Monitoring drought and salinity stress in agriculture by remote sensing for a sustainable future

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Chapter 5

Prospects of salt-tolerant potato to increase food productivity towards a zero hunger world

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Abstract

Sustainable agriculture and food security are critical aspects of the sustainable development goals (SDGs), but they are increasingly vulnerable to the impacts of global climate change. While salt-induced stress on crop growth and food production has been extensively studied, the quantification of the contribution of the utilization of saline soil to agricultural production (i.e., saline farming) on a global scale is still highly uncertain. This study aims to address this gap by evaluating the local and regional suitability areas for salt-tolerant potato cultivation in affected soils, thereby assessing the contribution of salt-tolerant potatoes to the current and future SDGs. We found that Oceania, out of all other continents, currently exhibits the greatest potential for enhancing food production through salt-tolerant potato cultivation in salt-affected soils. In particular, Australia emerges as the country with the most substantial increase in the local suitability and regional suitability area. Meanwhile, Kazakhstan, the Russian Federation, Iraq, and Lesotho also possess the capacity to address food shortage challenges and work towards achieving SDG targets by utilizing salt-tolerant potato cultivation. Furthermore, under various future scenarios, the extent of local suitability area for salt-tolerant potato will consistently expand despite the increasing severity of soil salinity. Hence, also under future climatic and salinity conditions, salt-tolerant crops may help to enhance food production and to successfully achieve SDG targets (with a 100% increase for countries like Kazakhstan and the Russian Federation) across various future scenarios. In combination, our study provides a way of evaluating salt-tolerant potato as a proxy of saline farming, enabling enhanced food production in salt-affected soils, thereby establishing the backbone for promoting saline farming practices, with the ultimate goal of ensuring food security and enhancing agricultural resilience.

5.1 Introduction

To ensure a safe and sustainable future for all, the United Nations (UN) has established the sustainable development goals (SDGs) for 2030, with sustainable agriculture and food security being essential components. Within this framework, SDG-2 specifies aims to improve agriculture system resilience to e.g. climate change, drought, and soil quality, to ensure sustainable food production by 2030 (UN 2015). To attain SDG-2 requires significant improvements to agricultural production both in terms of size and efficiency. However, SDG-2 is also persistently challenged by frequently occurring extreme events, sluggish economics, conflicts, inequality, and poverty. Hence, despite considerable progress, the world remains off track in achieving the zero hunger world goal under global climate change and there are still 1/10 people suffering from hunger in 2021 (UN 2022). Therefore, there is a pressing need for improved agricultural practices and optimal utilization of the available land area to ensure food security.

Salt affects approximately 11% of the world's irrigated area while soil salinity is projected to increase to 50% of the arable land by 2050 (Butcher et al. 2016; FAO 2011). Most of these increases are on arid or semi-arid lands where increasingly frequent extreme events (e.g., drought) are projected to increase soil salinity impacts (Chapter 2). Meanwhile, the availability of water suitable for irrigation is projected to be exacerbated in the coastal area due to sea-level rise and seawater intrusion in the near future (Chen and Mueller 2018). Salinity is a major pressure limiting crop growth and yield, resulting in an annual economic loss of 27.3 billion US dollars globally (Qadir et al. 2014). Thus, improving the utilization of salt-affected soils can be a critical step to contribute to a sustainable agricultural system. Although various attempts have been made to assess salt-affected soil areas at a regional scale or global scale (Corwin and Scudiero 2019; Hassani et al. 2021), there is not any regional or global analysis to couple soil salinity with food productivity in a quantitative way.

To address this challenge, salt farming has emerged as a new practice to promote crop utilization and contribute to food security in the present and foreseeable future. Salt-affected soils have been reclaimed through applications of various amendments, halophytes, and microorganisms, and optimizations in land use as well as irrigation and drainage strategies (Mukhopadhyay et al. 2021). Next to reclaiming salt-affected soils, cultivating salt-tolerant crops is a promising solution to tackle this problem (Rozema and Flowers 2008). Crops such as rice, wheat, maize, etc., have been screened for salt-tolerant genotypes with stable productivities (Farooq et al. 2015; Genc et al. 2019; Reddy et al. 2017). However, most of these salt-tolerant cereal cultivars have been primarily tested in local experimental settings, indicating a limited understanding of salt-tolerant crops' application on a large scale. Compared to these cereals, potato delivers higher calories per unit of water (Renault and Wallender 2000). Salt-tolerant potato, in particular, has a high value due to its high productivity and water-use efficiency allowing it to better utilize salt-affected soils (van Straten et al. 2020;2022).

Currently, several studies indicated that the cropland suitability for saline farming on the global and regional scale. A study using Global Agro-Ecological Zones (GAEZ) was conducted to evaluate potato suitability at a global scale based on the crop suitability index (FAO and IIASA 2012). However, neither the land suitability for salt-tolerant crops in moderate saline areas nor the potential impacts of such cultivation on global food productivity have been estimated over the world. Therefore, the estimation of suitable areas for salt-tolerant crops (e.g. potatoes) provides a critical foundation for the utilization of salt-affected soils for saline farming.

In response, we aim to evaluate the suitable area for salt-tolerant potato in salt-affected soils and assess the potential of cultivating salt-tolerant potato in these areas with respect to the UN sustainable development goals for the present and the near future in this study. For this, we generated a global suitability map for salt-tolerant potato taking multiple constraining factors including land cover, soil quality, and essential potato growing conditions into account. Then, the contribution of salt-tolerant potato was estimated at the continent level and country level to highlight the areas that benefit most towards achieving their SDGs. Moreover, in order to evaluate the future contribution of salt-tolerant potato, the changes in potentially suitable areas of salt-tolerant potato cultivation between the current state and different future scenarios were further analyzed. Consequently, our study provides insights into a better utilization of salt-affected soils by cultivating salt-tolerant potato to improve food security and agriculture resilience.

