A regionalised life cycle assessment model to globally assess the environmental implications of soil salinisation in irrigated agriculture

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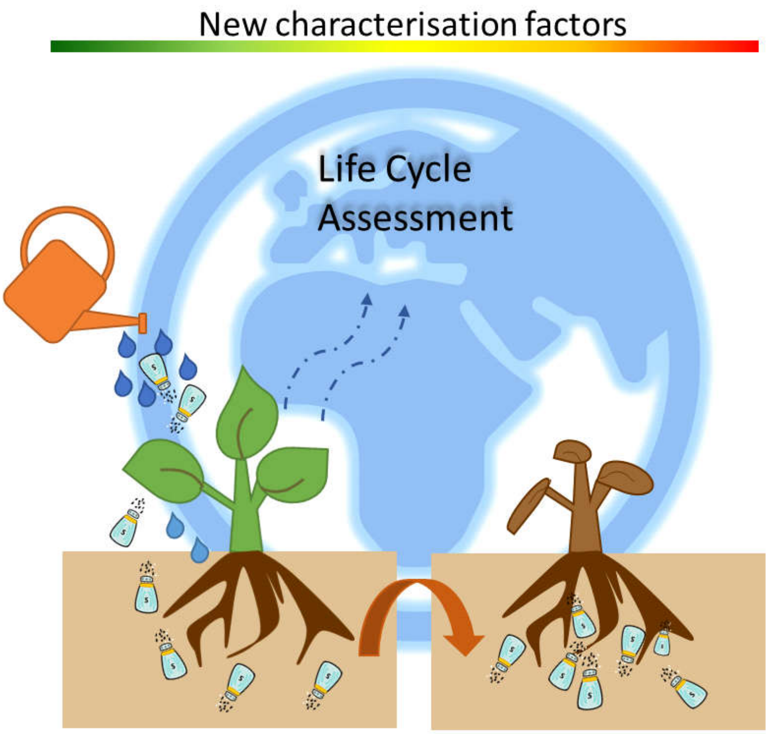
Abstract. We present a global, locally resolved life cycle assessment (LCA) model to assess the potential effects on soil quality due to the accumulation of water-soluble salts in the agricultural soil profile, allowing differentiation between agricultural practices. Using globally available soil and climate information and crop specific salt tolerances, the model quantifies the negative implications that salts in irrigation water have on soil quality, in terms of change in the soil electrical conductivity and the corresponding change in the amount of crops that can be grown at increasing soil salinity levels. To facilitate the use of the model, we provide a life cycle inventory tool with information on salts emitted with irrigation water per country and 160 crops. Global average soil susceptibility is 0.19 dS/m per g salt in 1 m^3 soil and the average resulting relative crop diversity loss is $5.7*10^{-02}$ per g salt in 1 m^3 soil. These average values vary tangibly as a function of the location. In most humid regions worldwide the characterisation factor is null, showing that in these cases soil salinisation due

to irrigation does not contribute to soil degradation. We displayed how to apply the model with a case study. The model serves for guiding decision-making processes towards improving the sustainability of irrigated agriculture.



TOC

- **Introduction**

Soil resources are under high stress worldwide, due in large part to improper agricultural practices.[1] The consequence of soil degradation is a decrease in the complexity of terrestrial ecosystems and the loss of productivity on the long-term.[2,3] According to the Global Assessment of Soil Degradation (GLASOD),[4] soil salinisation is considered to be the third major human-induced soil degradation process (70 Mha affected) after soil erosion (1300 Mha affected) and loss of nutrients (130 Mha affected). GLASOD was conducted thirty years ago, but it remains the only global harmonised effort to estimate the extent of soil degradation.[3]

Soil salinisation is the physical (i.e. soil structure) and chemical deterioration of the root zone as a result of salt accumulation. Depending on the salts (ions) involved and the soil pH, the problems affecting soil and the remediation techniques are different,[5,6] putting in evidence the complexity of the whole problem. Soil salinisation becomes a concern for agriculture when the accumulation of salt in soil reaches a level that affects soil properties and crop production in the long term. In extreme cases, farmers have to abandon their fields and convert forest land into agricultural land. This transformation leads to further soil degradation processes and adds to the pressure on climate due to the release of carbon stored in trees and soil. Moreover, the abandoned, degraded, agricultural land has a low spontaneous renaturalisation potential.

There are different mechanisms that trigger soil salinisation. One of the main anthropogenic reasons is the combined use of poor quality irrigation water and improper agricultural practices.[1] Mismanaged irrigation affects 35 Mha worldwide, i.e. 10% of total irrigated land,[7] and every year between 0.5 - 1 Mha add to the count of soil "lost" due to salinisation and waterlogging.[8] Irrigated areas in drylands (i.e. areas with an annual precipitation-to-potential evapotranspiration ratio lower than 0.65) are particularly prone to soil salinisation, because salt builds up more easily in a soil with little rainfall and high evapotranspiration.[9] Moreover, the odds are high that the problem will aggravate in the near future due to the spread of arid areas as a consequence of climate change[10] and the overexploitation of agricultural lands to produce more food, feed and fibres.

