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

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Chapter 1

General introduction

Food security is defined as a “situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life” by the Food and Agriculture Organization (FAO 2002). Food security is highly related to economic growth, human rights, poverty, society security and stability, and human health. As such, to ensure a secure and sustainable future for everyone, the United Nations (UN) has formulated sustainable development goals (SDGs) for 2030 highlighting sustainable agriculture and food security (in SDG 2) to be crucial pillars (UN 2015). However, in 2021, according to the FAO, 11.7% of the world's population experienced extreme food insecurity, and around 2.3 billion people were either moderately or severely food insecure (FAO 2022b; UN 2022). Despite the progress made from multiple perspectives towards SDG 2 (to ‘End hunger’), food insecurity, hunger, and malnutrition are still increasing in the world at the current state (FAO 2022b).

To feed 9.1 billion people in 2050, global food production needs to increase by 70% by 2050, and specifically that of developing counties to increase with 100% (FAO 2009; Tilman et al. 2011). Meanwhile, 670 million people are projected to face hunger in 2030 (FAO 2022b). The overall food demand is projected to rise by 35% to 56% by 2050 compared to the 2010 base year while simultaneously climate change is estimated to increase the challenges for food production even further (van Dijk et al. 2021). We therefore need to increase the productivity (in particular those of small-scale food producers, SDG 2.2), while ensuring “Sustainable food production and resilient agricultural practices (SDG 2.4), by “implementing resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to pending disasters (e.g., climate change, drought, flooding, and others), and that progressively improve land and soil quality”.

1.1 Threats to food production

Agricultural crops are frequently subjected to a variety of environmental stresses, which limit agricultural productivity and decrease food production. These stresses fall into two categories, namely biotic stress (i.e. disease pathogens infection, herbivores attacks, etc.) and abiotic stress (i.e., water scarcity, metal toxicities, extreme temperature, etc.) (Oshunsanya et al. 2019; Summy et al. 2020). Abiotic stress such as drought, frost, heat waves, and salinity negatively impact crop growth, crop development as well as crop quality (Audil et al. 2019). Abiotic stress was observed to be the dominant factor impacting crop productivity worldwide and is estimated to cause annually 51% - 82% of crop yield loss worldwide (Arun-Chinnappa et al. 2017; Mantri et al. 2012). Furthermore, climate change is expected to result in higher temperatures, altered rainfall patterns, and frequent extreme weather (Wheeler and von Braun 2013). These patterns were projected to increase the risk of abiotic stress (including but not limited to flood, drought, heat, etc.) regionally and globally, thus posing major constraints on food availability, access, utilization as well as stability (Lorenz and Kunstmann 2012; Rosenzweig et al. 2014; Wheeler and von Braun 2013). Therefore, it is crucial to recognize and estimate the impact of abiotic stress on food production to ensure food security.

As one of the major abiotic stresses, drought inhibits crop yield and distribution, causing substantial reductions in food production at a global scale (Eckardt et al. 2022; Madadgar et al. 2017). Over 40% of the global land area is affected by drought (Dunn et al. 2020) and it was estimated to cause \$124 billion economic loss annually worldwide (Tsegai et al. 2022). More than 2.3 billion people have experienced water stress in 2022, and approximately 160 million children have encountered severe and protracted droughts (Tsegai et al. 2022). Drought impacts three components of food security, namely availability (e.g. crop production), access (e.g. food price), and stability (sufficient access to food) both in direct and indirect ways (He et al. 2019). Over the previous four decades, droughts led to a loss in cereals production (i.e. maize, rice, and wheat) of 1820 million Mg globally (Lesk et al. 2016). Climate change is predicted to exacerbate drought frequency and severity, particularly in semi-arid regions already under severe water stress (Dai 2011, 2013). Meanwhile, there will be 700 million people in danger of being displaced by drought by 2030 (Tsegai et al. 2022). Thus, food security will be further threatened by frequent droughts in the future. Given this, there is a need to understand and evaluate drought effects on crops aiming to maintain food production.

