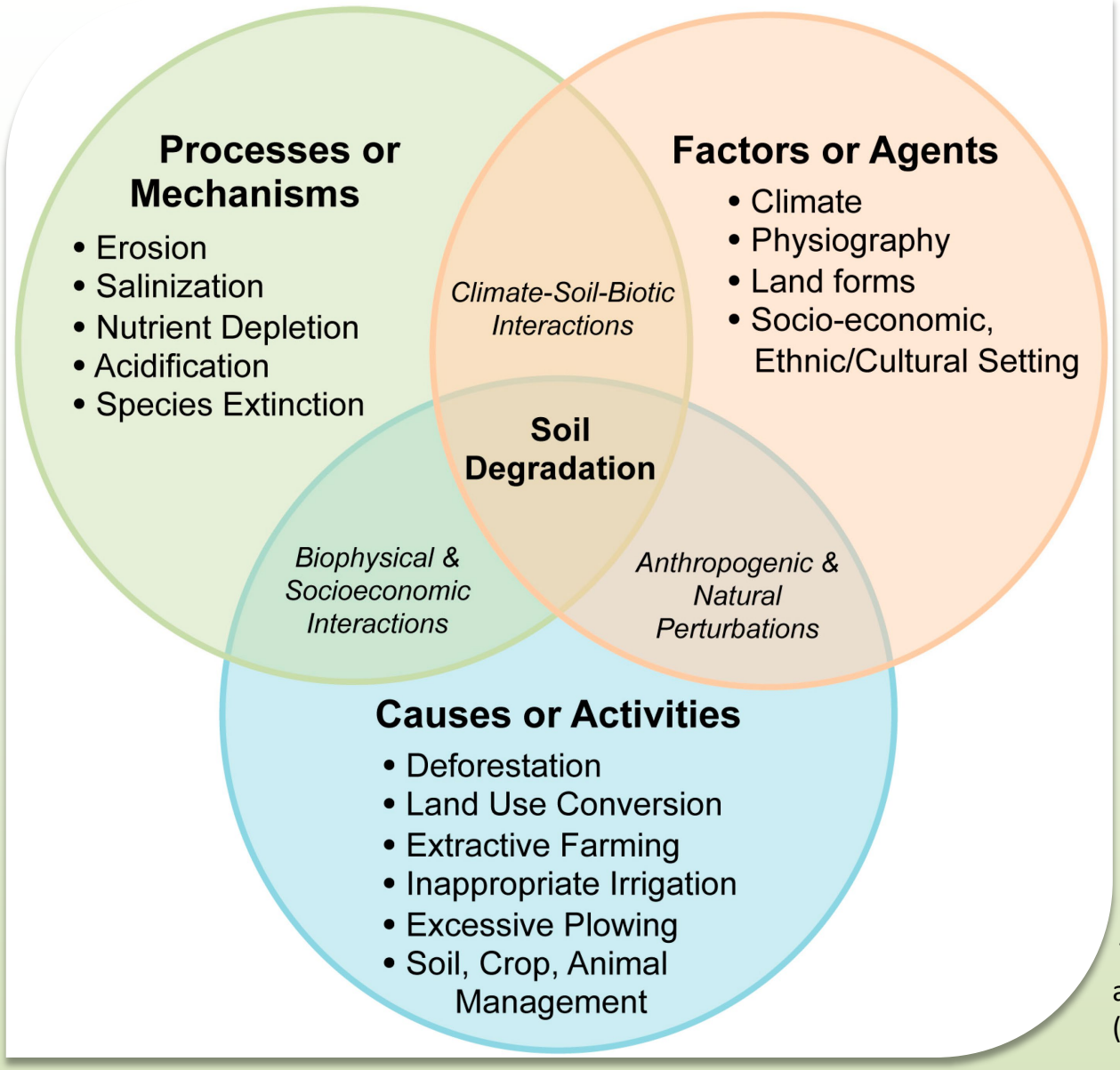
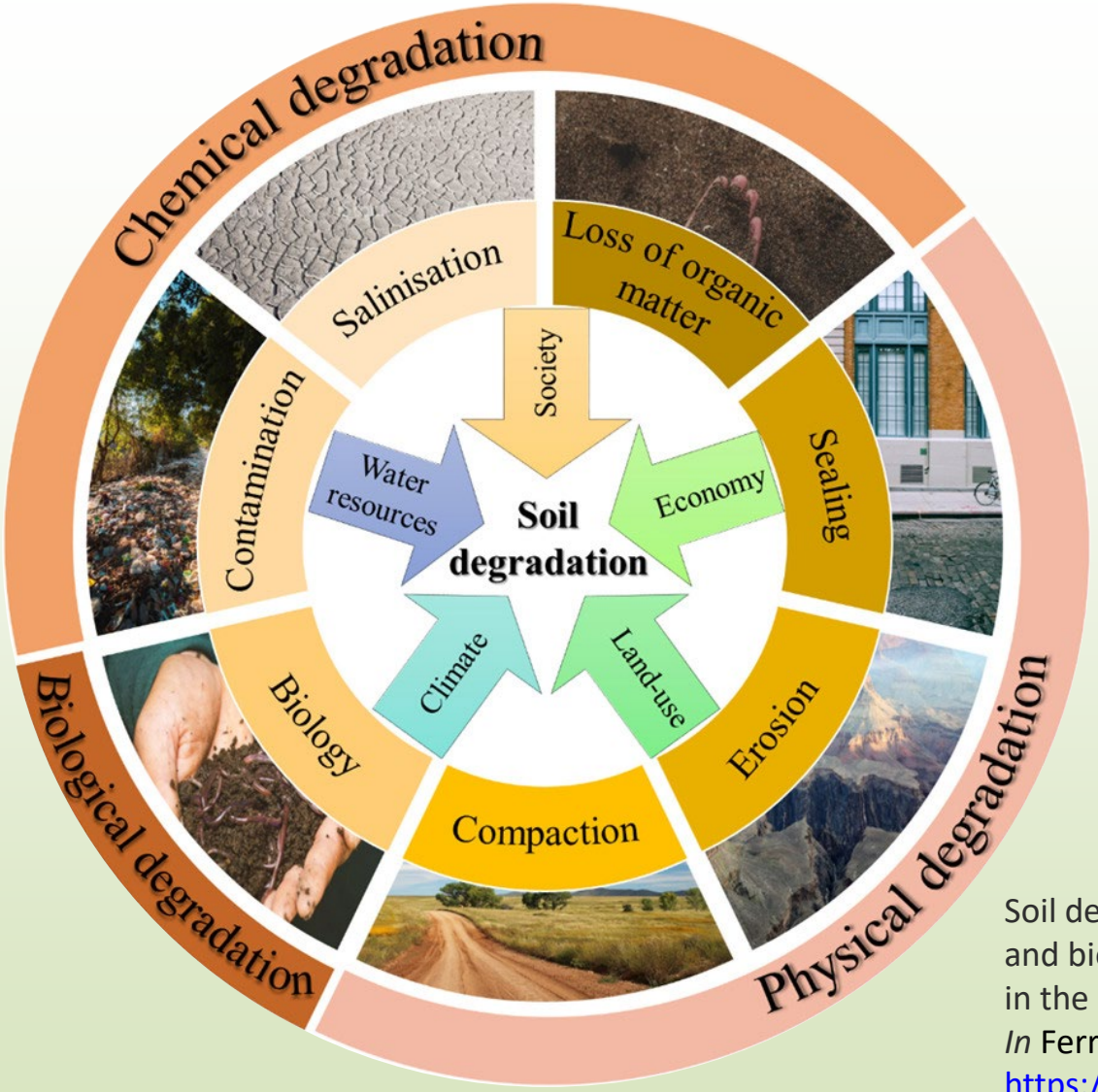
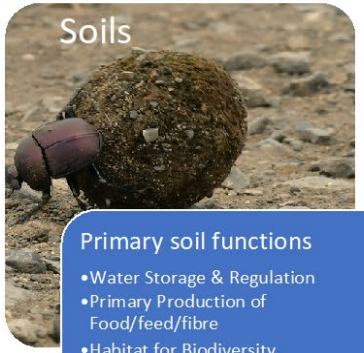


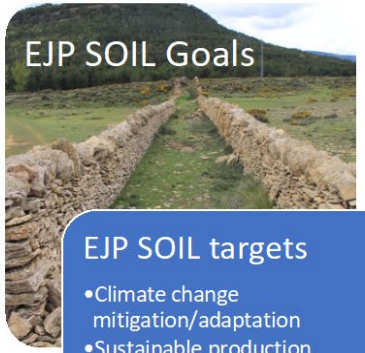
The process-factor-cause nexus as a driver of soil degradation (*In* Lal, 2015)



Soil degradation processes (physical, chemical and biological) are linked with major soil threats in the Mediterranean countries.
In Ferreira *et al.*, 2022.
https://doi.org/10.1016/j.scitotenv.2021.150106

Pressures, threats, challenges





Elements of Climate Smart Sustainable Soil Management

- Improved water storage & water use efficiency
- Control soil erosion & land degradation
- Improved soil biodiversity
- Improved soil structure management
- Improved nutrient management
- SOM management and C sequestration

Primary soil functions

- Water Storage & Regulation
- Primary Production of Food/feed/fibre
- Habitat for Biodiversity
- Nutrient Cycling
- Carbon sequestration and climate regulation

EJP SOIL targets

- Climate change mitigation/adaptation
- Sustainable production
- Enhanced ecosystem services: provisioning, regulating, supporting
- Soil restoration and avoid degradation

Land Management categories

- Agricultural systems
- Buffer strips and small landscape elements
- Crops/crop rotations
- Organic matter and nutrient management
- Tillage and traffic
- Crop protection
- Water management

Soil challenges

- Maintain/increase SOC
- Avoid N2O/CH4 emissions
- Avoid peat degradation
- Avoid soil erosion
- Avoid soil sealing
- Avoid salinization
- Avoid acidification
- Avoid contamination
- Optimal soil structure
- Enhance soil biodiversity
- Enhance soil nutrient retention/use efficiency
- Enhance water storage capacity