Salts accumulate in soil because plants take up water selectively, leaving salts behind. Irrigation water contains a mixture of salts, and irrigated soils will contain a similar mix but at higher concentrations if no measures are taken to avoid salt deposition. Principally, there are two complementary measures to avoid that salts build up in soil, namely leaching and draining. 1) With leaching, a portion of the salts from irrigation that accumulates in soil is flushed below the rooting depth if more water than consumed by the crop is added to the soil. Leaching can happen naturally (rainfall) or via irrigation water. High leaching (e.g. 50% more water than consumed by the crop) results in less salt accumulation than low leaching (e.g. only 5% more water than consumed by the crop) because more salts are washed away. The amount of leaching required depends on the quantity of salts in the water: with good quality water, the losses of the irrigation system will in general be sufficient to leach the salts out. Whereas with poor quality water larger amounts of water will be needed. 2) Drainage systems can collect the fraction of salts and water leached from the soil and dispose it in water collectors through a natural or artificial outlet. Poor drainage increases salinity of the aquifer underneath and rises the water table, with a risk of salt redeposition in soil via capillary rise. In short, the parameters involved in the flushing of salts from the soil profile are climate, water quality, amount of irrigation water and drainage.

Two measures of salinity are used: electrical conductivity (EC) and total dissolved solids (TDS) concentration. EC represents salt activity and is measured in decisiemens/m (dS/m) at 25°C. TDS includes all inorganic and organic dissociated anions and cations as well as undissociated dissolved species. EC depends on the salinity level (i.e. TDS, in mg/l) and salt composition.[11] Proxy conversion factors are used in the absence of more detailed water quality analysis, usually TDS (mg/l) $= 640$ ((mg×m)/(l/dS)) × EC (dS/m) (for EC<5 dS/m) and TDS (mg/l) $= 800$ ((mg×m)/(l/dS)) × EC (dS/m) (for EC >5 dS/m).[12]

Despite the hazard that irrigation-induced soil salinisation entails for agricultural systems, to date this environmental problem cannot be evaluated in large-scale quantitative sustainability assessment methods, such as life cycle assessment (LCA). LCA is a tool to help decision-makers identify the solution that best supports sustainable development by applying a system perspective. This means that all relevant impacts, among which irrigation-induced soil salinisation in case of agricultural activities, must be quantified.[13] Two problems hinder the assessment of soil salinisation with irrigation water in LCA. First, commonly used life cycle inventory (LCI) databases such as ecoinvent[14] lack information on salts emissions to soils. The second problem is that no global, regionalised life cycle impact assessment (LCIA) model quantifying the environmental impacts of a salt emission has been developed. Regionalisation means spatial differentiation and is a useful quality in a model for soil salinisation because soil properties vary widely, and consequently the environmental impacts of the salt emission. There are two soil salinisation LCIA models for assessing impacts of salts added with irrigation water, but both have important shortcomings that limit their operationalisation. The model of Feitz and Lundie[15] is based on the chemical composition of the irrigation water used, but the authors did not provide characterisation factors (CFs). Instead, CFs have to be calculated by the LCA practitioner based on a very detailed quality analysis of the irrigation water used, which is usually unfeasible due to data and time constraints. Leske and Buckley[16–18] developed CFs that quantify the impact of a salt emission into different possible release compartments (namely atmosphere, surface water, natural surface and agricultural surface). To compute CFs, the authors built a multimedia model representing the hydrology with salt transport and deposition processes in South-Africa. Despite its environmental relevance, its geographical validity is limited to South-Africa and the use in other countries is not recommended. Payen et al.[19] did a thorough review of salinisation impacts in LCA and provided recommendations on the key parameters to include in LCA models for irrigation-induced soil salinisation, but without operationalisation.

The goal of this research was to overcome current limitations in assessing impacts of salt emissions with irrigation water in LCA by developing a fully operational model that is 1) able to assess irrigation-induced soil salinisation impacts on a global level in a spatially-explicit manner; and that is 2) able to differentiate between salinisation impacts of different agricultural practices, which is useful for agricultural eco-innovation purposes. These objectives encompass methodological developments at both the LCI and LCIA steps as detailed in section 2. We applied the model to a hypothetical but realistic case study on rice cultivation for illustrative purposes. The soil salinisation model has been developed to be integrated in LCA, but it can also be used as a standalone environmental footprint tool.