5.2 Methodology

5.2.1 Data collection

5.2.1.1 Land cover map

A global land cover map was obtained from the GlobCover Portal (http://due.esrin.esa.int/page_globcover.php). The land cover map was generated by observations from the MERIS sensor in 300m resolution with the ENVISAT satellite mission. The land cover map included 22 classes which we reclassified as suitable or not suitable for crop cultivation based on the possibilities for agriculture practices (Table S5-1). Four classes were defined as suitable land types for potato cultivation, and given new code=1, water bodies were designated to code = 2, and the rest classes were designated to code = 0 (not suitable) (Table S5-3). The land cover map was resampled to 0.83 degrees with WGS84 projection using interpolation based on the majority method.

5.2.1.2 Potato distribution map

A potato harvest map in 2010 was created from the MapSPAM data center (https://mapspam.info/index.php/data/). The potato harvest dataset was reclassified to code 1(= distributed area, harvest area > 0 ha) and code 0 (= non-distributed area, harvest area > 0 ha). Afterward, based on the reclassified soil salinity map, we identified the area within 30 km surrounding current potato production lands as the buffer area (code = 2) (Table S5-3). Due to data limitations, this study did not take farmers' willingness for potato cultivation into account. Instead, it is assumed that in areas close to current potato production lands, the likelihood of potato adoption is high as it is presumably part of the local tradition.

5.2.1.3 World map

The world country map was obtained from ArcGIS HUB, named "World Countries (Generalized)" provided by ESRI (https://services.arcgis.com/P3ePLMYs2RVChkJx/arcgis/rest/services/World_Countries_(Generalized)/FeatureServer) for the world shapefile in 2022.

5.2.1.4 Soil quality map

Based on the soil parameters published by the Harmonized World Soil Database (HWSD), six soil attributes for crop cultivation, including nutrient availability (SQ1), nutrient retention capacity (SQ2), rooting conditions (SQ3), oxygen availability to roots (SQ4), toxicities (SQ6), and workability (SQ7) were extracted (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). Each of the six soil qualities was distributed into seven quantitative classes, including no or slight limitations=code 1, moderate limitations = code 2, sever limitations = code 3, very severe limitations = code 4, mainly non-soil = code 5, permafrost area = code 6, water bodies = code 7 (Fischer et al. 2008). All six soil quality maps were reclassified to two new classes, namely suitable (code = 1, no or slight limitations) or not suitable area (code = 0, all other classifications) (Table S5-2). The six soil quality maps were resampled to 0.83 degree with WGS84 projection using the interpolation of the nearest method.

5.2.1.5 Soil salinity map

A soil salinity map was created based on excess salts (SQ5) in HWSD (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). Soil salinity is measured by Electric Conductivity (EC, dS/m) or saturation of the exchange complex with sodium ions (Fischer et al.

2008). Future soil salinity maps were created based on four scenarios at a 0.5° resolution, including Representative Concentration Pathways (RCP) 4.5, RCP 8.5, Shared Socio-economic Pathways 2 (SSP2)-4.5, and SSP5-8.5 for two periods (the 2050s and 2100s) (Hassani et al. 2021). The RCP 4.5 and RCP 8.5 scenarios represent radiative forcing of 4.5 and 8.5 W m^{-2} in the year 2100 compared to pre-industrial conditions in the ensemble of CMIP5 (Coupled Model Inter-comparison Project Phase 5) data project with eight Global Circulation Models (GCMs) outputs. The SSP 2-4.5 and SSP 5-8.5 scenarios represent the projections forced by RCP 4.5 and RCP 8.5 global forcing pathways for SSP2 and SSP5 to the ensemble of CMIP6 (CMIP Phase 6) with eight Global Circulation Models (GCMs) outputs. Soil salinity maps of the current state and future scenarios were resampled to 0.83 degree with WGS84 projection using the interpolation of the nearest method.

5.2.1.6 Salt-tolerant potato suitability for salinity

Although the salt tolerance of potato is defined as 1.7 dS/m according to FAO investigation, some potato varieties are more tolerant of salinity than expected. Based on several years of field experiments, potato variety '927' showed no yield reduction up to 5.9 dS/m salinity level (de Vos et al. 2016; Oosterbaan 2019; van Straten et al. 2021). Considering that crops would probably already be grown when soil salinity varies between 0 dS/m to 2 dS/m, there is no added value for salt-tolerant potato to be cultivated there. So, the salt-tolerant potato's profitable salinity range was defined between 2.0 dS/m and 6.0 dS/m. Moreover, considering there is no distinction within "severe limitations - 4 dS/m to 8 dS/m-" of soil salinity (SQ5) from FAO, the soil salinity maps were reclassified to three classes, namely code0 = not suitable (< 2 dS/m or > 8 dS/m), code1 = high-suitable salinity (2 dS/m to 4 dS/m), and code2 = moderate-suitable salinity (4 dS/m to 8 dS/m) (Table S3).

5.2.2 The algorithm of soil suitability for salt-tolerant potato

The suitable map was generated based raster calculator in ArcGIS Pro using the following equation:

$$\text{Suitability index} = LSAL \times LLC \times LPD \times LNA \times LNRC \times LRC \times LOAR \times LTOX \times LWOR \quad (1)$$

LSAL = layer of soil salinity, LLC = layer of landcover, LPD = layer of potato distribution, LNA= layer of nutrient availability, LNRC = layer of nutrient retention capacity, LRC = layer of rooting conditions, LOAR = layer of oxygen availability to roots, LTOX = layer of toxicities, LWOR = layer of workability.

Thus, the local suitability area was determined on the occasions of LSALH =1 (high-suitable salinity, 2 dS/m to 4 dS/m) or LSALM = 2 (moderate-suitable salinity, 4 dS/m to 8 dS/m) with other layers' codes equalling 1. Though LPD = 1 suggests the presence of potato cultivation in the pixel, it should be noted that there are also salt-affected parts within the pixel. Meanwhile, the regional suitability area was determined when occurring in the buffer area close to current potato fields (LPD = 2) while LSALH =1(high-suitable salinity, 2 dS/m to 4 dS/m) or LSALM = 2 (moderate-suitable salinity, 4 dS/m to 8 dS/m), and other layers' codes equalling 1. According to different constraints, the suitability map was grouped into 12 categories (Table S5-4). Finally, the local suitability area and the regional suitability area were calculated at the continent level and country level based on zonal statistics in ArcGIS Pro (Figure 5.1).