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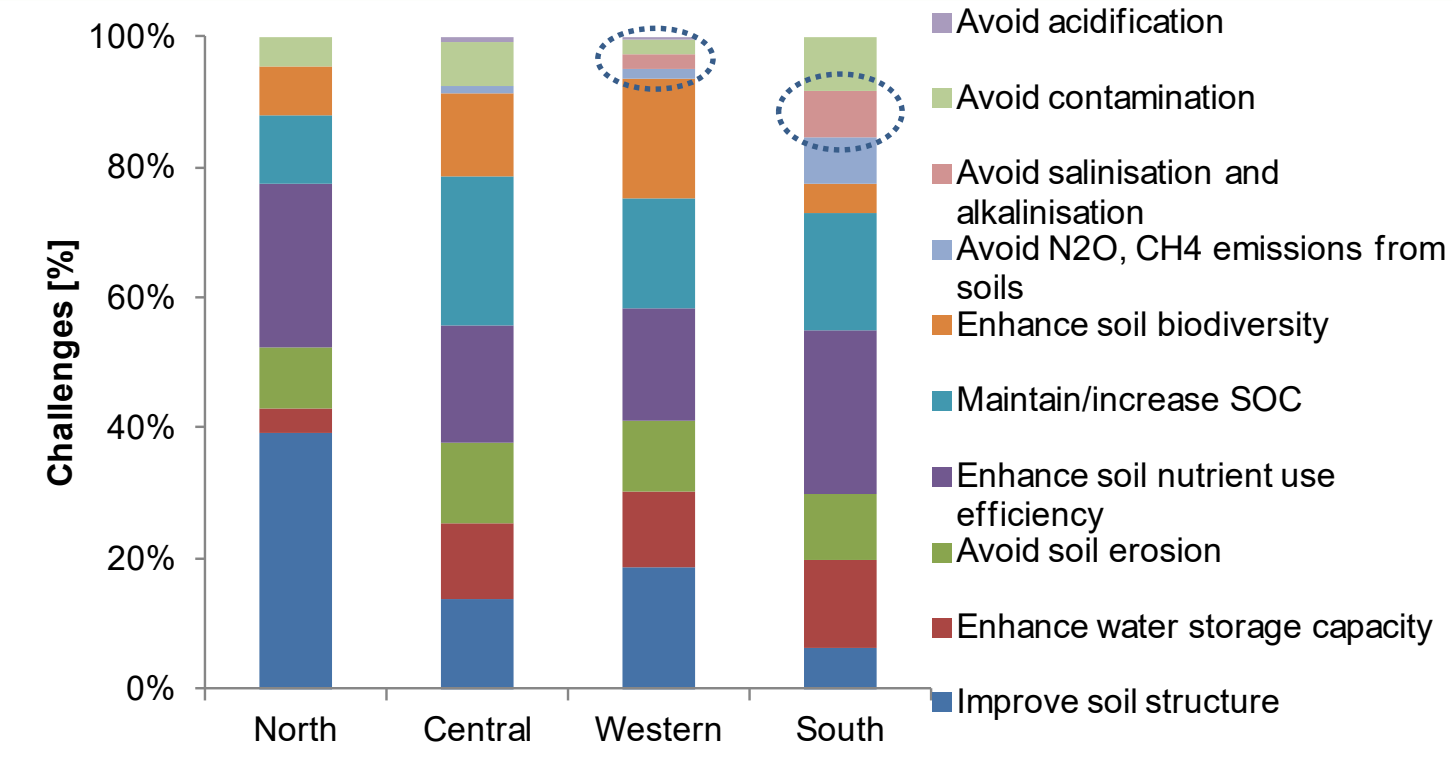
EJP SOIL Challenges

23 EJP SOIL countries



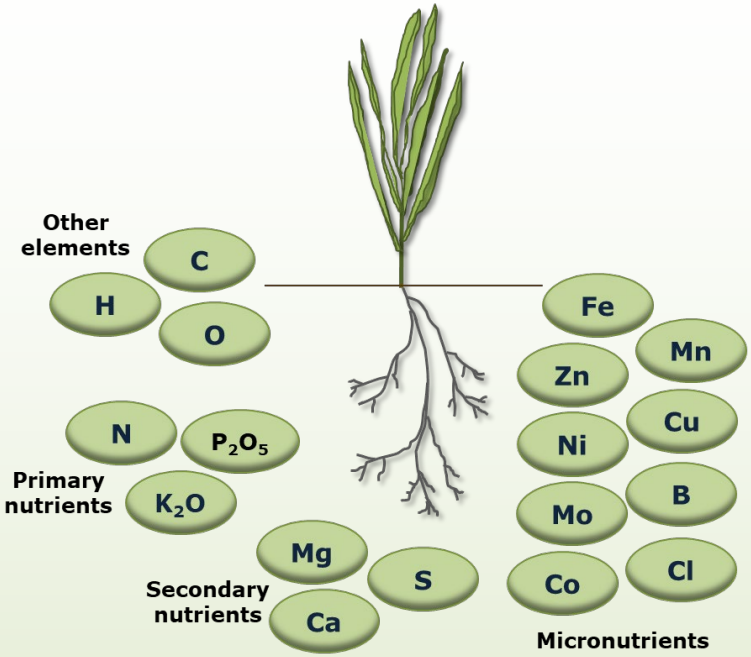
Northern Europe - Denmark, Norway, Sweden, and Finland
Central Europe - Austria, Czech Republic, Estonia, Germany, Hungary, Slovakia, Slovenia, Poland, Lithuania, Latvia, and Switzerland
Western Europe - Belgium, France, Netherlands, and United Kingdom
Southern Europe - Portugal, Spain, Italy, and Turkey

Agriculture is demanding in plant nutrition

Potential source of pollution (leaching, phreatic contamination, alterations in microbial ecosystems)

Primarily made from nonrenewable sources (including fossil fuels)

Costs are increasing



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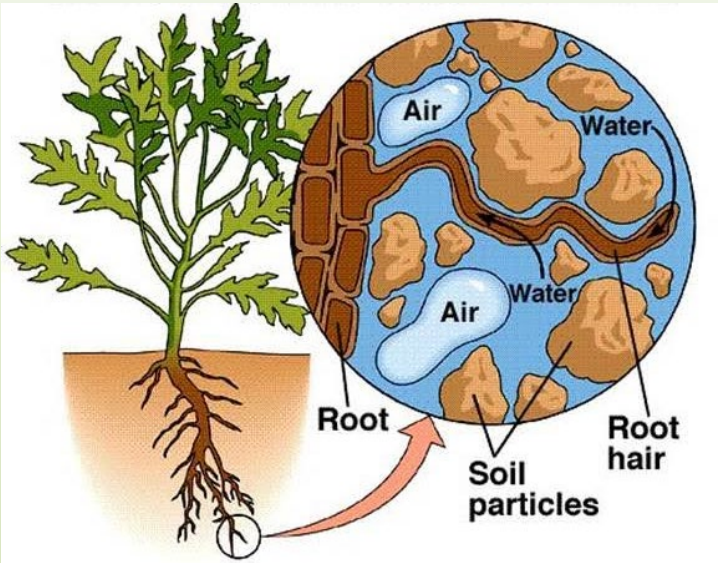
Soil salinity definition

potassium, magnesium, calcium, chlorides, sulphates, carbonates, bicarbonates and sodium

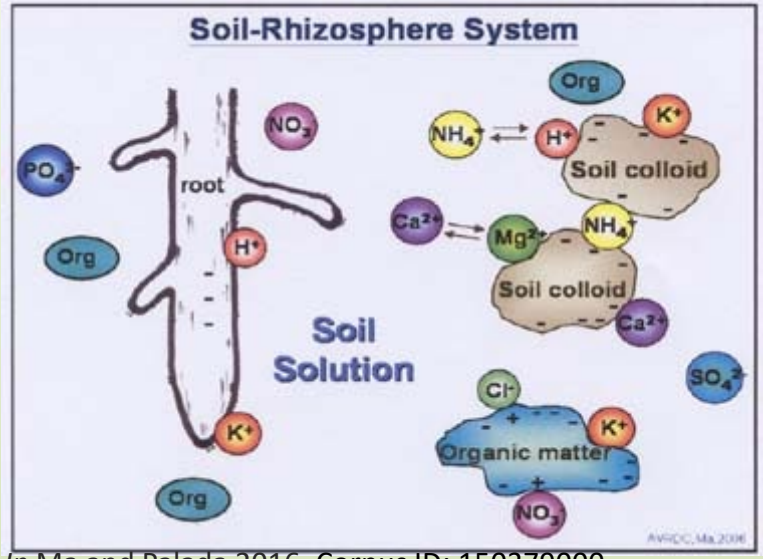
Concentration of dissolved salts in the soil solution

Na^+ Ca^{2+} Mg^{2+} K^+

Cl^- SO_4^{2-} $HCOO^{3-}$ CO_3^{2-} NO^{3-}



In ICSE Solutions for Class 10 Biology, 2019



In Ma and Palada 2016. Corpus ID: 150379000

Osmotic pressure of the soil solution increases with the concentration of dissolved salts, hindering the water absorption by plants. Salinity can also lead to nutritional imbalances or toxicity caused by specific ions.

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Soil solution

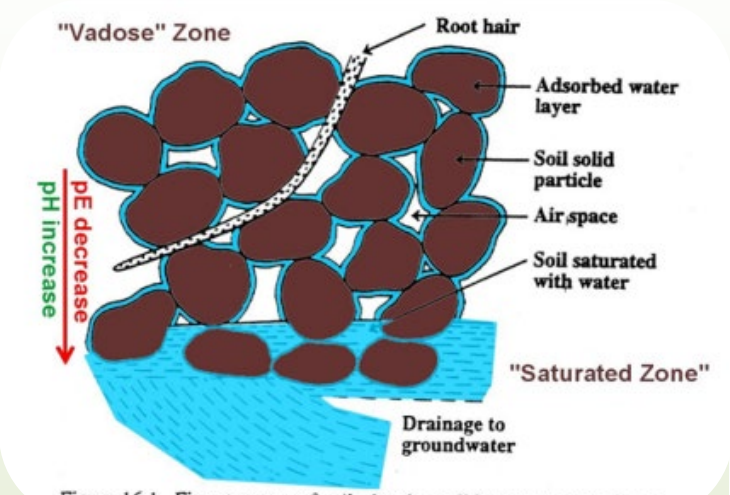
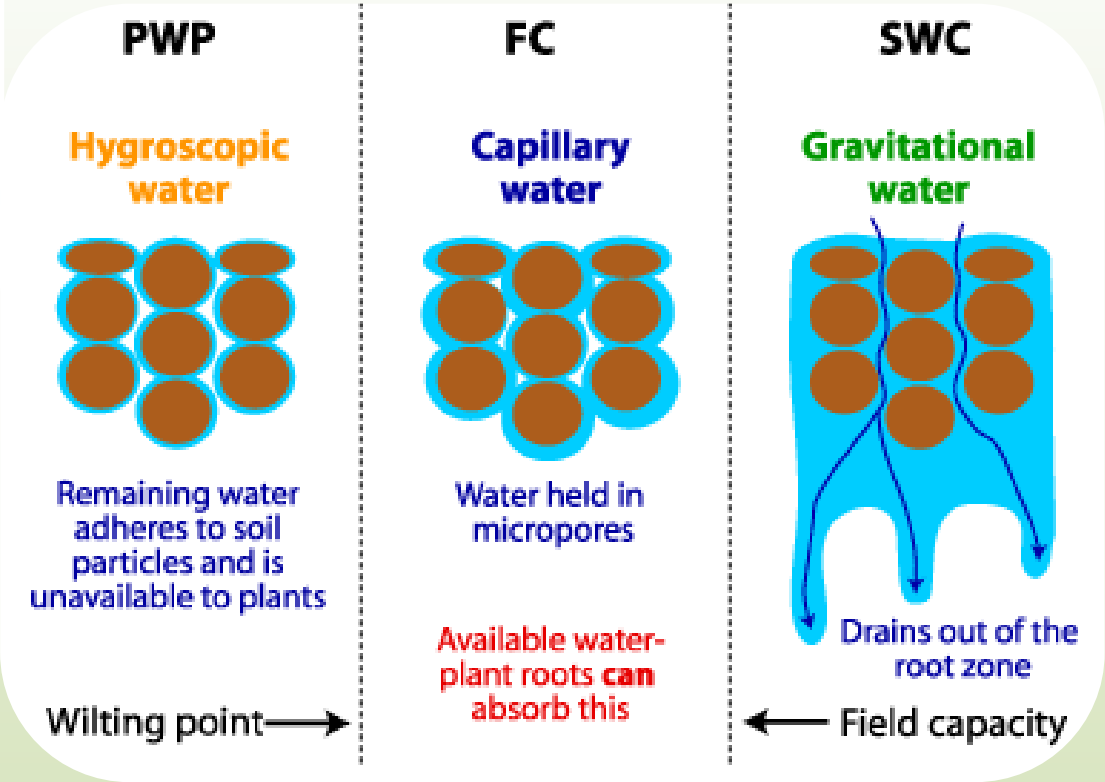


Figure 16.1. Fine structure of soil, showing solid, water, and air phases.