- **Materials and Methods**

  - **Model overview**

Figure 1 provides an overview of the framework that was followed to model impacts of salt emissions with irrigation water on the long-term soil quality, measured via the increase of soil electrical conductivity and the corresponding reduction in the amount of crops that can be grown at increasing soil salinity levels. To model the impacts, first the additional mass of salt in soil after a salt emission (i.e. salts not flushed from soil) is modelled. This modelling step is operationalised via a calculator that we called SaltLCI (see section 2.2), which is located in the cause-effect chain of Figure 1 on the boundary between the inventory data collection and the impact assessment phase (the rationale to do so is discussed in section 4.1). The parameters considered at the LCI step and included in the SaltLCI tool are the agricultural management parameters: salts in irrigation water, amount of irrigation water, leaching and drainage; and as climate parameter, the local aridity index. The result of the SaltLCI tool is an LCI elementary flow in grams of salt from the emission added to soil per functional unit (FU). A FU describes the function(s) provided by the analysed system. All the elementary flows of an LCA study must be quantitatively related to the FU. One of the model inputs to the SaltLCI tool is the location where the activity takes place, which is used for identifying the appropriate regional-dependent CF in the LCIA step. The CFs reflect, at midpoint level, the relative local sensitivity of a soil to a salt emission, depending on soil and climate properties. At damage level, they reflect the long-term crop diversity loss, which depends on both soil and climate properties and crop sensitivity to salinity. Midpoint indicators are at an intermediate position in the environmental causality chain depicted in Figure 1 linking salt emissions to the ultimate damage on soil quality and the services it provides. Indicators at damage level measure the final damage on the area of protection (AoP) and are therefore more relevant from an environmental protection viewpoint. The AoP, which identifies what we wish to protect, is called resources and ecosystem services. This AoP traditionally covers natural resources (e.g. fossil, mineral, water resources) and has recently been expanded to ecosystem services.[20,21] Multiplying the elementary flow of the LCI (e.g. from SaltLCI) and CFs (reported in this article), the user can calculate potential impacts on soil salinisation and on crop diversity loss due to a salt emission with irrigation water. All geospatial processing was carried out using ArcGIS Desktop.[22,23]

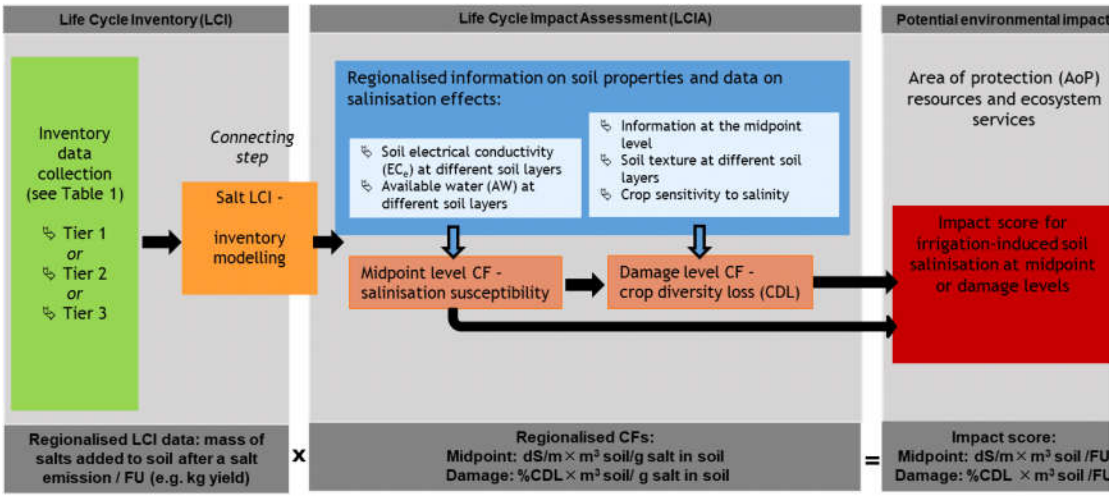


Figure 1. Schematic overview of the procedure followed to model impacts of salt emissions on soil degradation. Soil salinisation and crop diversity are used as indicators to measure impacts on soil quality and on its capacity to provide ecosystem services. FU: functional unit, i.e. reference unit in an LCA study.

- **SaltLCI tool**

The LCA practitioner does not usually know the mass of salts emitted and can neither retrieve this information from LCI databases. This limitation was overcome by developing a tiered (i.e. multi-level) calculation system as done by Stoessel et al.[24], which informs about the salt emitted with irrigation water and the fraction added to soil adapting its data requirements to the amount of data the user has.

SaltLCI is an excel tool and is available as Supporting Information (SI). The tool is organised in three tiers. Tier 1 requires less input data, while moving to higher tiers (tier 2 and tier 3) necessitates more effort in LCI data collection but improves accuracy and confidence in the inventory and hence in the final indicator result. Thus, whenever possible, the use of tier 3 should be privileged. The SaltLCI output (elementary flow) is the mass of salts added to the soil profile at equilibrium per FU (see further details in section S1, Equation S8). The output is given per crop yield (gram salts from the emission added to soil/kg crop), that is, yield is used as FU. Tier 1 provides average output values per country and crop and its use is recommended only for LCA studies of products with food ingredients without focus on the agricultural stage (e.g. LCA of ketchup, where the LCA user only knows that tomatoes used in the ketchup recipe come from Greece). Tier 2 allows for tailored scenarios at country scale and is useful for cases where the LCA user has a fairly good knowledge of the agricultural stage (e.g. the user knows the irrigation technology used to grow tomatoes in Greece for ketchup production). Finally, tier 3 is useful for the eco-innovation of agricultural systems, allowing the comparison of the amount of salts added to soil as a function of the agricultural practices applied (e.g. different leaching fractions and irrigation water qualities). Input data required at each tier, calculation steps and data sources used to calculate salt addition to soil with each tier are detailed in section S1.