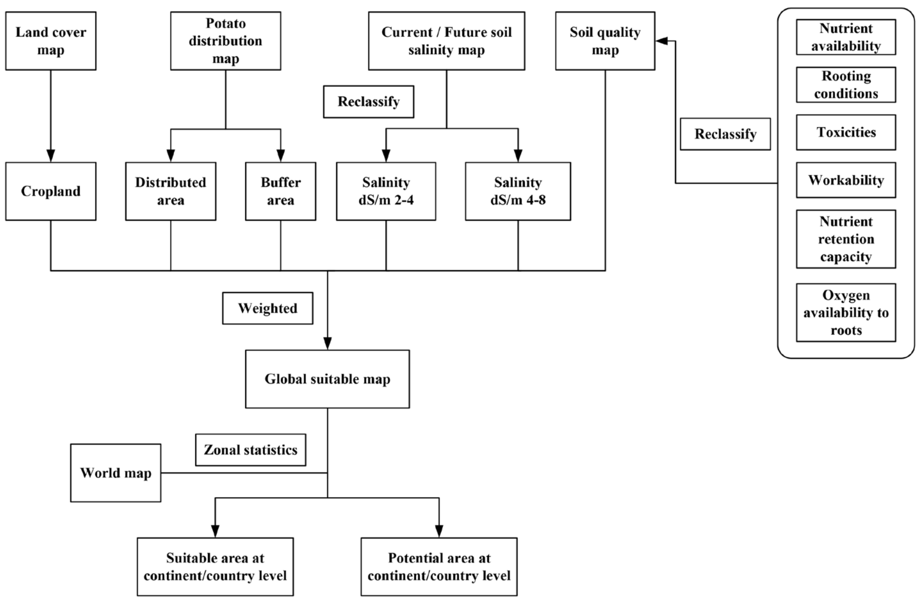

Figure 5.1 Technical workflow of the maps and data framework.

5.2.3 Data analysis

To investigate the contribution of salt-tolerant potato to salt-affected soils at the current state and in future scenarios at the global scale, the availability was calculated based on the following equation:

$$\text{PCTi} = \frac{Area_i}{Area_p + Area_i} \times 100\% \quad (2)$$

Where PCTi is the percentage, Areap is the current potato harvest area (https://mapspam.info/index.php/data/), and Areai is the local /regional suitability area of the salt-tolerant potato.

According to the latest sustainable development goals report in 2022 by the United Nations (UN 2022), it is evident that approximately 1 in 10 people globally are currently experiencing hunger, while almost 1 in 3 people lack consistent access to sufficient food. In response, international frameworks, such as the "Kunming-Montreal Global Biodiversity Framework" (GBF), aim to enhance the resilience of agricultural systems and improve food security (CBD 2022) for the year 2030. Specifically, Target 10 of the GBF, emphasizes that 30% of the world's land requires restoration to ensure sustainable management of the agriculture system. Thus, given the current gap in food production in terms of SDG 2 and GBF, we define 10% and 30% increasement as two thresholds to analyze the contribution of salt-tolerant potato cultivating in salt-affected areas. By focusing on the 10% and 30% increasement in food production, we aim to assess the viability and potential of this salt-tolerant crop in achieving the objectives of both SDG 2 and GBF. To investigate the critical countries where salt-tolerant potato helps to achieve the SDGs and GBF in the near future, the contribution was calculated based on the following equation:

$$\text{PCTt} = \frac{Area_i}{Area_{total}} \times 100\% \tag{3}$$

Where PCTt is the percentage, Areai is the local/regional suitability area of the salt-tolerant potato, and Areatotal is the total harvest area of all crops in 2021 (https://www.fao.org/faostat/en/#data/QCL).

The relative change between the local/regional suitability area under future scenarios and the current state was calculated based on the following equation:

$$\text{PCTr} = \frac{Area_f}{Area_f + Area_i} \times 100\% \tag{4}$$

Where PCTr is the relative change, Areaf is the future local/regional suitability area of the salt-tolerant potato, and Areai is the current local/regional suitability area of the salt-tolerant potato. In order to be consistent with the future soil salinity map' resolution, we compare the relative change at 0.5° (~ 55km) resolution. Given the coarse pixel size of the scenarios, both local and regional suitability were aggregated for future scenarios.

5.3 Results

5.3.1 Global suitability of salt-tolerant potato for salt-affected area

A global suitability map of salt-tolerant potato in salt-affected areas was created, as shown in Figure 5.2a. The highest suitability areas were concentrated around Kazakhstan, the Russian Federation, and northern India while some pieces were distributed in the western part of Australia. Thus, compared to other continents, Asia showed a larger extent of local suitability area for salt-tolerant cultivation.

In order to compare the contributions of salt-tolerant potato to salt-affected areas among different continents and countries, the availability of productive land for saline potato farming was further analyzed (Figure 5.2b and Figure 5.2c). Here, Oceania showed the highest availability of local and regional suitability areas, allowing to increase potato production by 99.24% and 98.28% in the local suitability area of highly (dS/m 2-4) and moderately (dS/m 4-8) saline conditions, and by 97.50% and 94.35% in regional suitability area of highly (dS/m 2-4), and moderately (dS/m 4-8) saline conditions, respectively. In contrast, Europe has the lowest availability in both locally and regionally suitable areas, with 44.08% more local land available that is highly suitable (dS/m 2-4), and 2.51% that is moderately suitable (dS/m 4-8), and 17.09% more regional land available that is highly suitable (dS/m 2-4), and 0.85% that is moderately suitable (dS/m 4-8).