Available water for plant growth



In https://www.agrilearner.com/type-of-soil-water/

1. Hygroscopic water - held tightly to the surface of soil particles by adsorption forces.
2. Capillary water- held by forces of surface tension and continuous films around soil particles and in the capillary spaces.
3. Gravitational water - that moves freely in response to gravity and drains out of the soil.

Soil salinity sources

Primary	Secondary
Geochemical weathering of salty parent material rocks	Irrigation with poor water quality or inadequate irrigation practices
Irregular distribution of rainfall	Improper drainage, low soil permeability
High aridity Index (AI= P/PET), high evapotranspiration	Overuse of inorganic and organic fertilizers
Seawater intrusion in coastal areas, seepage of saline groundwater	Inappropriate soil management
Tidal flooding	High water table
Atmospheric deposition	Exposure of land by deforestation

Soil salinity sources

Primary

Secondary

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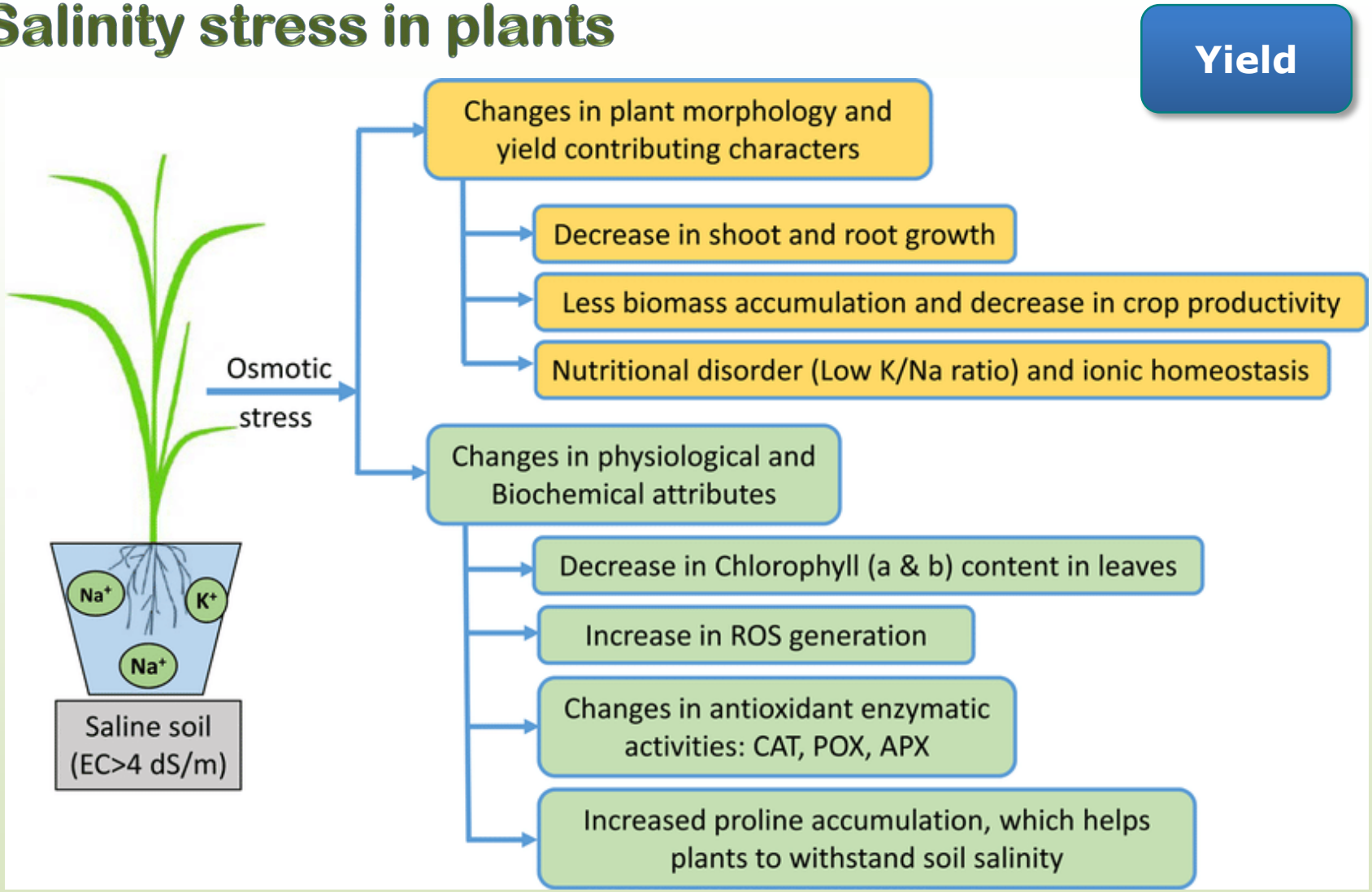
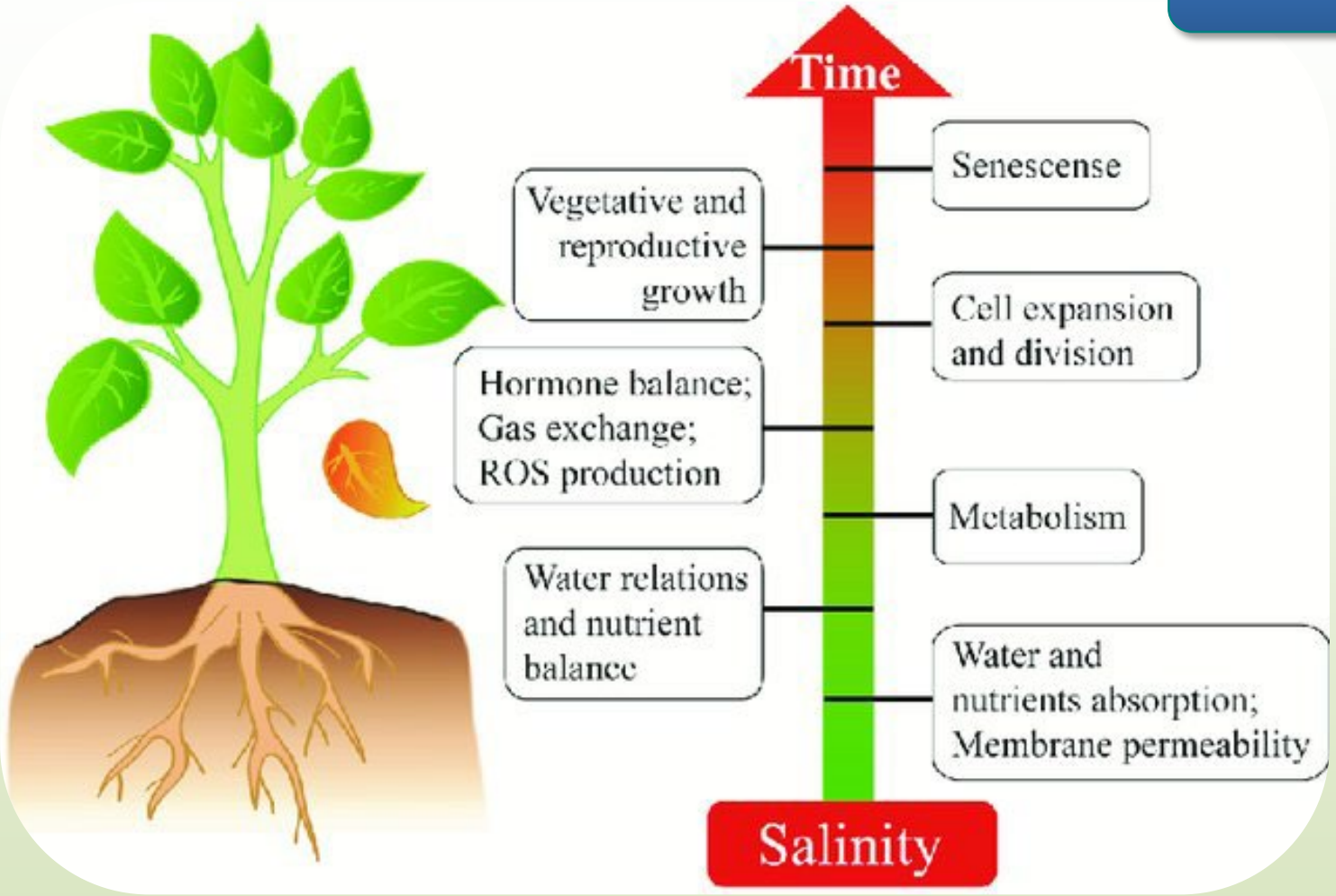
Salinity stress in plants



Plant responses to salt stress
In Kibria and Hoque, 2019. DOI: 10.4236/ojss.2019.911013

Salinity stress in plants

Yield



Hypothetical time scale changes in the physiology of plants grown under salt stress.
In Miranda *et al.*, 2019

Soil Salinity measurement

TDS (mg L^{-1})	Measurement of the mass of total dissolved solids (direct)
[C] (mgL^{-1})	Proportion and composition of salt species using spectrophotometry (direct)
EC (dSm^{-1})	Measurement of the electrical conductivity (indirect)

Laboratory

ECa (dSm^{-1})	Measurement of the apparent soil electrical conductivity. Non-invasive with the electromagnetic induction (EMI) and *in situ* with TDR or capacitance probes.
ER (dSm^{-1})	*In situ* measurement of electrical resistivity (ER)

Field

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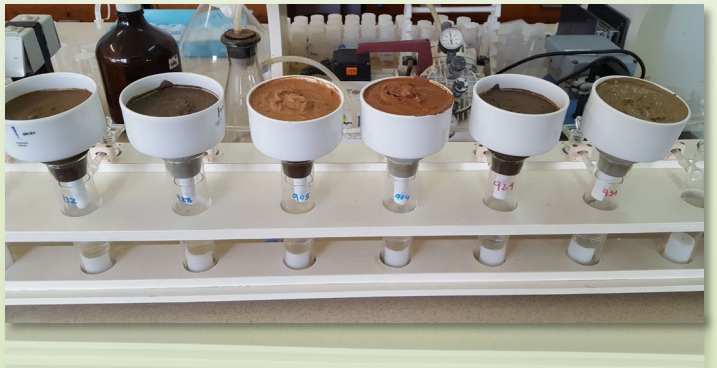
Soil Electrical Conductivity

Measures how easy an electrical impulse goes through the soil

Influenced by:

- Salts concentration and composition
- Porosity
- Texture (clay fraction and its mineralogy)
- Soil temperature (25°C)
- Soil water content

Saturated paste extract (ECe)



in many soils the water content of the saturated paste is ≈ 2x field capacity and the quadruple of wilting point

Soil:Water Extracts (m:v) in proportions 1:1; 1:2,5; 1:5

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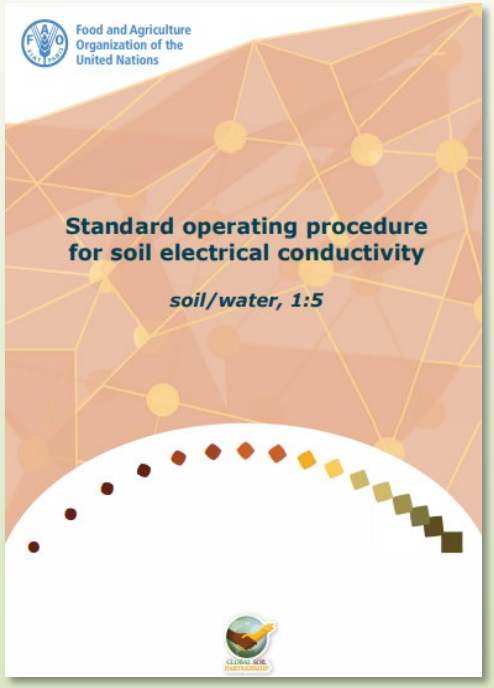
Soil Electrical Conductivity - SOP

GLOSOLAN
(Global Soil Laboratory Network)

Established in 2017 to build and strengthen the capacity of laboratories in soil analysis and to respond to the need for harmonizing soil analytical data (methods, units, data and information).

(1) provide reliable and comparable information between countries and projects;
(2) allow the generation of new harmonized soil data sets;
(3) support evidence-based decision making for sustainable soil management.

Soils:
if you cannot measure it, you cannot manage it



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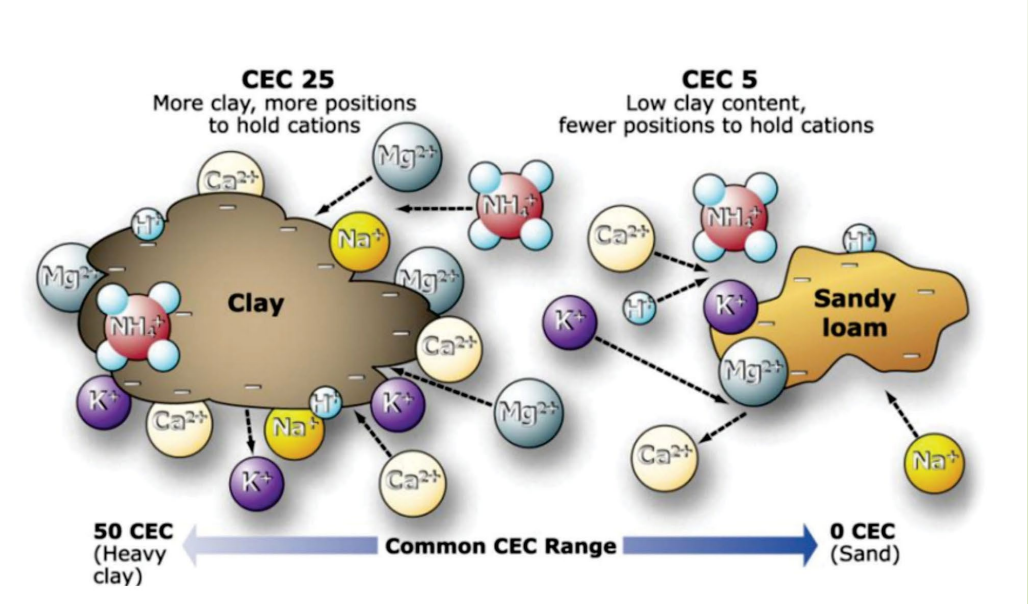
Soil sodicity definition

Accumulation of Na^+ salts bound to clay soil particles relative to other salt cations (Ca^{2+} and Mg^{2+})

Na^+ Ca^{2+} Mg^{2+} K^+

Cl^- SO_4^{2-} $HCOO^{3-}$ CO_3^{2-} NO^{3-}

SEM image of Kaolinite *In* Benchmark Geolabs, USA, 2017



In Basics of soil fertility, North Dakota State University, 2013

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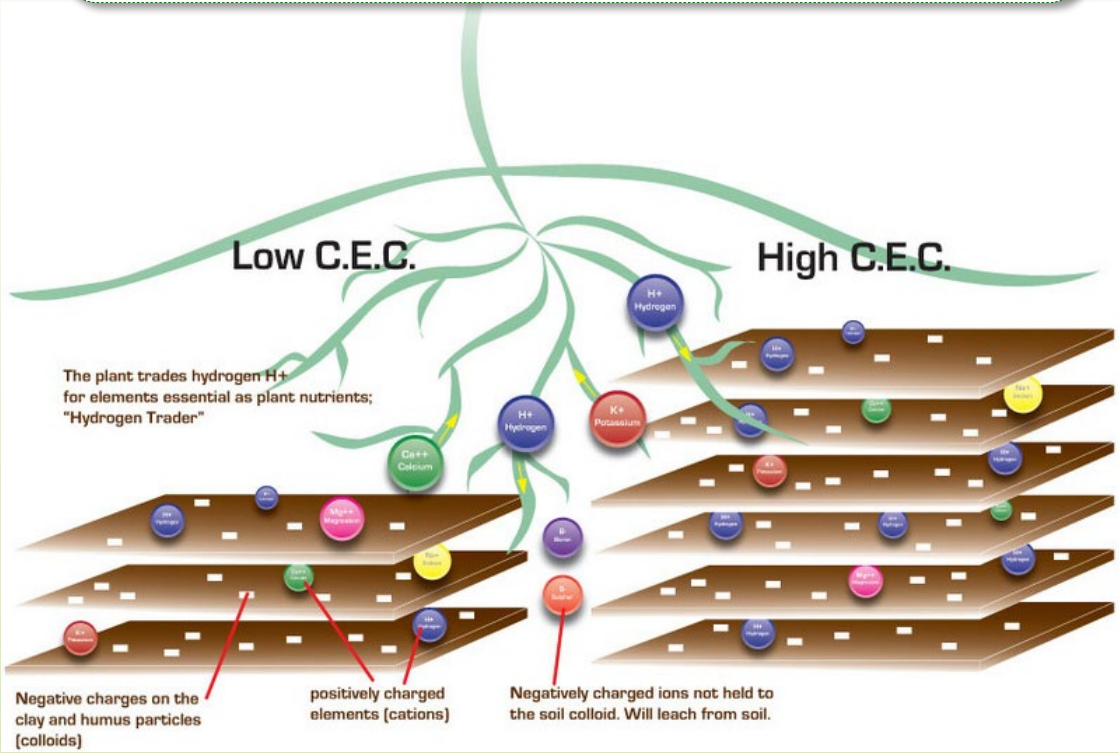
Soil exchange complex

Soils (often negatively charged) interact with nutrients (often positively charged) through cation exchange.



In https://www.superior.net.nz/pages/8-3/Understanding-the-Science

CEC

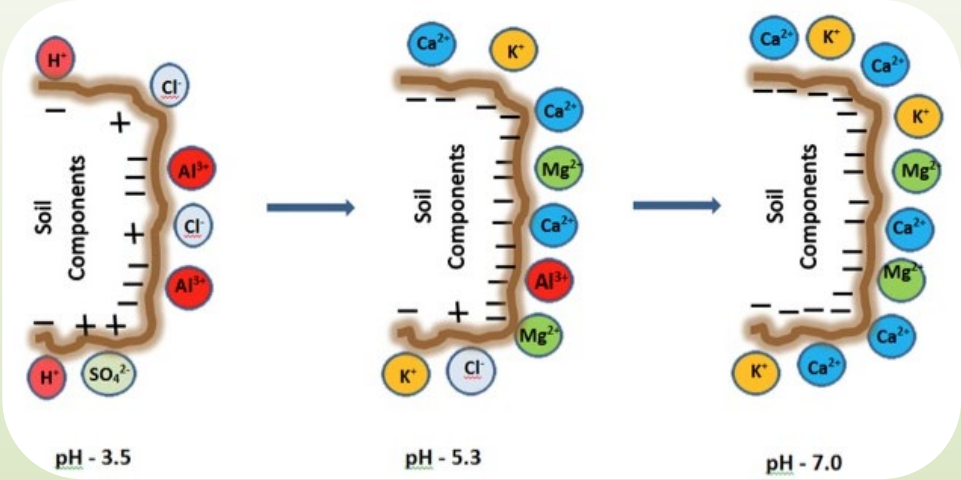
- is an **inherent** soil characteristic and is difficult to alter significantly
- **number of cation adsorption sites** per unit weight of soil
- the sum total of exchangeable cations that a soil can adsorb
- influences the soil's ability to **hold onto essential nutrients** and provides a **buffer** against soil acidification
- determines how frequently and in what **doses** it should receive **fertilizer**

https://scienceofagriculture.org/ch-cation.php

Typical CEC values in soils

Cation exchange capacities at pH 7.0 of different soil types, textures and soil organic matter

Soil and Soil Components	CEC (meq/100 g)
Clay Type	
Kaolinite	3-15
Illite	15-40
Montmorillonite	80-100
Soil Texture	
Sand	1-5
Fine Sandy Loam	5-10
Loam	5-15
Clay Loam	15-30
Clay	>30
Organic Matter	200-400



In UGA Cooperative Extension Circular 1040 Reviewed, University of Georgia, 2022

Soil sodicity measurements

ESP (%)	Describes the fraction of adsorbed Na from the cation exchange capacity (CEC) of the soil	**Laboratory**
SAR [$(mmol_c\ L^{-1})^{0.5}$]	Refers to the concentration of soluble Na relatively to the concentrations of soluble Ca and Mg, expressed in relation to the volume of the solution	

$$ESP = \frac{[\text{Exchange } Na^+]}{CEC} \text{ x } 100 \quad [\%]$$

OR

$$ESP = \frac{[\text{Exchange } Na^+]}{Exchangeable\ ([Ca^{2+}]+[Mg^{2+}]+[Na^+]+[K^+])} \text{ x } 100\ [\%]$$

where $[Na^+]$, $[Ca^{2+}]$, $[Mg^{2+}]$, $[K^+]$ are the concentrations of exchangeable cations in the soil exchange complex

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

where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are the concentrations of soluble cations measured in the soil saturation paste extract (Richards, 1954)

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Soil Sodicity effects

Degrades soil properties by weakening the bond between soil particles

- reduced flow of water through soil - limiting leaching and can cause salt to accumulate over time and the development of saline subsoils
- dispersion in the soil surface, causing crusting and sealing, which impedes water infiltration
- dispersion in the subsoil, accelerating erosion (can cause the appearance of gullies and tunnels)
- dense, cloddy and structureless soils as it destroys aggregation