- **Life cycle impact assessment: influence of the irrigation frequency**

Salts are unevenly distributed in different soil depths. We assumed that the additional mass of salts added to the soil distribute instantaneously and homogeneously in the entire profile, which results in a new equilibrium via linearly increasing concentrations from the old equilibrium (also referred to as background) in each soil layer, as per state of the art in LCIA. In irrigated lands where the movement of water through soil is not a limiting factor, salts tend to accumulate in deeper soil layers due to the downward movement of water with leached salts. Crops take up water from the upper, less saline soil layers if the soil is full of water, which happens when irrigation events are frequent (e.g. drip, sprinkler). As crops use water and the time interval between irrigations is extended (e.g. furrow, gravity), the upper root zone becomes increasingly depleted and the layers of most readily available water change towards lower, more saline layers. A water extraction pattern develops as a function of the frequency of irrigation events, which also determines the relative contribution of every soil layer to the average soil salinity and to the effects of salts on crop growth. Accordingly, two distinct soil electrical conductivity (EC_e)-weighted averages for every location of the world were derived, one for frequent irrigation systems (FI systems) and one for infrequent irrigation systems (II systems), as per Eq. 1.

Eq. 1

The patterns 60-30-7-3 for FI systems and 40-30-20-10 for II systems in Eq. 1 come from Ayers and Westcot.[25] These patterns are rough approximations, since in reality the quantitative water uptake is very specific to each soil profile, rooting depth and the rates of evaporation, transpiration, irrigation and drainage. We consider the simplification in Eq. 1 acceptable for the purpose of large-scale modelling. The resulting $EC_{e,FI}$ and $EC_{e,II}$ are subsequently used in the calculation of two sets of CFs at both midpoint and damage level, one to be used with FI systems (typically drip and sprinkler) and the other with II systems (typically furrow and gravity). The SaltLCI tool helps the LCA practitioner decide which set to choose, if FI or II, in tier 1 and tier 2 approaches.

EC_e values per soil depth were extracted from the ISRIC-WISE soil profile database.[26] This database contains information on 19 physical and chemical soil properties, including EC_e, on a 5 by 5 arc-minutes global grid. A grid cell is divided in five depth intervals of 20 cm and up to 100 cm depth, i.e. soil depth is 1 m. EC_e of the two deepest soil layers were averaged (arithmetic mean) to compute $EC_{e,depth4}$ in Eq. 1. The complexity of each grid cell varies from cells with only one soil type to cells with complex associations of up to eight soil types (e.g.

a grid cell may contain 60% of soil type 1 and 40% of soil type 2). Grid cells with the same soil types are aggregated in map units. For our large-scale assessment purpose, we considered only the dominant soil type in every map unit (i.e. soil type 1 in the example). This resulted in a total of 4931 globally distributed map units which contain 31% of the total amount of soil types. The median relative area of the dominant soil type within a map unit is 60%, with lower and upper quartiles of 50% and 70% respectively.[26] Missing EC_e information for a specific soil depth was disregarded in the calculation of the depth-weighted EC_e, which occurred only in 14 map unit records.

- **Calculation of midpoint level characterisation factors: soil salinisation susceptibility**

The electrical conductivity of a soil is indicative of its salinisation susceptibility. We assumed EC_e be dependent on three variables: 1) mass of salts in soil, 2) ionic composition of salts in soil, and 3) volume of water in soil, as per Eq. 2.

Eq. 2

Where the units of the CF are dS/m×m^3 soil/g salt in soil, to be interpreted as electrical conductivity per g salt in 1 m^3 soil, $EC_{e,\ \mathrm{Irrig\ freq}}$ (dS/m) corresponds to the soil-electrical-conductivity-weighted averages computed for frequent and infrequent irrigation systems with Eq. 1, and salts in $\mathrm{soil}_{\mathrm{background,Irrig\ Freq}}$ is the background mass of salts in soil for both irrigation frequencies. TDS is the salt concentration in soil moisture (g salt/m^3 water), C is the soil-water's ionic composition (mol/m^3 water) and AW is the volume of water in soil per soil volume (m^3 water/m^3 soil). The subscript Irrig freq means that the variables were calculated applying the weights per soil depth as in Eq. 1.

To operationalise the theoretical expression in Eq. 2, we introduced simplifications due to the lack of regionalised data about the ionic composition of salts in soil. These were (Eq. 3): 1) we omitted the ionic composition; 2) TDS was computed using the generic, linear conversion factors mentioned in the introduction and the spatially explicit EC_e-weighted averages of Eq. 1.

Eq. 3

In reality, EC_e-TDS conversion factors (here 640 or 800) depend on TDS and the dominant ions present in the soil, which vary between locations, seasons and water quality(ies) used to irrigate a soil[11] and should therefore be regionalised/seasonalised as new data become available, as they modify TDS to different extents.

Midpoint CFs reflect that soils react differently to a marginal addition of salt as a function of its salt and water content. The greater the mass of salts built-up in the soil profile and the lower the water volume to dissolve new salt additions, the higher its salinisation susceptibility.