Aside from drought, soil salinity is another major stress that negatively impacts agricultural production, particularly in the dry and semi-arid regions (El hasini et al. 2019). There are 954 million hectares (Mha) of salt-affected soil in 120 countries worldwide, leading to approximately 7% - 8% agriculture productivity loss (Meena et al. 2019; Yadav 2003). Soil salinity affects approximately 20% of the total cultivated land and 33% of the irrigated agricultural areas globally (Jamil et al. 2011; Metternicht and Zinck 2003) while the salt-affected area is predicted to expand at a rate of 1.0 - 2.0 Mha per year (ITPS and FAO 2015). With climate change in terms of changing rainfall patterns and increased temperature, water scarcity is expected to accelerate soil salinity in the near future (Eswar et al. 2021). Meanwhile, soil and groundwater salinity in arid regions and coastal regions can be exacerbated due to seawater intrusion caused by mean sea-level rise and excessive groundwater extraction (Dasgupta et al. 2015; Mukhopadhyay et al. 2021). Therefore, soil salinity urgently needs to be tackled to enable food security and a sustainable agriculture system to balance soil degradation and population expansion.

Although the impacts of drought and salinity stress on food production have been evaluated individually for a variety of crops, under natural conditions, crops normally face a combination of abiotic stresses in natural and agricultural ecosystems, such as drought and salinity, which result in greater yield loss than either stress alone (Mittler 2006). Drought and salinity interact to produce a combined effect when soil water evaporates and salt concentrations increase in the soil solution (Munns 2002). Salinity has been observed to considerably rise in rivers during hydrological droughts because of reduced river levels (Jones and van Vliet 2018; Mosley 2015). Moreover, salinity stress is expected to frequently accompany drought on cultivated land, especially in coastal, arid, and semi-arid regions (Angon et al. 2022; Corwin 2020). Thus, more frequent and severe droughts will therefore intensify the accumulation of salinization, a combination that leads to adverse impacts on food production and sustainable agricultural development.

1.2 Impact pathways of drought and salinity

Drought-induced water stress decreases crop yield by delaying crop maturation and slowing root growth, which results in less available food, especially in areas (like sub-Saharan Africa) that are heavily reliant on rain-fed agriculture (He et al. 2019). Moreover, drought directly impacts plant transpiration processes, leading to the short to long-term closure of the stomata, hampering photosynthesis and thus crop productivity (Farooq et al. 2009). In response to drought stress, plants are observed to reduce leaf area and leaf chlorophyll content, increase leaf thickness, and decrease the activities of photosynthetic enzymes (Yang et al. 2021). Due to altered plant-water interactions, CO_2 assimilation, cell membrane damage, oxidative stress, and enzyme inhibition, drought stress decreases plant growth and productivity (Kousik et al. 2022).

Salinity-induced stress negatively affects crop growth in two growth responses, namely osmotic stress and ion toxicity (Munns and Tester 2008; Shrivastava and Kumar 2015). The presence of high salt concentration in the soil solution can adversely impact the water acquisition capacity of crops. Moreover, salinity stress inhibits plant growth due to specific-ion toxicities (in particular induced by high concentrations of Na^+) and the subsequent nutritional imbalances of other cations (such as K^+ and Ca^{2+}). The co-occurrence of reduced water uptake, ion toxicity, and nutrient imbalances results in a reduction in crop yields (Shrivastava and Kumar 2015).