At the country level, we found the top 15 countries (i.e., Australia, Mozambique, Pakistan, Argentina, Iran, Kazakhstan, India, Russian Federation, Canada, Senegal, United States, Zimbabwe, Chad, Spain, and Syria) that benefit greatly from cultivating salt-tolerant potatoes. Among these countries, Australia has the highest potential, with land area increases of 99.43% in the local suitability area (dS/m 2-4), 98.11% in the local suitability area (dS/m 4-8), 98.67% in the regional suitability area (dS/m 2-4), and 95.69% in the regional suitability area (dS/m 4-8), respectively. Interestingly, Senegal does not have any local suitability area for salt-tolerant potato while Senegal showed notable regional suitability areas at the current state. In addition, Chad had only local suitability areas at two salinity levels without any regional suitability areas.

Overall, Oceania had the highest possibility to improve food production while Europe had the least capacity for increasing production by salt-tolerant potato cultivation in salt-affected soils.

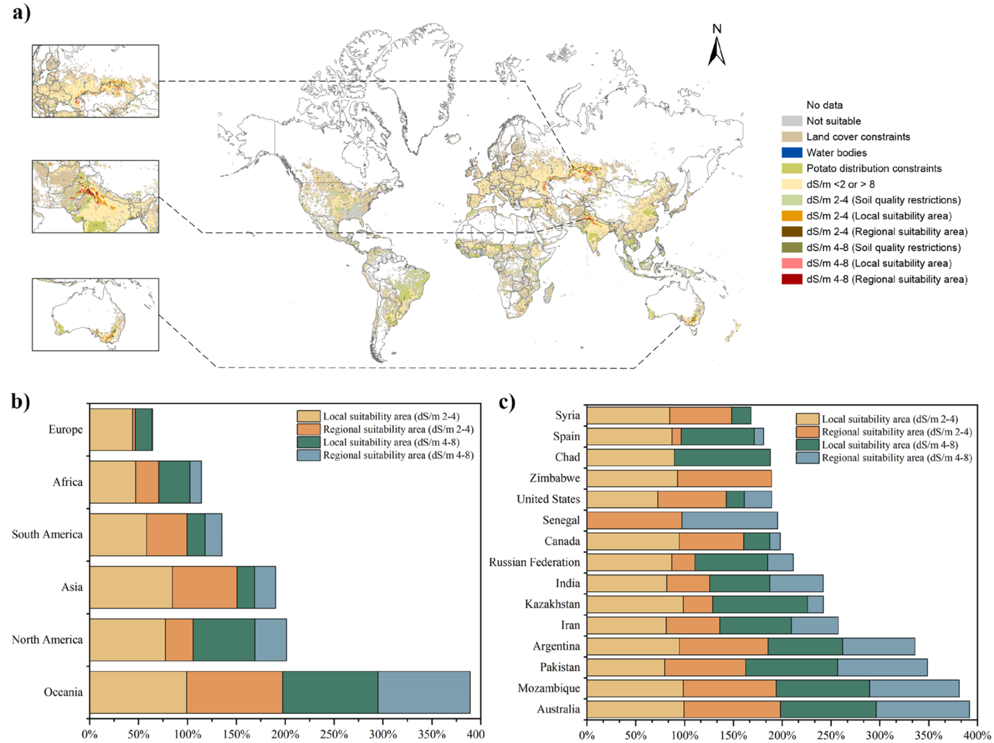

Figure 5.2 a) Global suitability map for the salt-tolerant potato. b) The availability of local and regional suitability areas for salt-tolerant potato at the continent level. c) The availability of local and regional suitability areas for salt-tolerant potato at the country-level.

5.3.2 Contribution of salt-tolerant potato to SDGs

As there were various countries showing promising potential to increase food production by better utilizing salt-affected soils, the contribution of local suitability and regional suitability areas for achieving SDGs was analyzed (Figure 5.3a and Figure 5.3b). When making use of the local suitability area for saline potato farming, Kazakhstan, the Russian Federation, Australia, Iraq, and Lesotho could already achieve their SDG2 targets (of a 10% increase to deal with current food shortages).

In particular, Kazakhstan showed the highest possibility for achieving the SDG2 target as well as the GBF target thanks to its availability of 41.88% local suitability area compared to the current crop harvested area. Based on the sum of the local suitability and regional suitability area, additional countries including New Zealand, Mozambique, and Pakistan can succeed in achieving the SDG2 target while Kazakhstan was still the only country that can accomplish the GBF target.

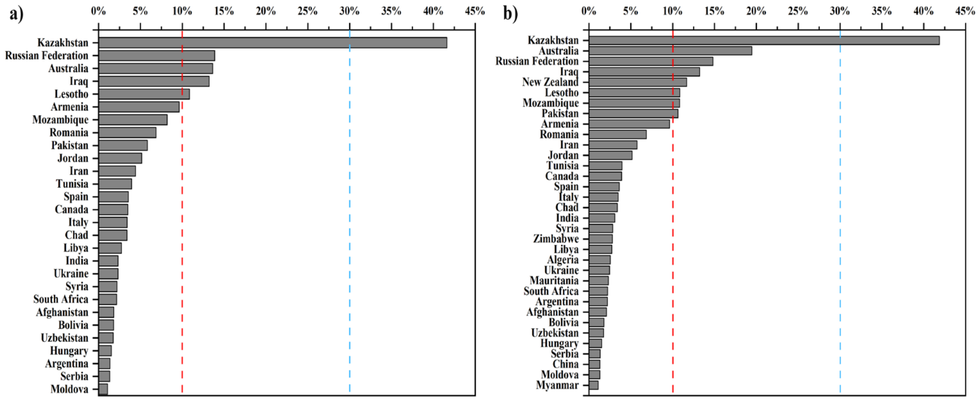

Figure 5.3 The critical countries with a high contribution of salt-tolerant potato in terms of a) the local suitability area, b) local suitability area + regional suitability area. The red line (10%) indicates the SDG2 target in the 2030 agenda. The Blue line (30%) indicates the GBF target for 2030.