Salt content per water volume (i.e. TDS) was transformed to salt content per soil volume using information on soil-water content (AW). Existing soil databases at the global scale with a reasonable resolution do not have information on AW, thus we had to estimate it. Trabucco[27] provided a global high-resolution soil-water balance dataset although assuming uniform soils globally, while our interest was in highlighting spatially variable soil properties. Accordingly, a proxy measure of AW per soil unit and irrigation frequency was estimated by applying Eq. 4.

Eq. 4

Where $TAWC_{Irrig\ freq}$ (m^3 water/ m^3 soil) stands for total available water capacity of a soil, weighted per soil depth as indicated in Eq. 1; P (mm) is annual precipitation and ET_0 (mm) is annual potential evapotranspiration. P and ET_0 data were sourced from the spatially-resolved climate data from New et al[28] and TAWC per soil depth was taken from ISRIC-WISE.[26] AW was estimated at 5' resolution, distinguishing between frequent and infrequent irrigation schemes, following the rationale explained in section 2.3. The calculation in Eq. 4 is based on the assumption that water actually available in soil depends on two parameters: 1) the capacity of the soil to store water (total available water capacity, TAWC), and 2) its water saturation (as percentage of filling of TAWC from 0% to 100%). For the saturation we assumed that the only water exchanges controlling it are the major flows between soil and atmosphere, that is, P and ET_0. The ratio between P and ET_0 (P/ET_0) is called aridity index. The lower the precipitation and the higher the potential evapotranspiration, the more arid an area and the drier its soils, i.e. the lower the saturation of TAWC. Arid areas have aridity indices between 0 and 0.65 while humid areas have indices >0.65 sometimes reaching values >1, in which case it was truncated to 1. Aridity indices were used in Eq. 4 as percentages directly multiplied with TAWC to provide a rough estimation of AW. Soils in humid areas are closer to water saturation, and thus any marginal addition of salt will be diluted in all the available soil water. Salt concentration in soil, and its associated EC_e, will only increase very slightly. On the other hand, soil moisture in dry soils is low, so that with any salt addition the ratio of change of TDS and hence EC_e will be higher.

The characterisation model includes the background mass of salts in soil, that is, the mass of salt in soil before a new addition of salts from irrigation (i.e. LCI). The background concentration aims at identifying how sensitive a soil is to a new salt addition, which depends on soil properties and climate conditions.

- **Calculation of damage level characterisation factors: crop diversity loss**

CFs at damage level have units of CDL per g salt in 1 m^3 soil (% CDL× m^3 soil/g salt in soil) and were calculated with the following equation:

Eq. 5

As shown in Eq. 5, the modelling up to the damage is calculated via the midpoint impact indicator and an effect factor (EF). As with midpoint CFs, CFs at damage level also assume marginality, thus a change in crop diversity depends only on background salt conditions. The EF takes into account that salt concentration in soil above a certain threshold affects biomass production, thus its capacity to deliver ecosystem services. Not all crops are equally affected by salinity. The relationship between salt concentration in soil and crop production is well studied and salt tolerance guidelines for most commonly marketable crops are available. General guidelines classify crops into four categories, from very sensitive crops to tolerant crops, according to the maximum salt concentration they can withstand for a specific percent yield potential, ranging from 100% (no crop losses) to 0% (maximum crop loss). For example, salt tolerant crops such as barley and cotton do not experience any reduction in crop yield (i.e. 100% yield) until EC_e>7.5 dS/m, whereas sensitive crops (e.g. almond, orange) start having yield losses (i.e. <100% yield) at EC_e<1.7 dS/m.[25] In general, vegetable crops and fruit trees show a higher sensitivity to soil salinity than cereals and forages. Furthermore, soil texture is an important parameter in determining how sensitive a crop is to the salt accumulated in a soil profile. The lower the amount of clay particles, the greater the osmotic pressure the salts exert. Osmotic pressure refrains plants from taking up soil water, thereby eventually affecting plants' growth.[5]

In practical terms, we constructed a non-linear crop sensitivity distribution model to derive the EFs (Equation 6). This model describes the statistical relationship between soil electrical conductivity and clay content in soil (independent variables) and the potentially negative effects on crops (dependent variable), using crop diversity loss as a metric. To build this model, we proceeded as follows: 1) we obtained information on EC_e thresholds for each crop salt tolerance category (from sensitive to tolerant crops) associated with a 90% yield potential (10% yield reduction) as a function of soil texture; 2) we gathered information about the salt tolerance category of 157 agricultural crops; 3) based on steps 1 and 2, we calculated the cumulative relative amount of affected crops at increasing salinity levels; 4) we built equations in Equation 6 based on step 3; 5) we calculated the derivative of the curves in Eq. 6; 6) Using EC_e from the midpoint CFs and soil texture from the ISRIC-WISE soil profile database[26] for every soil map unit (weighted per soil depth as specified in Eq 1), we obtained marginal, regionalised EFs for frequent irrigation and infrequent irrigation systems. A detailed description on these methodological steps is provided in section S3 of the SI.