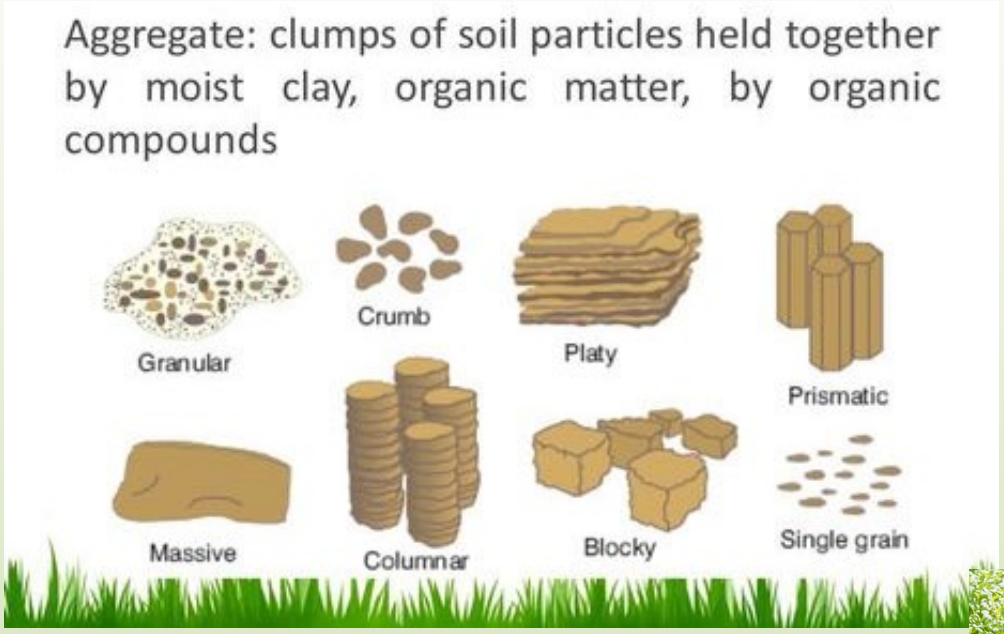
Destruction of soil structure as a result of excess sodium (Source: Soil Atlas of Europe)

Soil Sodicity

Saline build-up on the dry bed of the Brukunga pyrites mine tailings idam, Australia
Author: John Coppi, 1992
http://www.scienceimage.csiro.au

Soil Sodicity evaluation

Soil Structure



Indicators

(some common signs include):

- poor vegetation or crop growth
- poor water infiltration
- surface crusting
- dense or hard subsoil
- prismatic or columnar structure in the subsoil
- soapy feel when wetting
- pH > 8.5
- shallow rooting depth

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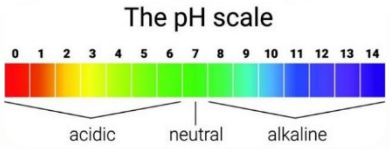
Alkaline Soils definition



Soils with pH > 7.5
Accumulation of dissolved calcium carbonate minerals in the soil solution

$CaCO_3$ $HCOO^{3-}$ CO_3^{2-} Ca^{2+} Na^+ Mg^{2+} K^+ Cl^- SO_4^{2-} NO^{3-}

high concentrations of carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) which have the ability to neutralize acids

Soil with a high pH level (> 7.5)

In Alberta Environmental Farm Plan, www.albertaEFP.com.

Contains sufficient Na levels to interfere with the growth of most crops.
Defined as having a very high degree of alkalinity (pH of 8.5 or greater) or a high ESP content (15 % or more of the exchange capacity), or both

The Global Map of salt-affected soils defines soil as salt-affected when the pH is above 8.2 (FAO, 2021)

Alkaline Soils sources

Primary

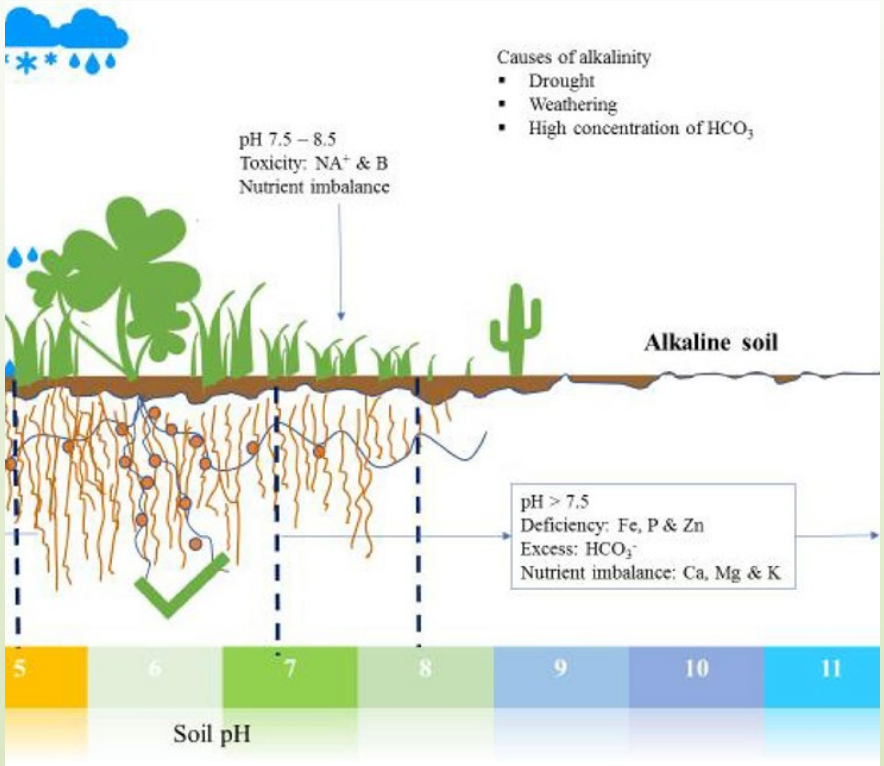
- Natural weathering processes of silicates, Al silicates and carbonate containing compounds Na^+, Mg^{2+}, K^+, and Ca^{2+} linked to silicates being hydrolyzed and subsequent OH^- release
- Drought or very irregular distribution of rainfall (high evaporation and insufficient leaching)
- Associated with arid and semi-arid regions and with desertification

Secondary

- Irrigation practices with groundwater high in sodium bicarbonates and carbonates
- Demand for Al in the world has contributed to increased alkalinity in surrounding ecosystems because mining and disposing of the alkaline bauxite residue
- Over liming practices (should carefully consider the knowledge of soil acidity)

Alkaline Soils effects

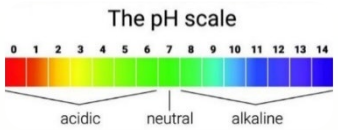
Alkalinity affects the solubility of nutrients and other elements needed by plants and can lead to both deficiency and toxicity.

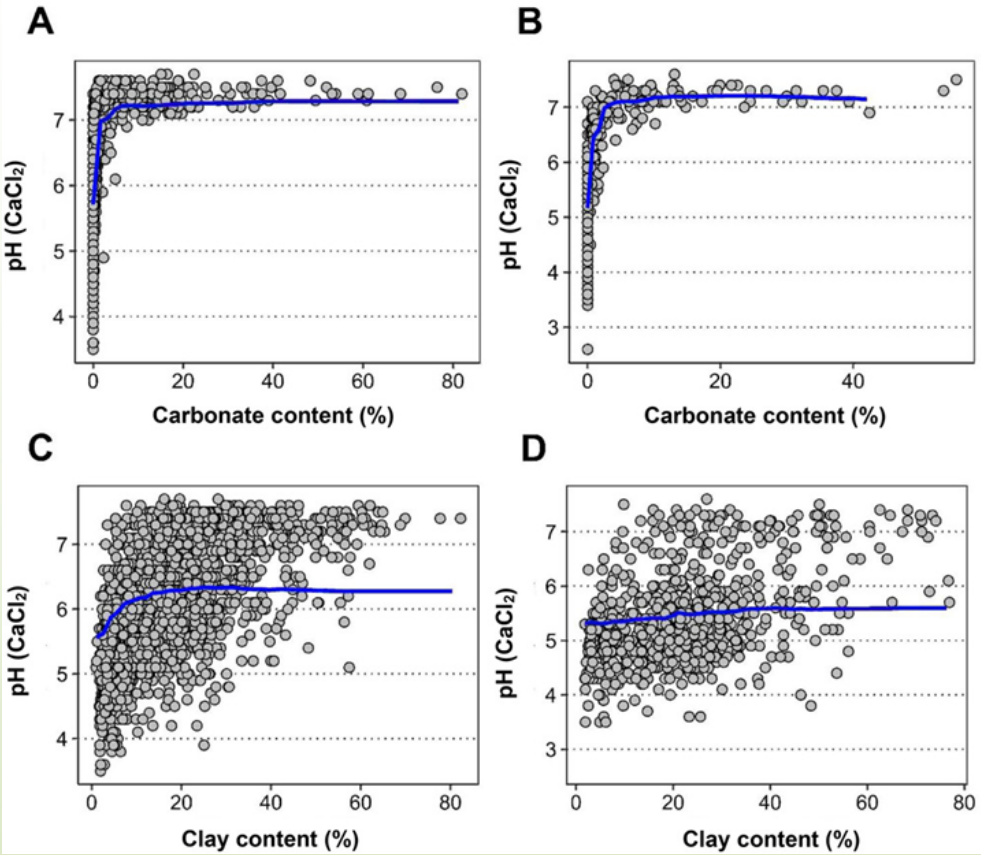


Msimbira and Smith, 2020
https://doi.org/10.3389/fsufs.2020.00106

- **Soil pHw > 7** - generally caused by the predominance of anions such as bicarbonates and carbonates, while phosphates, borates and some organic molecules can also contribute to high pH.
- **Soil pHw > 7 and pHw < 8** – Ca bicarbonate and carbonate are the dominant salts. These salts are only sparingly soluble and do not cause severe problems for plant growth.
- **Soil pHw < 8** - alkalinity is insignificant in relation to plant growth.
- **Soil pHw > 8** - classified as alkaline and will have significant amounts of Na bicarbonate and also high quantities of Na attached to clay particles (sodicity) and this will affect crop growth and productivity.
- **Soil pHw > 9** - the soils are 'highly alkaline' and invariably strongly sodic and will contain significant amounts of Na carbonate. Soils may have toxic amounts of bicarbonate, carbonate and aluminate (a form of Al found in high pH) ions. In addition, nutrient deficiency is likely to be a major problem since many nutrients become unavailable.

Alkaline Soils effects

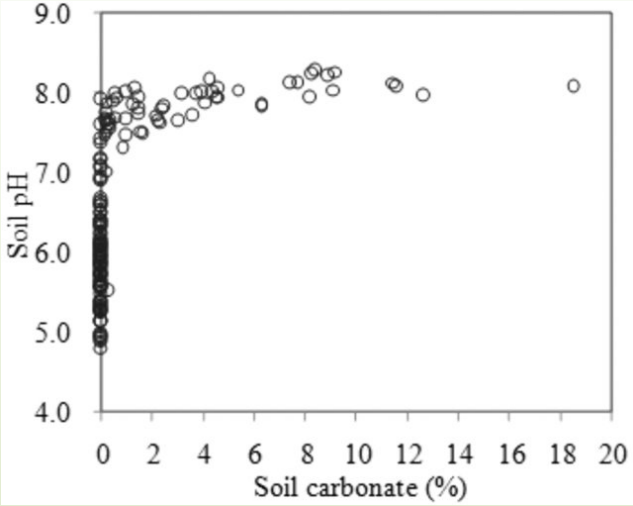




Muller *et al.* 2021, Inventory and assessment of pH in cropland and grassland soils in Germany.
https://doi.org/10.1002/jpln.202100063

Critical role of soil carbonate and its impact on heavy metal bioavailability

Relation between soil pH and carbonate concentration (n = 150).