The combination of salinity and drought exerts an even more detrimental effect on plant growth, photosynthesis, oxidative balance, and ionic balance compared to the individual stresses alone (Angon et al. 2022). Both drought and salinity impacts on crops are highly dependent on e.g. growth stage and cultivar (Hopmans et al. 2021;

Xu et al. 2019). Indeed, numerous studies indicate the detrimental effects of combined drought and salt stress on crops (Hussain et al. 2020; Ors and Suarez 2017). However, these studies are limited to a few crop varieties and large regional uncertainties and do not consider real-life agriculture settings. Consequently, there is still a major gap in our knowledge regarding the comprehensive evaluation of the individual and collective impacts of co-occurring stresses (e.g., salinity and drought) on divergent crop varieties in real-life scenarios, especially on a large-scale.

1.3 Large-scale monitoring of food production

To improve food security, agricultural productivity around the world (and in particular of small-scale food producers) needs to double (SDG 2.3). In order to track progress along this target, it requires detailed estimations of crop yield and production. Traditionally, crop yield and production are estimated on the basis of in-season variables from field surveys in combination with crop simulation models, statistical regression models, and historical data (Basso and Liu 2019; Calvao and Pessoa 2015). However, considering their time-consuming and substantial running cost, these methods are inefficient for large-scale applications (Calvao and Pessoa 2015). Moreover, field estimates of soil salinity impacts on crops are limited by the small-scale nature of many experiments (Corwin and Scudiero 2019; Eswar et al. 2021).

There is a wide range of crop simulation models available, including DSSAT (Jones et al. 2003), EPIC (Williams et al. 1989), and WOFOST (Diepen et al. 1989). These models couple descriptions of eco-physiological processes (such as nutrient uptake, water uptake, and photosynthesis) to large-scale climate variables and management variables to estimate crop growth and crop yields. Most of these models include the impacts of water shortage on crop growth as one of their key elements. However, they are mostly unable to deliver accurate projections of the impacts of local climate variables as well as of extreme events (e.g. drought and storms) (Rauff and Bello 2015). Moreover, there exist only a few attempts to evaluate crop yield under salinity stress based on modified crop simulation models, such as CROPGRO, ORYZA v3, and APSIM-Oryza (Radanielson et al. 2018; Webber et al. 2010). Consequently, crop simulation models so far have been constrained by the simplification of the scenarios and uncertainties/availability of input parameters (Wang et al. 2013a). Finally, statistical regression models are likely unable to capture the interaction of the climate-soil-plant-management continuum in light of the increased number of extreme events with climate change, leading to inaccurate yield outcomes (Basso and Liu 2019). Hence, for large-scale applications, alternative methods are essential. Remote sensing poses a promising tool to aid in the global food security, by providing reliable information on both the extent of arable land as well as the food production on those lands.

1.3.1 Remote sensing estimation of arable land area extent

Remote sensing already is used extensively to characterize the extent and reduction of agricultural areas under productive and sustainable agriculture, using land cover maps, such as Global Land Cover (GLC) 2000, CORINE Land Cover, GlobCover 2009, GlobeLand30, etc (Radwan et al. 2021). Likewise, several more agricultural-dedicated products have been produced, including the Global irrigated area map (GIAM) at 1km resolution (Thenkabail et al. 2009), Global Rain-fed, Irrigated, and Paddy Croplands (GRIPC) map at 500m resolution in 2005 (Salmon et al. 2015), and the European Space Agency's Climate Change Initiative-Land Cover (ESA-CCI) at 300 m resolution in 2000, 2005, and 2011 (Bontemps et al. 2013), to map irrigated area and non-irrigated area at global scale (Karthikeyan et al. 2020). In addition, remote sensing can not only be used to detect agricultural areas but it can also be applied to identify different crop types. The Cropland Data Layer (CDL) products covering the Continental United States were developed each year from 2008 to 2022 at 30m resolution by integrating multiple satellite imageries including Landsat 8, Landsat 9 OLI/TIRS, the ISRO ResourceSat-2 LISS-3, and Sentinel-2 during crop growing season (Boryan et al. 2011). While such remote sensing land cover maps provide an ideal manner to monitor the extent and change of suitable arable land, they do not provide information regarding the suitability of the land for agricultural production.