Eq. 6

- **Spatial aggregation of characterisation factors**

CFs were resolved at 5 arc-minutes spatial resolution and are useful when information on the exact salt emission location is available, matching the spatial requirements of the tier 3 modelling approach in SaltLCI. However, the user of large-scale models such as LCA usually only knows the country or at the best the sub-country region where the emission happens. To facilitate the impact assessment of agricultural processes where the exact location is unknown and that are modelled using tier 1 and tier 2 in the LCI we aggregated via a median CF at sub-country and country levels. We chose the median as measure of central tendency because the median is more robust against outliers than the arithmetic mean. We checked for the distribution of grid cell level CFs at global scale and none of >50 probability distributions showed a good fit to the data. Therefore, besides the median, we reported information on the minimum, the maximum, the arithmetic mean and the standard deviation as a pragmatic solution to estimate uncertainty due to spatial aggregation as recommended in current LCIA guidance.[29] For the aggregation at sub-country level, the WMO subregions were used.[30] WMO distinguishes 486 sub-regions worldwide delineated following a mixture of geographical and hydrological criteria. For the aggregation at country level, we used the world countries layer from Esri,[31] representing the political borders as they existed in January 2017. Areas for which no CF is available (i.e. no data values) were excluded from the statistical analysis.

- **Results**

  - **SaltLCI tool: average salt emission values per crop and country**

Average salt emission values with irrigation water for 160 crops at country scale are available in the SaltLCI tool and are used as input data to calculate average values of salt added to soil based on default crop management practices per country in tier 1 and on tailored scenarios in tier 2. Figure 2 shows the statistics of the salt emissions per crop and country. Cowpea is associated with the median emission level among all crops (160 g salt/kg crop) and Peru is associated with the median emission level among all countries (157 g salt/kg crop). The latter statistic was calculated considering the arithmetic average of the emissions per kg crop of all crops produced in the country. Crops above the 95th percentile have all high irrigation requirements. Furthermore, vanilla and almond are cultivated in Mexico and Spain, two countries with high irrigation water salinity. The top country in terms of average emissions per kg yield is Turkey, because irrigation water has twice the concentration of salts than the immediately subsequent countries. Russia is associated with virtually 0 g salt emitted per kg yield due to the very low and questionable TDS in surface and ground water bodies reported in GEMstat.[32] Thus, we raise a flag of caution when using salt emission values in this country. SaltLCI tool covers most harvested mass on global croplands and is useful for LCA and other large-scale assessment studies.

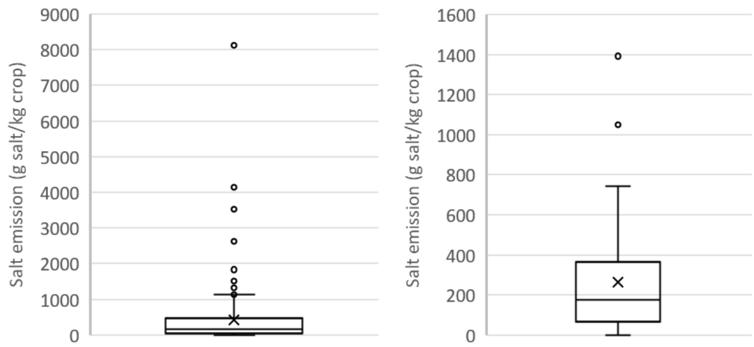


Figure 2. Box plots of salt emissions with irrigation water (in g salt/kg crop). "A" shows the statistics per crop and "B" per country, the latter calculated using the arithmetic mean of all the crops grown in a country. The centre line of each box is the median, the cross is the arithmetic mean, the outer lines are the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles. The circles indicate outliers.

- **Midpoint level characterisation factors**

Spatially-variable CFs for frequent irrigation and infrequent irrigation agricultural practices to be used for an assessment at midpoint level are shown in Figure 3A and provided in the SI as georeferenced maps. The higher the midpoint CF, the more susceptible a soil is to a marginal addition of salts. Values have been limited to a range from 0 to 10 dS/m×m^3/g salt in soil. The upper cut-off value of 10 was given to less than 0.6% of the land surface. This area is entirely located in Eastern Sahara, where crop growth is not possible due to hyper-arid conditions. The global midpoint CF (arithmetic) mean is 0.190 dS/m×m^3/g salt in soil for FI systems and 0.191 dS/m×m^3/g salt in soil for II systems. The global median for both irrigation frequencies is very close to 0 (1.22E-02 dS/m×m^3/g salt in soil for FI and 1.25E-02 dS/m×m^3/g salt in soil for II). This happens because positive CFs have in general very low values and because 43% of the global terrestrial surface has a midpoint CF = 0, irrespective of the irrigation system used. Any emission of salt with irrigation water in areas with CF=0 will not lead to a potential, negative impact on soil quality. Null CF values are mostly located in humid areas spread over the five continents (e.g. Scandinavia, Central Africa, Brazil). In humid areas, salts that irrigation may have brought to the soil are washed away with rainfall. In areas with positive CFs, soils vary widely in susceptibility to salinisation. The largest potential impacts are observed in dry lands located in northern African regions and impacts are also expected to be moderately high in the south of Saudi Arabia. As a rule of thumb, CFs for FI are slightly lower than its II counterparts in a given location in Africa and Europe and slightly larger in America and central Asia, but the differences between both irrigation options are rarely greater than 5% (Figure 3A), which reveals that in most cases there is no clear preference for an irrigation system. Midpoint CFs aggregated to global, country and sub-country levels using the median are provided in the excel file of the SI. The minimum, maximum, range, arithmetic mean, standard deviation and sum are also provided for each aggregated unit to better showcase the different degree of spatial variability within each aggregation unit.