5.3.3 Global suitability of salt-tolerant potato in the future

Given that soil salinity was projected to increase with global climate change, the relative change in the local suitability areas for salt-tolerant potato cultivation under future scenarios was evaluated for two different future periods, namely 2050 and 2100 (Figure 5.4). The relative change patterns of the four scenarios were similar, even though they differed in detail. Thus, the relative change under RCP85 was chosen to represent the local suitability area changes in the future while other results are presented in the supplementary information (Figure S5-1). In both periods, more salt-affected soil was detected under different future scenarios (i.e. the area with dS/m 2-4 and dS/m 4-8 will increase more than the area with dS/m>8) and therefore resulted in consistently increased the local suitability area for salt-tolerant potato in comparison to the present. Although the local suitability area in Asia was the largest under the four scenarios, North America was projected to have the average highest increase compared with the current local suitability area. Meanwhile, South America showed overall the lowest increase in the local suitability area in future scenarios both for 2050 and 2100. Moreover, there was a higher increase in the local suitability area in dS/m 2-4 in Asia and Europe while other continents including South America, Oceania, Africa, and North America showed a higher incense in the local suitability area in dS/m 4-8 in 2050 as well as 2100.

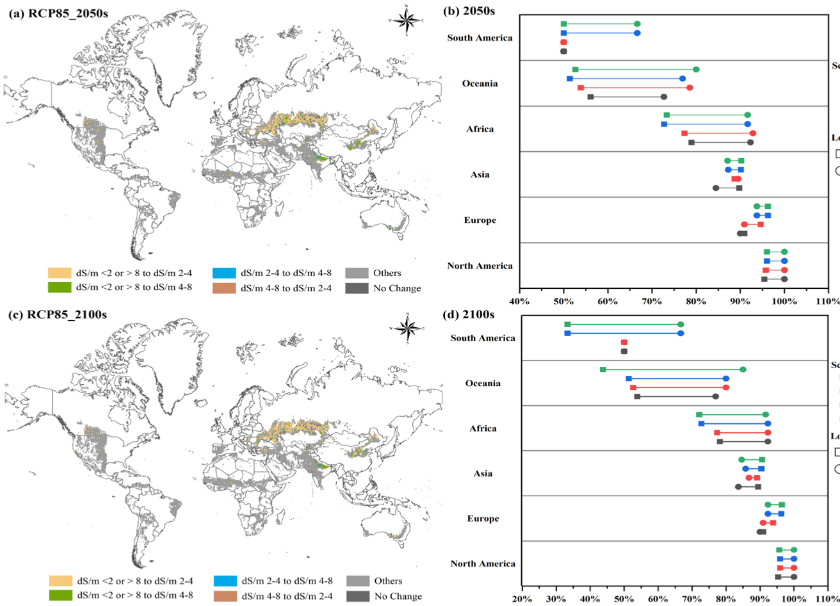

Figure 5.4 (a) Relative change in suitability for saline farming under the RCP85 scenario in the 2050s. (b) The increase in the local suitability area for salt-tolerant potato in the 2050s under different scenarios at the continent level. (c) Relative change in suitability in the 2100s under the RCP85 scenario. (d) The increase in the local suitability area for salt-tolerant potato in 2100s under different scenarios at the continent level.

5.3.4 Contributions of salt-tolerant potato to SDGs in the future

As all continents showed an increase in the local suitability area for salt-tolerant potato, the contribution of these increases for the sustainability targets was analyzed (Figure 5.5). The contributions varied slightly for the different future scenarios. In general, the contributions were higher for most countries under the SSP245 and SSP585 scenarios, compared to the RCP45 and RCP85 scenarios. There were 20 countries with an average increase of over 10% (i.e. achieving SDG-2) under different scenarios in the 2050s and 2100s around the world. Kazakhstan, Russian Federation, Ukraine, Hungry, and Romania were projected to be the top 5 countries with an average high increase of more than 30% both in the 2050s and 2100s. These increases indicate that these countries achieve their GBF target as well. There was even an increase of over 100% for Kazakhstan and the Russian Federation under all scenarios in the 2050s and 2100s. Therefore, Kazakhstan, the Russian Federation, Ukraine, Hungry, and Romania were critical countries to improve food production and achieve sustainable agriculture system by cultivating salt-tolerant potato in salt-affected soil in the future. Moreover, Kazakhstan and the Russian Federation even showed significant potential to secure sustainable food production with over 100% increasement by extending salt-tolerant potato cultivation in the salt-affected area across all four scenarios.

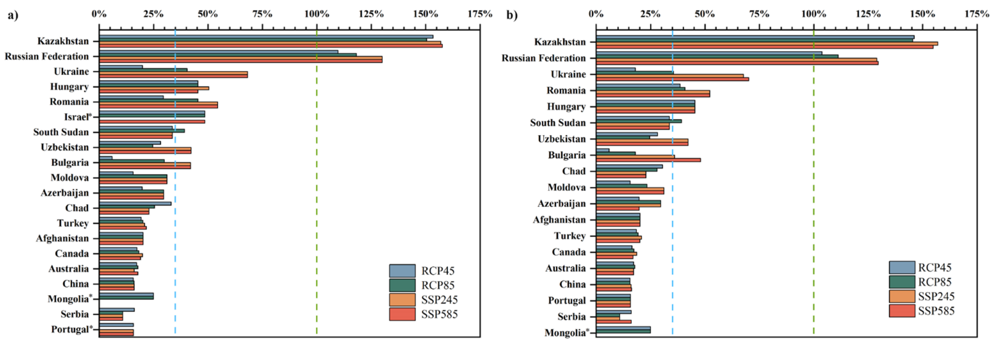

Figure 5.5 The critical countries with high contributions of salt-tolerant potato in a) 2050s, b) 2100s. The blue line (30%) indicates the GBF target for 2030. The green line (100%) indicates doubling the current harvested area. * indicates absent scenarios for that country.

5.4 Discussion

5.4.1 Hotspot areas for salt-tolerant potato cultivation

Among the six continents, Oceania had the highest relative amounts of the local suitability area for saline farming while Asia had the largest (absolute) area for growing salt-tolerant potato on salt-affected soil (Figure 5.2). Salt-affected area has been mapped regionally and globally using various technologies. Asia is commonly identified as the continent with the highest risks of saline soils in the current state and the near future (e.g. Ivushkin et al. 2019; Hassani et al. 2020). Nevertheless, considering the current potato cultivated area, Oceania showed higher potential than Asia, for promoting salt-tolerant potato on salt-affected soil given its suitability. This might be due to the current relatively low potato cultivation in Oceania with only 0.5% market share in global potato production (Bartosz Mickiewicz et al. 2022).