In response, remote sensing has also been extensively used to estimate soil properties that affect crop growth and food production. Specifically remote soil properties, including soil minerals (e.g. clay minerals, carbonate minerals, silicate minerals), soil organic matter, soil surface roughness, and soil moisture, have been retrieved from different satellite platforms (e.g. ASTER (Nawar et al. 2015)) with high confidence (Wang et al. 2023a). This has allowed the production of various datasets (e.g. FAO soils portal, Global Soil Information System (GloSIS), Global Earth Observation System of Systems (GEOSS) portal) that provide maps of various soil properties at the regional scale to global scale (ISRIC 2023). In addition to monitoring the previous and current state of soil properties, remote sensing shows a high potential to predict soil property changes in future scenarios. Hassani et al. (2021) predicted soil salinity (ECe) under four different future scenarios in the 2050s and 2100s based on remote sensing data using Machine Learning (ML) algorithms. Hence, remote sensing does not only contribute to evaluating current food production at a large scale but also remote sensing can also be used to project future food production.

1.3.2 Remote sensing estimation of crop growth

Remote sensing also poses a promising way to monitor agricultural production on arable lands with timely, synoptic, and reliable information covering multiple spatial and temporal scales (Calvao and Pessoa 2015; Karthikeyan et al. 2020). By characterizing crop growth on these lands, satellite remote sensing (e.g. Landsat, MODIS, SPOT-Vegetation, etc.) has been used to monitor crop productivity at medium- to high- resolutions (Basso and Liu 2019). Meanwhile, with the development of cloud-computing platforms (e.g., Amazon, Microsoft AI, and Google Earth Engine (GEE)), the capabilities of crop monitoring frameworks to access and process such satellite data have also been improved (Wu et al. 2023). Crop monitoring primarily focuses on providing qualitative information on crop conditions at the desired temporal-spatial scale, which is essential for policy-making and supporting early warning systems for food security (López-Lozano and Baruth 2019). Crop biophysical characteristics are viewed as proxies for crop conditions. To monitor the growth status of crops, multispectral vegetation indices (VIs) have been established, which provide a simplified view on the morphological, physiological, and biophysical traits of crops (Wu et al. 2023).

Normalized Difference Vegetation Index (NDVI) (Tucker 1979) is the most popular VI for assessing the dynamics and health of vegetation. NDVI has been used for evaluating crop growing conditions and predicting crop yield and can be retrieved from different satellites (Basso and Liu 2019). In addition to NDVI, other VIs such as Enhanced Vegetation Index (EVI) (Liu and Huete 1995), the Perpendicular Vegetation Index (PVI) (Rondeaux et al. 1996), the Soil Adjusted Vegetation Index (SAVI) (Huete 1988), and the Green-Red Vegetation Index (GRVI) (Motohka et al. 2010), are proposed to monitor crop growth and production. However, these VIs are usually affected by uncertainties due to differences in background (e.g. soil color), crop type, crop phenology, and crop rotation. For instance, NDVI is often affected by inherent nonlinear interactions with biophysical parameters and the background's optical properties and saturates when it comes to high biomass levels (Calvao and Pessoa 2015; López-Lozano and Baruth 2019; Wu et al. 2023).

In addition, drought (impact) indicators have been developed, e.g. the Vegetation Health Index (VHI) (Kogan 1997), the Vegetation Condition Index (VCI) (Kogan 1995b), and the Normalized Difference Water Index (NDWI) anomalies (Gao 1996). However, these drought indicators have their own distinct drawbacks that restrict their utility as drought early warning signals (Liu et al. 2016). Typically, there is a lag time between the onset of a drought and the subsequent response in vegetation. This lag time poses a challenge in accurately assessing the impact of drought on vegetation (Ji and Peters 2003; Zhang et al. 2016). Likewise, vegetation indices, that are employed for monitoring crop salinity stress, are also subject to limitations in relation to background noise, the presence of halophytes, and spatial resolution (Allbed and Kumar 2013; Metternicht and Zinck 2003). As a consequence, the results obtained from different indices vary, and most applications utilizing these indicators focus on local scales and specific crop types. Thus, a method that can directly evaluate crop condition and health based on directly measured crop parameters under stress conditions is required to effectively monitor crop growth under stressed conditions using remote sensing.