- **Damage level characterisation factors**

Figure 3B shows regionalised damage level CFs for frequent irrigation and infrequent irrigation systems which are available in georeferenced format in the SI as well. The higher the value of the CF, the less crop options the soil can support per salt unit added to the soil, thus the higher the damage on the soil's capacity to deliver ecosystem services. Damage CFs take values from 0 to 3.2 %CDL×m^3/g salt in soil, being the global arithmetic mean 5.70E-02 %CDL×m^3/g salt in soil for FI systems and 5.73E-02 %CDL×m^3/g salt in soil for II systems. The global median is nearly 0, namely 3.20E-03 %CDL×m^3/g salt in soil for both FI and II systems. A damage CF=1, for instance, represents a loss of 1% of crop diversity (i.e. how many) per gram of salt in the soil profile. As for midpoint CFs, the highest CFs at damage level are found in dry areas of northern Africa, followed by southern regions in Saudi Arabia. Although the CFs trend at both impact levels is the same, midpoint CFs have a larger spread than damage CFs (0 to 10 vs 0 to 3.2, respectively). This is because in the damage indicator EFs that are multiplied with the midpoint CFs have values below 1 (Figure 3C). Higher EFs were allocated to higher quality soils (i.e those with lower EC_e and higher clay content), offsetting a fraction of the midpoint impact value, for instance, in Eastern Australia and Southern Africa. Around 2% of the EFs were negative and have been transformed to 0. These EFs are in soil units with an EC_e>20 dS/m, which corresponds to soils so salinized that crops no longer produce any yield and the potential for further yield drop is thus null. Most of these soils are located in the very degraded, irrigated lands of the Aral Sea basin and the Caspian Sea basin in Kazakhstan. A total of 45% of the terrestrial surface has damage CFs equal to 0 and are situated in the areas where midpoint CFs are zero plus the areas where EFs were set null. Globally, EFs for II systems are either equal or around 5% smaller than EFs for FI systems, because deeper soil layers, which have a higher relative importance under II practices (Eq. 1), usually have greater EC_e and thus lower quality to safeguard from a pure resource perspective. This leads to areas with a FI-to-II ratio of 1 for the midpoint indicator having slightly smaller damage level CFs for II practices. The SI excel file contains the median and other estimates of uncertainty for damage level CFs aggregated at global, country and sub-country scales.

Figure 3. Worldwide CFs resolved at 5' resolution at the midpoint level ("A") and at the damage assessment level ("B"). Row "C" displays the EFs. In all three cases, the image on the left is for FI systems, in the middle for II systems and on the right is the FI-to-II ratio. Values of the FI-to-II ratio <1 mean that FI systems lead to lower potential impacts and are preferred over II systems, while values >1 mean that FI systems perform worse than II systems. White areas in the FI-to-II ratio are for regions where CF =0 for both FI and II systems.

- **Illustrative example**

To demonstrate how to apply the model described herein, we employed an illustrative example on rice cultivation in the Ebro delta, Spain (section S3). The FU is 1 kg rice at farm. The example evaluates an innovative practice aimed at reducing freshwater consumption using drip irrigation instead of flooding. In the study area, salt concentration in irrigation water is high (TDS = 800 mg/l). The whole impact pathway as shown in Figure 1 is applied, assuming different levels of detail for LCI data availability, which also affects the spatial resolution of the CF that can be applied, being either country, sub-country or at grid cell level. Results reveal that, from a soil salinisation perspective, drip irrigation is not recommendable. Focusing on the drip irrigation scenario, use of tier 3 reveals higher salt addition in soil than for tier 2 and tier 1. This is because tier 3 considers the high salinity of the irrigation water and the reduced flushing effect that drip irrigation has on the salts added to the soil, while lower tiers do not. At the LCIA, CFs for the specific grid cell are lower than for the whole country (Spain) and sub-country region (east coast of Spain). Higher LCI results for tier 3 are partially neutralised by lower sensitivity of the soil in the CF due to lower salt background concentration in the specific cell area.

- **Discussion**

  - **Model characteristics**

The developed model serves to perform quantitative, comparative assessments of the potential impacts on soil resources due to the accumulation of salts in agricultural soils from salt emissions via irrigation water. The model can discriminate between crops, irrigation technologies and use of leaching and drainage systems, in any location of the world, being therefore useful to rank farming practices in terms of soil salinisation impacts.