Wang *et al.* 2015, *Sci Rep* https://doi.org/10.1038/srep12735

There is a crucial change between soil pH and carbonate concentration during the soil acidification process, i.e., soil pH shows a tipping point at the pH of 7 and carbonate concentration near zero.

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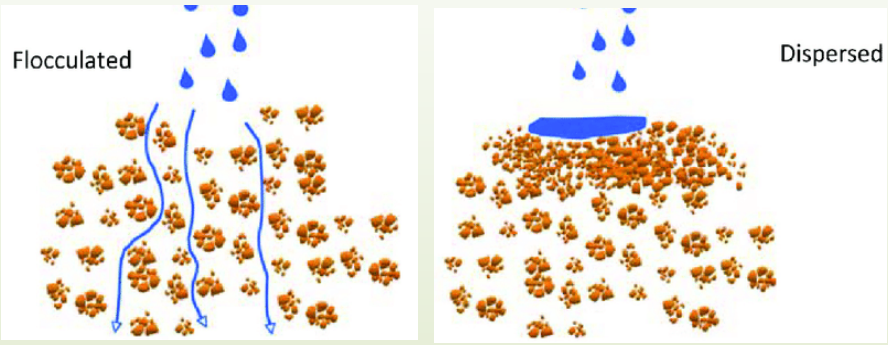
Alkaline Soils effects

Unfavorable physico-chemical properties mainly due to the dominating presence of Na carbonate which causes the clay particles in the soil to swell



- soils are typically highly porous, freely draining and saturated with calcium carbonate
- concentration of dissolved carbonate minerals, which react with water to form OH^- that accumulate in the soil solution
- also influenced by the $[CO_2]$, which increases with roots and microbiome respiration, and can partly counteract the formation of OH^-
- the abundance of Ca^{2+} in the soil solution limits P-solubility by forming sparingly soluble Ca-P compounds. Also, the carbonates can precipitate forming calcite, which has limited solubility (soil pH typically < 8)
- with large relative $[Na^+]$ in the soil solution, the solubility of Na carbonates can make pH increase well > 8

Alkaline Soils evaluation

Simple soil dispersion test

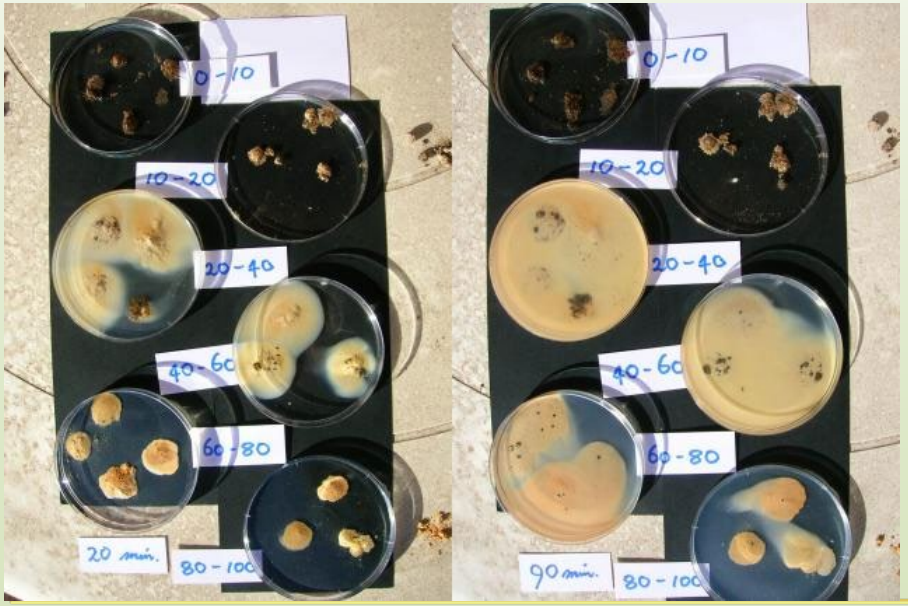
The dispersive behaviour of a soil indicates the level of sodicity

Procedure:

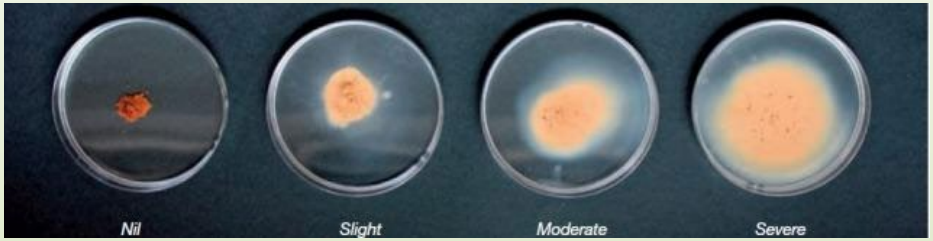
1. collect dry soil aggregates from different depths in a soil profile
2. place the soil aggregates into a clear jar of distilled water, taking care not to mix or agitate the soil

Observation:

1. often, but not always, aggregates slake (crumble) soon after being placed in the water - this is not dispersion
2. water around the edges of the aggregate in a dispersive soil will become cloudy and milky looking (looks dirty) because of the dispersed clay
3. in highly dispersive soils, will be obvious after ≈ 10-30 min.; for a moderately dispersive soil it may take 2 h



Dispersion test on samples at different depths in a soil profile at 10 minutes (left) and 90 minutes (right)



Degrees of soil dispersion (nil to severe) for soils that are non-sodic to highly sodic (from left to right)

Source: Australian Department of Primary Industries and Regional Development's Agriculture and Food

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Classification

Type	Soil EC ($dS\ m^{-1}$)	Soil pH	Soil ESP	Soil SAR	Soil physical condition
Saline	>4.0	<8.5	<15	<13	normal
Sodic	<4.0	>8.5	>15	>13	poor
Saline-sodic	>4.0	<8.5*	>15	>13	normal

*Notes: EC–electrical conductivity; ESP–exchangeable sodium percentage; SAR–sodium adsorption ratio; * despite many exceptions of saline-sodic soils with pH > 8.5. Source: FAO/UNESCO (1974).*

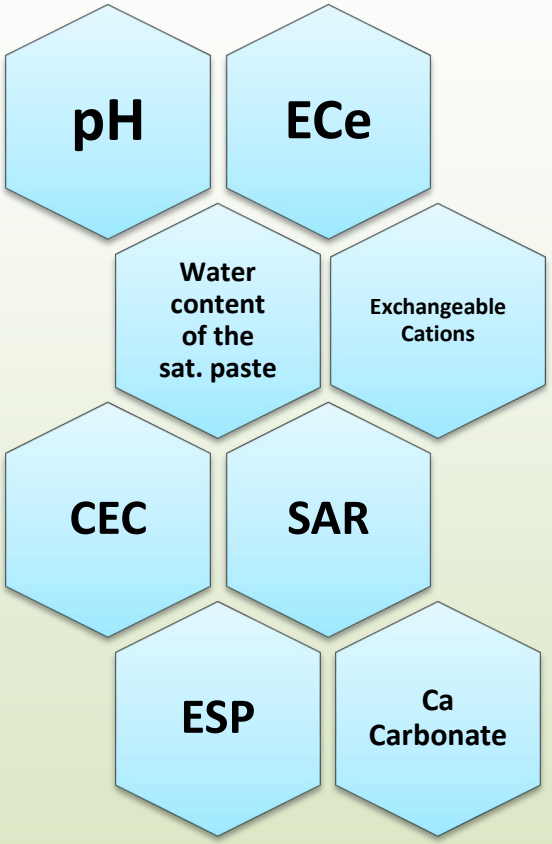
To date, there is no widely accepted definition of a sodic soil.

The USSL Staff (1954) defined sodic soils as those whose physical properties are adversely affected by the presence of Na and suggested that an ESP of 15 should separate sodic from non-sodic soils.

The USSL Staff (1954) added the reservation that this limit must be regarded as somewhat arbitrary and tentative.

Assessment of salt-affected soils

Analysis	Units	What is measured?	Interpretation of test data
pH	Scale of 0–14	Acidity or alkalinity.	Assesses whether pH is favorable for target crop. Indicates potential solubility of soil minerals and nutrients. One indicator of potential sodic soil conditions.
Electrical conductivity (EC)	dS/m or mmhos/cm	Ability of soil solution to conduct electricity. See Tables 3 and 4 for interpretation.	The higher the EC, the more dissolved ions the soil contains. See Tables 3 and 4 for interpretation.
Exchangeable cations	meq/100 g	Calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na). Concentration of cations that are adsorbed to negatively charged surfaces in soil.	Estimates sodium hazard by calculation of exchangeable sodium percentage (ESP). Estimates gypsum requirement for sodic soil reclamation.
Cation exchange capacity (CEC)	meq/100 g	Capacity of soil to hold positively charged ions (cations).	The higher the CEC, the more gypsum is needed to adjust SAR and ESP.
Specific elements	ppm	Boron (B), chloride (Cl), sodium (Na). Concentration of element in soil solution.	Assesses potential for toxicity of element to plants.
Sodium adsorption ratio (SAR[a])	unitless	Relative concentrations of sodium, magnesium and calcium. Calculated from cation concentrations in a saturated paste extract.	Assesses sodium hazard in soil or irrigation water (Figure 3).
Exchangeable sodium percentage (ESP)[a]	%	Percentage of the total cation exchange sites in soil occupied by sodium.	Sodium hazard increases as ESP increases. The ESP is used to determine gypsum requirement for treatment of sodium-affected soils.
Calcium carbonate equivalent	%	Percentage of soil by weight that is undissolved carbonates.	If calcium carbonate is present, it usually is not economical to adjust pH below 8. In this case, acidifying soil amendments such as elemental sulfur or sulfuric acid can be used instead of gypsum for sodic soil reclamation.