1.4 Remote sensing monitoring food security under stress based on plant traits

Plant functional traits are identified as physiological, structural, biochemical, or phenological characteristics that impact plant species fitness by indirectly affecting growth, reproduction, resource use, survival, etc. (Cornelissen et al. 2003; Violle et al. 2007). Plant functional traits have been used to quantify species-specific responses and stress strategies to environmental stress (Kramp et al. 2022; Lavorel and Garnier 2002). Plant functional traits have been proposed to address plant responses to drought and salinity stress for a variety of plants. In particular, leaf water and economic traits are considered to demonstrate coordination in drought and saline environments (Anderegg et al. 2019; Kramp et al. 2022). However, most studies concentrated on the individual roles of a given trait functioning on a specific stress (Caruso et al. 2019). Given stress is frequently coupled and plant functional traits can express the tolerance of plants to various stresses (Sack and Buckley 2020), an approach that can simultaneously analyze multiple traits and multiple vegetation or crop types is required to evaluate the responses of plants to combined stresses at a large scale.

Plant traits can be estimated qualitatively or quantitatively from remote sensing data. Qualitative methods involve the utilization of classification techniques that employ a predefined set of decision rules to assign image pixels with comparable spectral properties to distinct thematic vegetation classes. Qualitative approaches employed for the interpretation of optical remote sensing data can be classified into two groups: empirical methods (e.g. VI) and physical methods (e.g. radiative transfer models (RTMs)), or a combination of both (Homolova et al. 2013). In particular, hyperspectral data has been demonstrated to have a significant ability to identify biophysical and biochemical characteristics (Serbin et al. 2015; Serbin et al. 2016). Plant traits such as leaf chlorophyll content (Cab), leaf water content (Cw), leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (FAPAR), and the fraction of vegetation cover (FVC) have been assessed with high accuracy and fidelity from remote sensing (Colombo et al. 2008; Myneni et al. 2002; Zarco-Tejada et al. 2004). Hence, remote sensing traits associated with different functioning aspects provides a foundation for a comprehensive understanding of crop conditions at a large scale.

Plant traits that can be assessed by remote sensing also show a tremendous potential for characterizing vegetative stress in different species (Gerhards et al. 2019; Vereecken et al. 2012). Berger et al. (2022) reviewed the response of plants to drought stress with optimal sensing domains for different traits. The study indicated that the responses of crops to stress with different durations can be detected by remote sensing. LAI, Cab, Cw, FVC, and FAPAR retrieved from multiply satellites (e.g., MODIS, Sentinel-2, SPOT-VGT1/2, and PROBA-V) are identified as key variables in drought or salinity impact monitoring due to their sensitivity of vegetation stress (Berger et al. 2022; Jiao et al. 2021; Richter et al. 2008; Zhang et al. 2015). Moreover, FAPAR anomalies serve as a crucial component in calculating comprehensive drought indicators: the Combined Drought Indicator (CDI) in the European Drought Observatory and the Risk of Drought Impact for Agriculture (RDrI-Agri) indicator in the Global Drought Observatory (Cammalleri et al. 2019). Although there are several studies evaluating crop response to drought and salinity stress based on remote sensing traits, these studies are limited to specific traits, crop types, and singular stress. Thus, there is still a challenge to simultaneously assess the co-occurrence stress impact on divergent crops based on traits assessed by remote sensing at a large scale.