The SaltLCI inventory tool models the salts from irrigation added to soil at equilibrium, which is a modelling step typically included in the LCIA phase of an LCA study. LCA guidelines recommend to clearly delineate the boundaries between the LCI and the LCIA by including the modelling of the dynamic fate processes of the product system under analysis in the LCI and the modelling of the steady-state fate processes that happen beyond any human control, thus independently of the agricultural practice, in the LCIA.[33,34] However, in our model, the calculation of the addition of salts in soil at steady state resulting from irrigation is done at the inventory as a connecting step between LCI and LCIA because our approach lumps all fate processes together as a function of the leaching and drainage management. The dynamic nature of soil salinity in large-scale modelling was tackled by Payen,[35] who developed a daily time step model called E.T. and used it in LCA to calculate water and salt balances on a mandarin orchard irrigated with a drip system. E.T. was developed to allow LCA-based eco-design of cropping systems, but is unfortunately not published yet. Although meant to be used in LCA, it requires a non-negligible amount of data regarding soil properties and agricultural practice to describe the system under study. Data intensiveness is a limitation for most LCA applications: practitioners usually do not know where the product under assessment comes from, let alone the irrigation technology and the soil characteristics of the production site. In this respect, the tiered approach of the SaltLCI tool suits different levels of data availability and potential uses.

CFs are very different across the globe because soil and climate are local factors that play an important role in soil salinisation impacts. This highlights the importance of performing a regionalised assessment of salt emissions, thus only using the global median CFs when information at a finer resolution is not available. In most humid regions CFs are 0, making it unnecessary to include impacts of soil salinisation with irrigation water in quantitative sustainability assessments of agricultural products grown in humid areas. In areas with positive CFs, variation is mainly attributable to geographic location, while the difference between CFs due to the irrigation system used at a given spot is very small. This happens because soil properties considered in the definition of the CFs vary more over space than with depth.

For damage level CFs, higher EFs ($\Delta CDL/\Delta EC_e$) were allocated to higher quality soils. The rationale behind this choice is that good quality soils are scarcer and serve to a greater diversity of purposes, which is the asset we want to protect for future uses. The concept of crop diversity loss to quantify damage on soil quality and ecosystem services is original. One of the advantages of using damage indicators is that they allow for comparing and adding impact results of different contributing impact categories. In the context of this article, this means that impacts of other soil degradation processes, such as erosion, compaction and change of the carbon stock must also be measurable in terms of crop diversity loss, which is indeed the case (see section S4) and thus shows the added value of the concept for use in LCA.

The midpoint impact score, obtained from multiplying the LCI flow associated to the FU and the corresponding midpoint CF, has units of dS/m × m^3 soil per FU and informs about the potential impact of the FU on the increase of the electrical conductivity of the soil used to fulfil the function assessed. The increase of the soil's EC_e reduces its usability potential. The damage impact score (LCI per FU × damage CF) has units of CDL× m^3 soil per FU and informs about the potential impact of the FU on the diversity of crops that will grow in the affected soil. The midpoint indicator is more versatile as it can be used for any type of land use, whereas the damage indicator is informative only for agricultural LCAs. This leaves the door open for the development of indicators for other land uses/land use changes (e.g. potentially disappeared fraction of natural vegetation species due to soil salinisation in natural areas).

- **Model limitations**

The most important limitation of the model for use in sustainability assessments is that it focuses on impacts due to salt accumulation in one single environmental compartment, that is, in agricultural soil. However, salts leached from the soil profile may accumulate in aquifers and water bodies downstream, leading to potential environmental impacts off-site. A regionalised, global multimedia model predicting the transport of salts from soils to aquifers and surface water bodies could solve this problem and help prioritise decisions following an integrated life cycle assessment perspective. To this end, operationalising the multimedia hydrological fate modelling presented by Núñez et al[36] can be of much help. A major drawback of the model is the focus on soil salinisation with irrigation water, whereas land use change, brine disposal and overuse of coastal ground water bodies are anthropogenic drivers that may concomitantly lead to salt accumulation in agricultural soils.[19] Another limitation is that we assumed that the movement of water in the soil profile is not affected by the presence of a sodic horizon. Sodic layers prevent water transmission due to structural problems, restricting leaching and drainage and eventually leading to salt accumulation in the soil.[7]

The model is an empirical model based on the establishment of correlations between salts in soil and presumed effects on soil electrical conductivity and crop diversity.

Sources of uncertainties different from aggregating CFs (section S5) and a comparison of the modelling approach we applied compared to other land use impact assessment models in the LCA framework (section S6) are described in the SI.

Associated content

Supporting information. Excel file: SaltLCI tool, input data to the SaltLCI, and characterisation factors at sub-country, country and global scales. Word file: description of the SaltLCI tool, LCIA model choices, and sources of uncertainty affecting the overall model. Raster files: characterisation factors at 5 arc-minutes resolution.

Declaration of interest

The authors declare no competing financial interest.

Acknowledgements

Funding for this research was provided by the German Research Foundation through the "Water Footprint in the Manufacturing Industries – Methods, Tool and Optimization Strategies" project (GZ: FI 1622/4-1) and for the Beatriu de Pinós postdoctoral programme of the Government of Catalonia's Secretariat for Universities and Research of the Ministry of

Economy and Knowledge. M. Núñez thanks the CERCA Programme of the Generalitat de Catalonia and the Consolidated Research Group TERRA (AGAUR, ref. 2017 SGR 1290). We are very grateful to Markus Berger, Stéphane Follain, Arnaud Hélias, Sandra Payen, Ralph Rosenbaum, Thomas Sonderegger, and the anonymous referees for their valuable inputs.

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