Suggested soil analyses for assessment of salt-affected soil problems.
https://extension.oregonstate.edu/pub/pnw-601

Shahid *et al.,* 2018. Soil Salinity: Historical Perspectives and a World Overview of the Problem

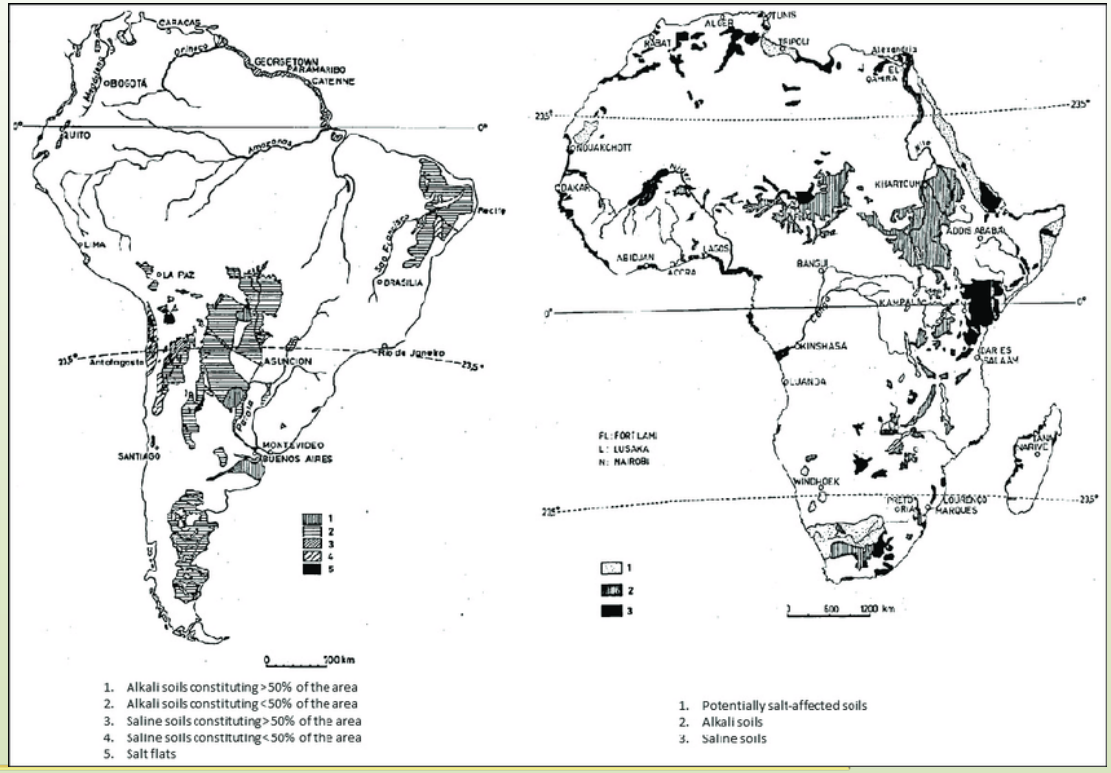
Reaching **10 % of the arable land** affected by salinity and sodicity.

Between **25 – 30 % of irrigated lands** are salt affected and essentially commercially unproductive.

One billion ha are covered with saline and/or sodic soils.

Szabolcs (1989) developed the first world map of salt-affected soils, based on the FAO World Soil Map, estimating **955 Mha**.

Worldwide, some **10 Mha of irrigated land is abandoned** annually because of salinization, sodication and waterlogging (Szabolcs 1989).



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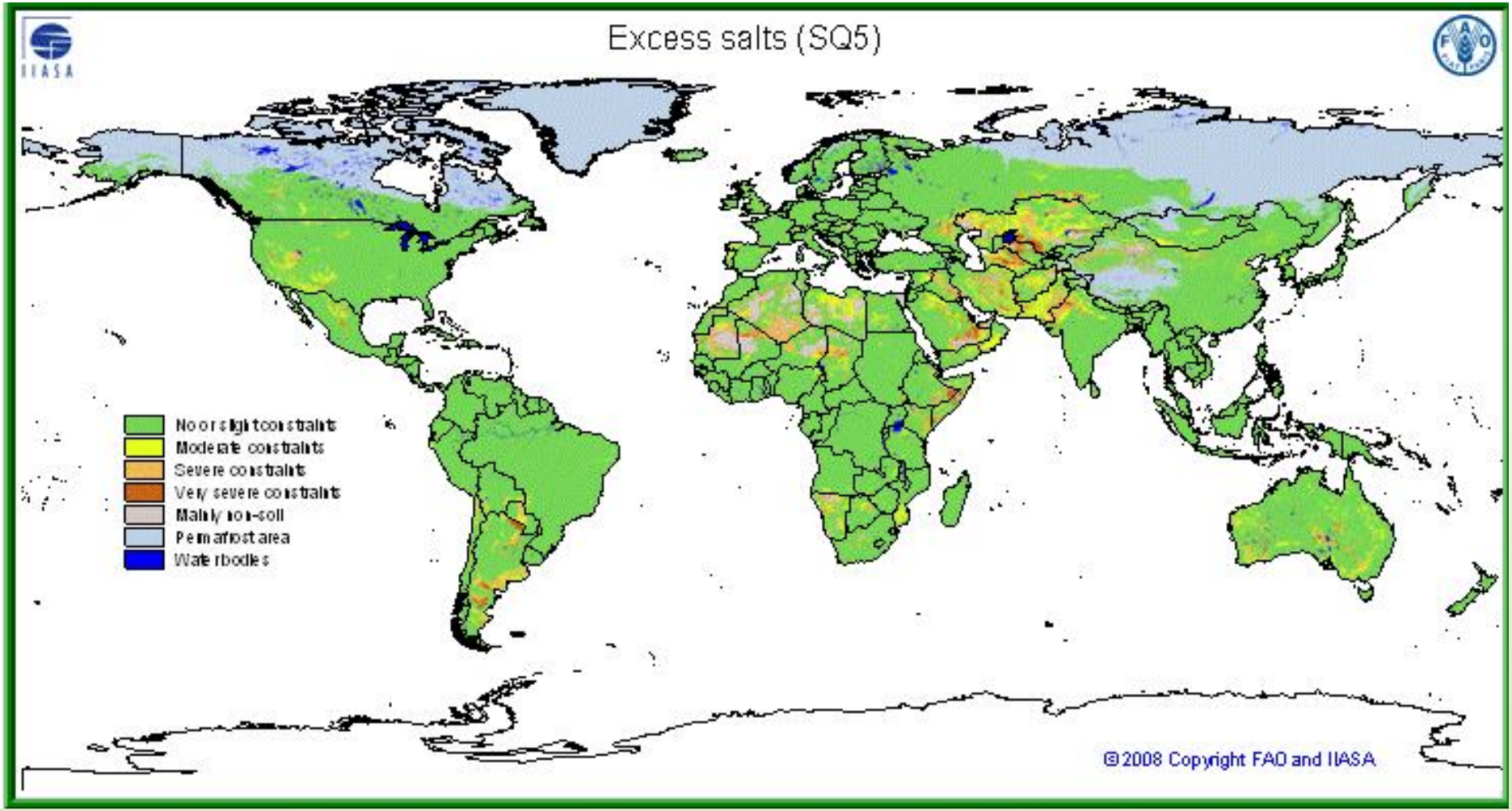


Soil salinization map, as derived from Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009. http:// www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soildatabase-v12/en/). An improved derivation of this map was published in Wicke et al. (2011).

Wicke *et al.* (2011) made an estimation based on the Harmonized World Soil Database, reaching **1125 Mha**.

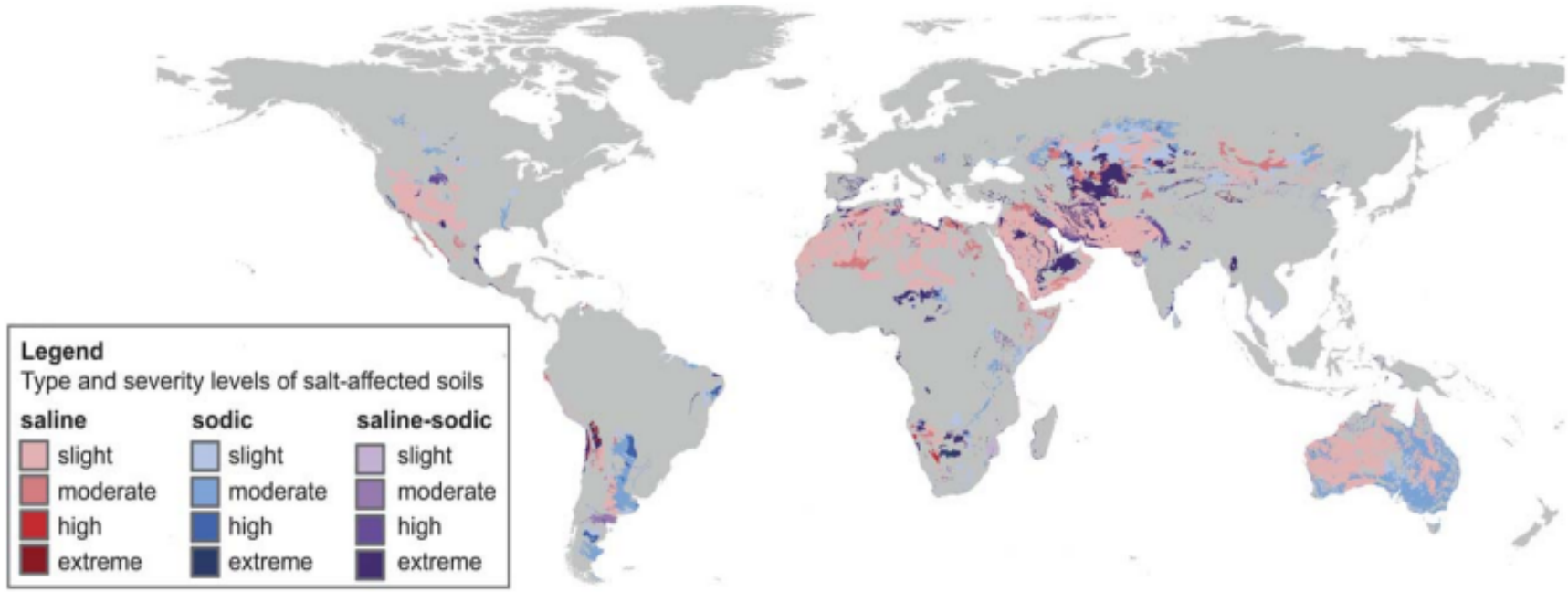
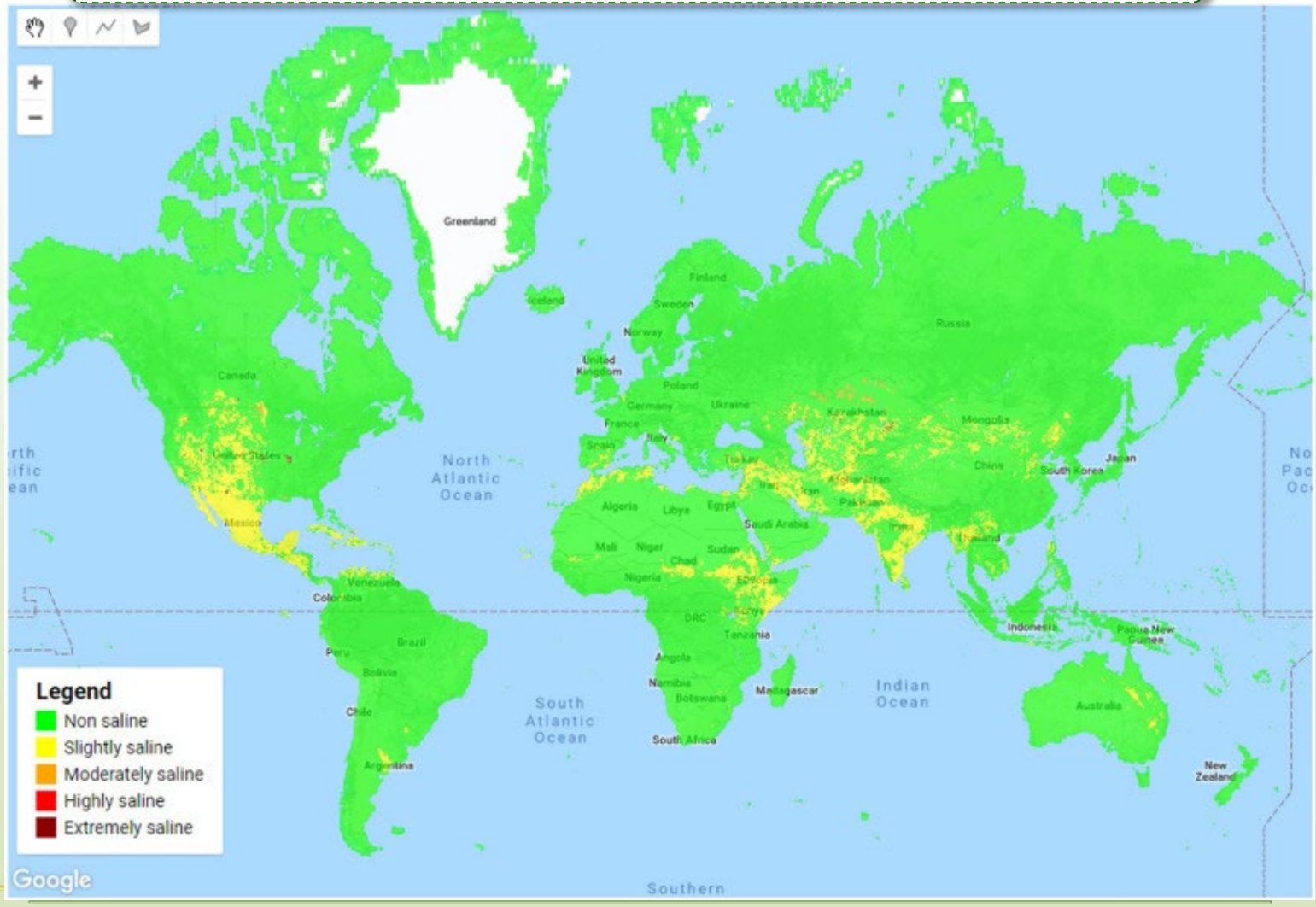