1.5 Research aims and questions

This research aims to evaluate the impact of drought and salinity stress on agriculture and sustainable development goals using remote sensing technology. In this Ph.D. thesis, the following research questions have been addressed:

- Which remote sensing features are available to monitor crops under drought and salinity stress and what are the shortcomings of the various features? (Chapter 2)
- How can the impacts of drought and salinity stress on crop traits be evaluated simultaneously using remote sensing observations (Sentinel-2) in a quantitative way? (Chapter 3 & Chapter 4)
- How to evaluate the tolerance of diverse crops to drought and salinity stress in real-life agriculture settings by remote sensing (Sentinel-2)? (Chapter 4)
- How to utilize the salt-affected area by cultivating salt-tolerant potato to enhance global food production and secure SDG 2.4? (Chapter 5)

1.6 Thesis outline

First, I illustrated an overview of food security and its associated threats, emphasizing the potential of remotely sensed plant functional traits to monitor crop responses under drought and salinity stress at large scale (Chapter 1). A systematic review was conducted to evaluate the current capacity of remote sensing to detect the impact of drought and salinity stress on crops based on vegetation indices (VIs) and plant traits (Chapter 2). Based on multiple plant traits retrieved from remote sensing observations, I developed a novel approach to estimate the impacts of drought, salinity, and their combination on crop growth in the Netherlands (Chapter 3). Next, I upscaled this approach to assess the tolerance of eight crops to drought, salinity, and their combination based on five functional traits across the entire U.S. continent throughout the crop growing season from remote sensing (Chapter 4). Then, I quantified the viability and potential of enhancing food production and achieving SDG 2 by planting salt-tolerant potato in salt-affected areas in present and future scenarios (Chapter 5). Finally, the challenges and implications of remote sensing in agricultural applications for a sustainable future were discussed based on the principal findings of this thesis (Chapter 6). Figure 1.1 shows the conceptual scheme of this thesis.

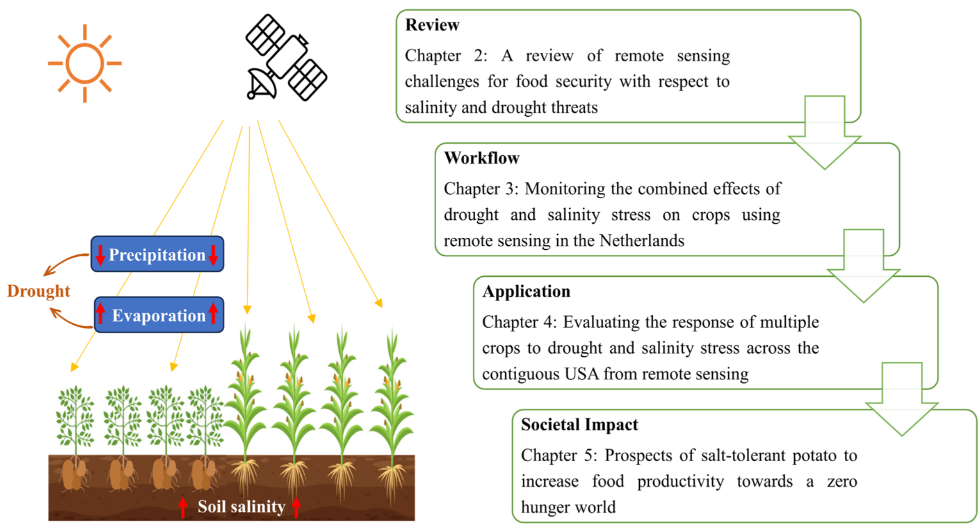

Figure 1.1 Conceptual scheme of the topics of Chapters 2, 3, 4, and 5.

Chapter 1: General introduction

This chapter provides a general introduction on food security and threats (particularly due to abiotic stress) for food security. Then, the chapter illustrates the high potential of remote sensing technologies in monitoring food production at a large scale by their capacity to map land cover, detect soil properties, and monitor vegetation properties both in the present and the future. In addition, this chapter highlights the significance of remotely sensed plant functional traits to monitor crop responses under drought and salinity stress in real-life scenarios for large-scale applications. The research aims, questions, and individual chapters of this thesis are outlined.