At the country level, Australia, Mozambique, Pakistan, Argentina, Iran, Kazakhstan, India, Russian Federation, Canada, Senegal, United States, Zimbabwe, Chad, Spain, and Syria were critical countries with high capacity for enhancing food production by promoting salt-tolerant potato cultivation in salt-affected soil (Figure 5.2). This is in line with various studies indicating that these countries have a significant salt-induced soil degradation problem (e.g. Hassani et al. 2020) and major economic costs due to salt-induced soil degradation (Qadir et al. 2014; Rengasamy, 2002; Rengasamy, 2006). Moreover, consistent with our results, Russia, Argentina, China, the United States, and Kazakhstan were identified as the most promising countries to develop saline agriculture (ECe > 4 dS/m) based on an analysis taking suitable conditions for agriculture into account (Negacz et al. 2022). Therefore, these hotspot areas with a high potential to better utilize salt-affected soil by cultivating salt-tolerant potato match with the high-risk areas in terms of soil salinity while their potential strength might differ due to their current potato cultivation status.

Our assessment of the regional suitability contribution of salt-tolerant potato for global food production in salt-affected areas is based on limitations due to salt tolerance only. However, over 70% of the global salt-affected soil area is distributed in arid and semi-arid regions, including but not limited to Pakistan, India, Australia, Egypt, and Central Asia (Li et al. 2016). Thus, most regions that suffer from soil salinity stress are expected to experience the frequently compounded impact of both drought and salinity (Chapter 2 & Chapter 3). In this study, the threshold of salt-tolerant potato was determined under strict conditions without drought. Given that the side effect of drought is excluded in our current analysis, the local suitability area might be overestimated for arid and semi-arid regions unless irrigation water is available. Another critical assumption is that farmers close to or in buffer areas of 30km around current potato production regions are willing to adopt (salt-tolerant) potato cultivation. This assumption may be most likely for developing nations that struggle with food security. In contrast, developed countries may prefer high-value halophytes with high-end markets such as Salicornia, which fetches up to 12 GBP/kg in the United Kingdom (Negacz et al. 2021). Despite these assumptions, we believe that the results of our study are generally robust.

5.4.2 The role of salt-tolerant potato towards SDGs

Cultivating salt-tolerant potato is a promising way to close the current food production gap to achieve SDG-2 targets for various countries. Negacz et al. (2021) conclude that saline agriculture can foster achieving SDGs, especially for SDG2 and SDG8 in saline soils for those regions with high salt-induced problems and that struggle with food security and water scarcity. These countries were estimated to have to increase over 10% of the current food production to satisfy their food requirements with an increasing population. Countries like Kazakhstan (and others) show that they may easily comply with such requirements when embracing salt-tolerant potato (Figure 5.3). According to FAO (2017), the salt-affected irrigation area in Kazakhstan is about 19.6% of the total irrigated area and has grown by almost 44% in 20 years (1997-2017). Although innovative technologies e.g., drainage, allowed to reclaim soil salinity and maintain crop production (FAO 2022a; Tanirbergenov et al. 2020), the cost and efficiency need to be further evaluated. This study suggests and provides an alternative solution for improving sustainable food supply through cultivating salt-tolerant potato in salt-affected soils.

Cultivating salt-tolerant potato does not only benefit food production within the SDG-2 target but also contributes to achieving the GBF target. Salinity has shown negative impacts on plant species variety and below-ground biodiversity, including the quantity and activity of soil microbes (IPCC 2019; Rahman et al. 2011). In order to control soil salinity and reduce its adverse effects on biodiversity, the replacement by salinity-tolerant species and revegetation where necessary have been adopted as main measures in forest systems (IPCC 2019; Rahman 2020). Likewise, we found that salt-tolerant crop cultivation may be profitable for achieving the GBF target (e.g. target 10) by preventing soil degradation, especially for the regions that suffered from salt-induced stress. In addition to increasing the revenue through greater yields than with conventional crops, the management of saline soils can mitigate economic and climate migration (SDG 8) (Negacz et al. 2021). Moreover, managing soil salinization is essential to accomplishing SDG15 "Life on Land", with particular emphasis on target 15.3 -combat desertification, and restore degraded land and soil- (Singh 2021). Meanwhile, saline farming may reduce the demand for high-quality irrigation water, which facilitates having enough drinking water (SDG6) (Keesstra et al. 2018) for other agricultural applications. Therefore, considering SDGs in close connection to each other shows that salt-tolerant potato is not only a proxy for success in food production (SDG2), but can also make a crucial contribution to other SDGs.

5.4.3 Salt farming contributes to a sustainable future world

In addition, our study also shows how salt-tolerant potato growth may have a notable contribution to sustainable food production with future climate change. It is expected that salt-affected soils are growing at a rate of 1-2 Mhectares per year (Abbas et al. 2013) and the rate was predicted to speed up shortly as a result of climate change (Hassani et al. 2021). Interestingly, despite the increase in salinity, there will be more suitable areas for salt-tolerant potato (Figure 5.4 and Figure S5-1), suggesting that the increase in moderate saline areas is larger than the increase in severely affected areas. This provides additional opportunities for saline farming. The changes observed in the local suitability area, while transitioning from the current state to different future scenarios, exhibited a degree of resemblance. However, a stronger increase in the local suitability area was evident under CMIP6 models (SSP245 and SSP585) compared to CMIP5 models (RCP4.5 and RCP8.5). This difference can be driven by different predictors and GCMs involved in CMIP5 and CMIP6 models (Eyring et al. 2016; Hassani et al. 2021).