Fig. 1 Global salt-affected soils, by type and severity (based on data from the HWSD[25]). (This map indicates the location of salt-affected soils worldwide but does not properly represent their areal extent as a result of multiple soil units per mapping unit of the HWSD. Multiple soil units are defined because mapping units are not generally homogeneous in soil characteristics. Up to nine soil units may be defined per mapping unit, and the map depicts the whole mapping unit to be salt-affected even if only one of the soil units is salt-affected. For the areal extent of salt-affected soils see Table 6.)

Soil salinization map, improved derivation of Harmonized World Soil Database map published in Wicke *et al.* (2011)

Ivushkin *et al.* (2019) used remote sensing, data from the World Soil Information System, and modelling, reaching an estimation of **1050 Mha**.



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Ivushkin et al. 2019, https://doi.org/10.1016/j.rse.2019.111260

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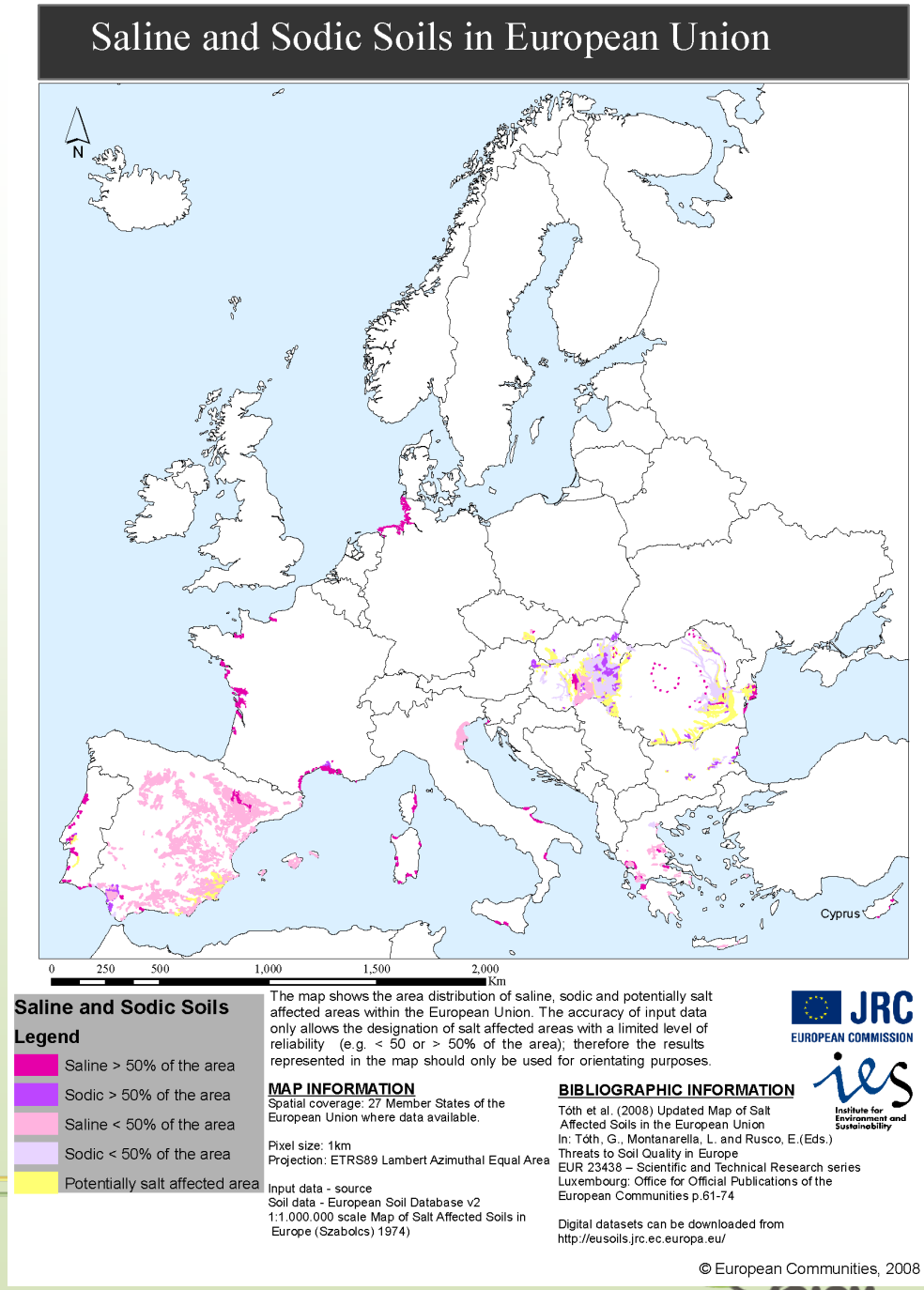
Updated Map of Salt Affected Soils in the European Union Tóth *et al.* (2008)

Soil data - European Soil Database v2 , 1:1.000.000 scale Map of Salt Affected Soils in Europe (Szabolcs 1974)

The **Saline and Sodic Soils Map** shows the area distribution of saline, sodic and potentially salt affected areas within the European Union



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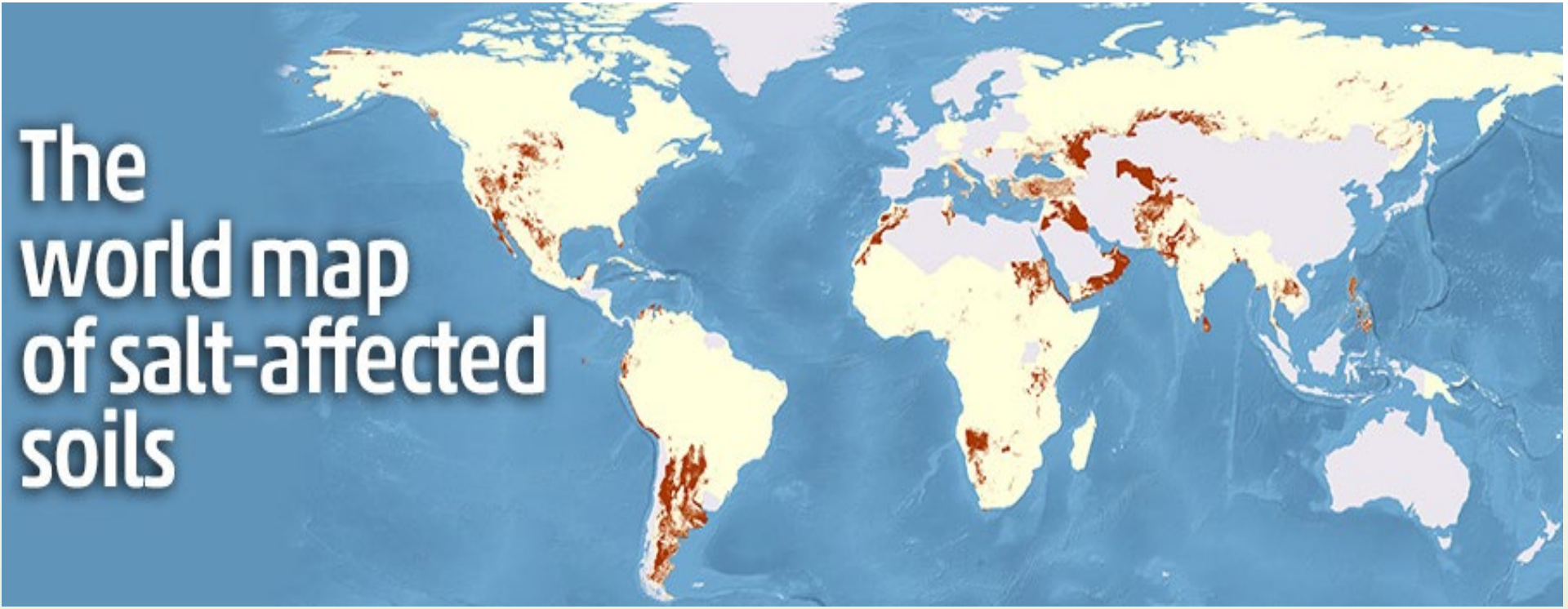

- GSP Initiative to bridge the gap on consistent SAS update
- Develop information for appropriate management of SAS

- Developed harmonization tools (manual, guidelines, software) and reached 133 countries
- Focused on soil property map (EC, pH, ESP) and SAS maps

Results by 424 Mha of topsoil (0-30 cm) and 833 Mha of subsoil (30-100 cm)

Estimate is based on nationally collected data, representing 73% of the world's land area

SAS are distributed around the globe, but **two-thirds of the area** is located in **arid and semi-arid climates**

In the EU, recent estimates point out to 1.5 % of the total area affected by secondary salinisation, located mainly in the Mediterranean and Central European countries

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https://www.fao.org/global-soil-partnership/gsasmap/en/

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Salt-affected soils: discovering a missed reality

FAO

4:11 min

https://youtu.be/kQcax3Rv4oA

https://www.youtube.com/watch?v=kQcax3Rv4oA&t=149s

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