Chapter 2: A review of remote sensing challenges for food security with respect to salinity and drought threats

This chapter presents a systematic review on the current ability of remote sensing to identify and assess the impacts of drought and salinity stress on agricultural crops through vegetation indices and plant traits. We found that there are still several challenges remaining for using remote sensing to monitor drought and salinity stress impacts on crop growth. VIs do not provide consistently accurate estimation of these impacts while plant traits are promising to directly link to the biochemical/biophysical pathway of crop growth, thereby reflecting the stress response mechanisms.

Chapter 3: Monitoring the combined effects of drought and salinity stress on crops using remote sensing in the Netherlands

In this chapter, a novel approach is presented to evaluate the impacts of drought, salinity, and their combination on five crop traits, including leaf area index (LAI), leaf chlorophyll content (Cab), leaf water content (Cw), the fraction of absorbed photosynthetically active radiation (FAPAR) and the fraction of vegetation cover (FVC) using remote sensing in the Netherlands. The separate and combined effects of drought and salinity stress on five traits were quantitatively assessed. The results indicate that the exacerbating effects of co-occurring drought and salinity stress highly depended on the moment in the growing season. Moreover, LAI, FAPAR, and FVC impact most under severe drought conditions for maize and potato while Cab and Cw are generally more inhibited by combined drought and salinity stress. As a result, the proposed approach provides a way to simultaneously assess the impact of drought and salinity stress on crops from remote sensing with possible large-scale applications.

Chapter 4: Evaluating crop-specific responses to drought and salinity stress from remote sensing

Food security is facing a significant challenge by co-occurring stresses (e.g., salinity and drought) under global climate change. Extreme weather events are projected to become more frequent, impacting crop performance and reducing crop yields under these adverse conditions. Complementary to existing field trials of controlled small-scale experiments, this chapter assesses the responses of various crops to the occurrence of drought and salinity stress, alone and collectively across the entire U.S. continent in real-life agricultural conditions, using five traits representative of different plant functions by remote sensing. The results show the differential responses of crops to these stresses. Stress impacts were highly time-dependent, and crops were more susceptible to combined drought and salinity than to individual stresses, although stress impacts varied significantly between species and over time. Prior to decreasing their water or chlorophyll levels, most crops initially decreased primary production capability by decreasing LAI. This chapter creates a quantitative foundation to inform sustainable food production, aiding in monitoring food security upon global climate change.

Chapter 5: Prospects of salt-tolerant potato to increase food productivity towards a zero hunger world

Food security and sustainable agriculture are crucial elements of achieving the SDGs, but global climate change is threatening them increasingly. This chapter estimates the local suitability and the regional suitability areas for salt-tolerant potato cultivation in salt-affected soils to allow for achieving SDGs in current and future scenarios. The results reveal that Oceania (particularly Australia) has the greatest potential for enhancing food production through salt-tolerant potato cultivation in salt-affected soils. In addition, Kazakhstan, the Russian Federation, and Australia can address food shortage challenges and achieve sustainable development goals in the current state as well as in future scenarios. In this chapter, salt-tolerant potatoes are evaluated as a proxy for saline farming, allowing for increased food production in salt-affected areas and laying the groundwork for promoting saline farming practices to enhance agricultural resilience and ensure food security.

Chapter 6: General discussion

This chapter synthesizes the principal findings with a discussion on the limitations and prospects of this thesis. It emphasizes the potential and feasibility of monitoring food security by trait-based evaluation although there are still a few challenges remaining in agricultural applications from remote sensing. In addition, this chapter elaborates on the implications of remote sensing for securing sustainable goals at a global scale, both in the current state as well as in the future.