Saline farming, which salt-tolerant potato is a part of, contributes to creating a more sustainable world. In this study, salt-tolerant potato showed to be a promising crop to improve food production in salt-affected areas both in the current state and future scenarios and therefore achieving various sustainability targets in different ways (Figure 5.4 and Figure 5.5). Salicornia, as a typical halophyte, was identified as one the most important genera that have high adaptability to saline environments and therefore applied could be in food, pharmacy, bioenergy, and ecology field as a sustainable crop (Cárdenas-Pérez et al. 2021). However, saline farming is more than growing Salicornia but also has a potential contribution to food security as a whole (e.g. salt-tolerant potato). There have been several studies conducted to test the opportunity of producing food through saline farming based on several salt-tolerant crops including rice, barley, quinoa, beetroot, etc. (de Vos et al. 2021; ICBA 2015; Wang et al. 2013b). Although these studies demonstrated the potential application of divergent salt-tolerant crops for saline farming, they were currently fragmented in space, only covering a limited area. Given the impact of climate change, saline farming would be a promising global solution for salt-affected regions. Thus, our study provides a backbone to get more insight into how saline farming contributes to sustainable development with future climate change threats on a global scale.

5.5 Conclusions

In this study, we assessed the viability and potential of cultivating salt-tolerant potatoes in salt-affected soils, aiming to explore the role of salt-tolerant potato varieties in achieving sustainable development goals in the present and future climate. We found that Oceania showed the greatest potential for enhancing food production through salt-tolerant potato cultivation in salt-affected soils, while Europe demonstrated the lowest capacity for increasing production in this regard under the current state. Under different future scenarios, all continents show an expansion in the areas suitable for salt-tolerant potato cultivation. Moreover, we identified a number of countries that could crucially benefit through the promotion of salt-tolerant potato cultivation in salt-affected soils for enhancing food production. Specifically, Kazakhstan, the Russian Federation, Australia, Iraq, and Lesotho possess the capability to address their food shortage challenges and achieve sustainable development goals by cultivating salt-tolerant potatoes under the current state. Meanwhile, Kazakhstan, the Russian Federation, Ukraine, Hungary, and Romania were crucial countries by growing salt-tolerant potatoes in salt-affected soil for enhancing food production and achieving a sustainable agriculture system in the future. Consequently, our study proposed valuable insights into growing salt-tolerant potato to optimize the utilization of salt-affected soils, and therefore built the foundation for saline farming globally to secure food security and strengthen agricultural resilience.

5.6 Author contributions

Wen Wen: Conceptualization, Methodology, Investigation, Writing--original draft, Writing--review and editing. Joris Timmermans: Methodology, Supervision, Writing--review and editing. Daan Hooimeijer: Conceptualization, Methodology, Investigation. Peter M. van Bodegom: Conceptualization, Methodology, Supervision, Writing--review and editing.

5.7 Supporting information

Table S5-1. Reclassification of land cover classes

Value	Label	Reclassification
11	Post-flooding or irrigated croplands (or aquatic)	Suitable
14	Rainfed croplands	Suitable
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	Suitable
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	Suitable
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	Not suitable
50	Closed (>40%) broadleaved deciduous forest (>5m)	Not suitable
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	Not suitable
70	Closed (>40%) needleleaved evergreen forest (>5m)	Not suitable
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	Not suitable
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	Not suitable
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	Not suitable
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)	Not suitable
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	Not suitable
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	Not suitable
150	Sparse (<15%) vegetation	Not suitable
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water	Not suitable
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water	Not suitable
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	Not suitable
190	Artificial surfaces and associated areas (Urban areas >50%)	Not suitable
200	Bare areas	Not suitable
210	Water bodies	Not suitable
220	Permanent snow and ice	Not suitable
230	No data (burnt areas, clouds)	Not suitable

Table S5-2. Classification of soil qualities. Only classes 1 to class 4 correspond to an evaluation of soil constraints for plant growth.

Qualitative classes	Salinity (dS/m)	Growth potential (%)	Organic carbon (%)	Impermeable layer (cm)	Cation exchange capacity (cmol/kg)	Obstacle to roots (cm)	Toxicities (pH)	$CaCO_3$ content (%)
1. No or slight limitations	< 2	80-100	> 2.0	0-150	> 40	60-80	5.5-7.2	< 2
2. Moderate limitations	2-4	60-80	1.2-2.0	80-150	20-40	40-60	7.2-8.5	2-5
3. Sever limitations	4-8	40-60	0.6-1.2	40-80	10-20	20-40	4.5-5.5	5-25
4. Very severe limitations	8-16	< 40	0.2-0.6	< 40	4-10	0-80	> 8.5	25-40
5. Mainly non-soil	> 16	0	< 0.2	0	< 4	0-20	< 4.5	> 40
6. Permafrost area	--	--	--	--	--	--	--	--
7. Water bodies	--	--	--	--	--	--	--	--

Table S5-3. Reclassification of constraint variables.

Data Layer	Raw value	Suitable y(1)/n(0)
Land cover	40-230	0
	11, 14, 20, 30	1
	210	2
Potato distribution	Buffer_30km	2
	1	1
	0	0
Excess salt (SQ5)	1, 4-7	0
	2 (2-4 dS/m)	1
	3 (4-8 dS/m)	2
Nutrient availability (SQ1)	2-7	0
	1	1
Nutrient retention capacity (SQ2)	2-7	0
	1	1
Rooting conditions (SQ3)	2-7	0
	1	1
Oxygen availability to roots (SQ4)	2-7	0
	1	1
Toxicities (SQ6)	2-7	0
	1	1
Workability (SQ7)	2-7	0
	1	1

Table S5-4. Labels of suitability index based on reclassifications of constraints.

Label	Necessary conditions
No data	$L_{all} = 0$
Not suitable	$L_x = 0$
Land cover constraints	$L_{LC} = 0$
Water bodies	$L_{LC} = 2$
Potato distribution constraints	$L_{LC} = 1$ and $L_{PD} = 0$
dS/m <2 or > 8	$L_{LC} = 1$, $L_{PD} = 1$, and $L_{SAL} = 0$
dS/m 2-4 (soil quality restrictions)	$L_{LC} = 1$, $L_{PD} = 1$, $L_{SALH} = 1$, and $L_x = 0$
Local area with high suitability (dS/m 2-4)	$L_{LC} = 1$, $L_{PD} = 1$, $L_{SALH} = 1$, $L_{NA} = 1$, $L_{NRC} = 1$, $L_{RC} = 1$, $L_{OAR} = 1$, $L_{TOX} = 1$, $L_{WOR} = 1$
Regional area with high suitability (dS/m 2-4)	$L_{LC} = 1$, $L_{PD} = 2$, $L_{SALH} = 1$, $L_{NA} = 1$, $L_{NRC} = 1$, $L_{RC} = 1$, $L_{OAR} = 1$, $L_{TOX} = 1$, $L_{WOR} = 1$
dS/m 4-8 (soil quality restrictions)	$L_{LC} = 1$, $L_{PD} = 1$, $L_{SALM} = 2$, and $L_x = 0$
Local area with moderate suitability (dS/m 4-8)	$L_{LC} = 1$, $L_{PD} = 1$, $L_{SALM} = 2$, $L_{NA} = 1$, $L_{NRC} = 1$, $L_{RC} = 1$, $L_{OAR} = 1$, $L_{TOX} = 1$, $L_{WOR} = 1$
Regional area with moderate suitability (dS/m 4-8)	$L_{LC} = 1$, $L_{PD} = 2$, $L_{SALM} = 2$, $L_{NA} = 1$, $L_{NRC} = 1$, $L_{RC} = 1$, $L_{OAR} = 1$, $L_{TOX} = 1$, $L_{WOR} = 1$

L_{SAL} = layer of soil salinity, L_{LC} = layer of landcover, L_{PD} = layer of potato distribution, L_{NA} = layer of nutrient availability, L_{NRC} = layer of nutrient retention capacity, L_{RC} = layer of rooting conditions, L_{OAR} = layer of oxygen availability to roots, L_{TOX} = layer of toxicities, L_{WOR} = layer of workability, L_x = any layers, L_{all} = all layers

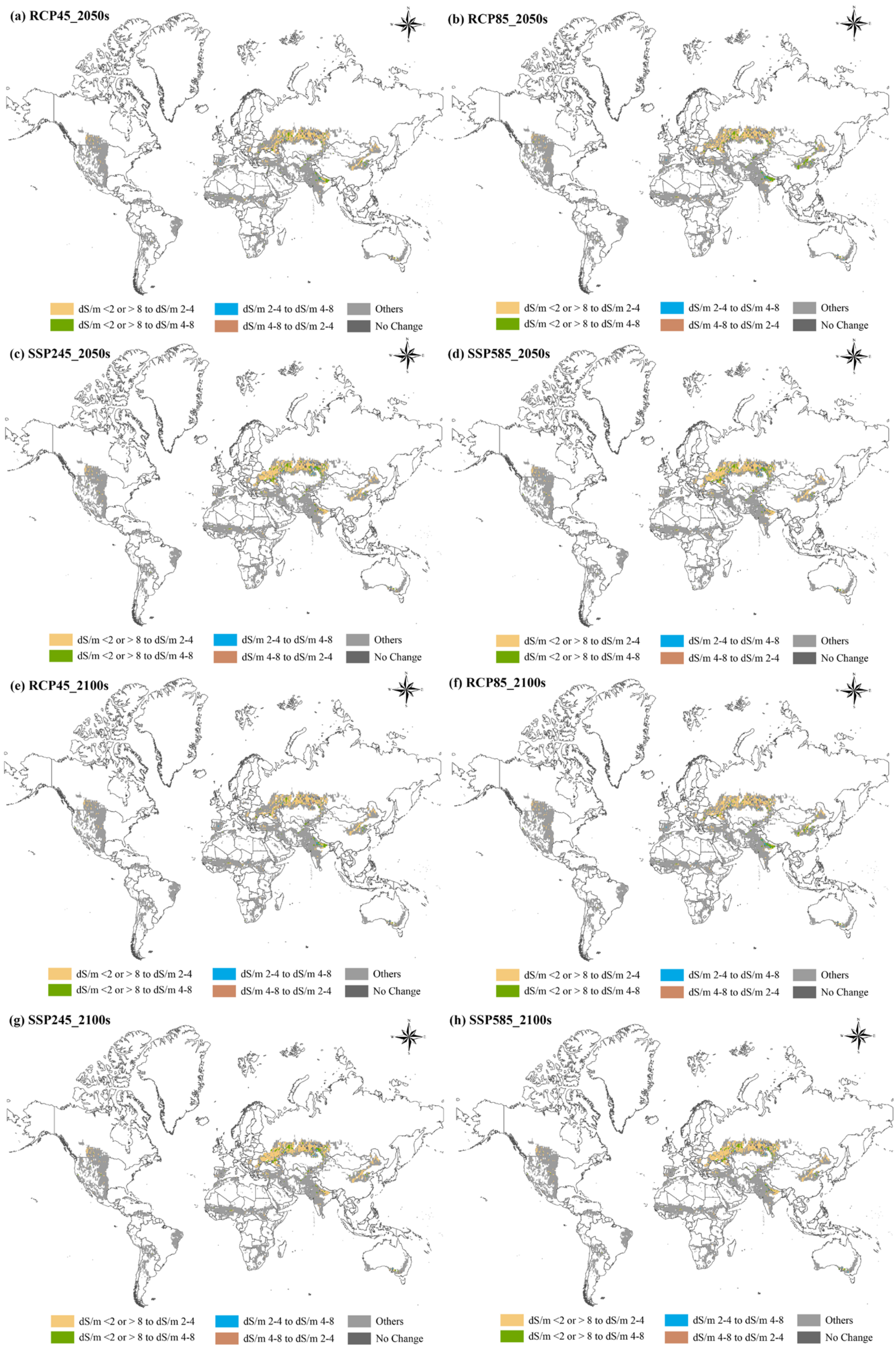

Figure S5-1. a) - d) maps of relative change in suitability in 2050 under different scenarios. e) - h) Relative change in suitability in 2100 under different scenarios.