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

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Chapter 6

General discussion

Food security is projected to be challenged by the increasing co-occurrence of stresses with global climate change. Of these stresses drought and salinity are considered to be the main constraints for food production by their impacts on crop growth. Large-scale monitoring and quantification of the individual and combined impacts of drought and salinity stress on crop growth give rise to significant challenges related to spatial-temporal variability, data integration, crop variability, etc. Remote sensing offers potential solutions through detailed and timely detection of crop health. In this thesis, I evaluated the impact of drought and salinity stress on agriculture and sustainable development goals using remote sensing technology. Specifically, I assessed (i) which remote sensing features are available to monitor crops under drought and salinity stress, (ii) how drought and salinity stress on crop traits can be evaluated using remote sensing observations, (iii) what the tolerance of diverse crops in respect to drought and salinity stress was in real-life agriculture settings, and (iv) where cultivating salt-tolerant potato could be introduced to enhance global food production and secure. This chapter aims to synthesize the main findings of these research questions and provide a comprehensive discussion on the limitations and prospects for future studies, and implications to achieve sustainable development goals. Our insights can be used to enhance crop management and hence food security.

To answer the research question, I first reviewed the current capacity of remote sensing to detect the impacts of drought and salinity stress on crops based on the use of vegetation indices (VIs) and plant traits (Chapter 2). Next, a novel approach that utilized multiple plant traits derived from remote sensing data was used to estimate the effects of drought, salinity, and their combination on crop growth in the Netherlands (Chapter 3). Based on the approach developed in Chapter 3, the tolerance of eight different crops to drought, salinity, and their combined stress was assessed across the entire U.S. continent throughout the crop growing season from sentinel-2 observations (Chapter 4). Finally, to answer where the biggest opportunity exists (with respect to achieving Sustainable Development Goal 2), I quantified the potential of enhancing food production by cultivating salt-tolerant potato species in salt-affected areas under present and future scenarios (Chapter 5).

The findings of this thesis highlight the potential of remote sensing-derived traits for evaluating crop growth under stress conditions (explored in more detail in section 6.1). Through a systematic review, positive correlations were identified between specific plant traits and stress response mechanisms, indicating the potential of plant traits as indicators (Chapter 2). However, the spectral signals related to drought and salinity stress exhibited inconsistencies across various crop traits due to variations in growth stage, soil properties, stress severity and duration, and environmental conditions. In response, a novel workflow that integrates multiple traits derived from remote sensing was developed to evaluate the real-life impacts of drought, salinity, and their combined influence on crop growth in the Netherlands (Chapter 3). By employing a pair-wise method within this workflow, I quantified the stress impacts over a select range of crops and growth conditions. Afterwards, I upscaled this workflow to cover a wider range of crops and spatial conditions and applied it across the entire U.S. continent throughout the crop growing season in 2021 (Chapter 4). In this analysis, I found stress impacts to be significantly dependent on the specific moment in the growing season, with crops are generally more sensitive to the combined effects of salinity and drought stress compared to the singular stress (Chapter 3 & Chapter 4). Nevertheless, the observed stress impacts showed significant variations over time and among different crop species. Notably, most crops experienced an initial reduction in primary production capacity through a decrease in Leaf Area Index (LAI) before experiencing reductions in water or chlorophyll contents (Chapter 4). Finally, we assessed how the above-mentioned information could be used in combating food insecurity by identifying areas where salt-tolerant crops (i.e., potato) could be cultivated. Out of six continents, Oceania was found to exhibit the greatest potential for enhancing food production through better utilization of the salt-affected area (Chapter 5). In addition, Kazakhstan, the Russian Federation, Australia, Iraq, and Lesotho also show a potential to address their food shortage challenges and achieve sustainable development goals by cultivating salt-tolerant potatoes. Furthermore, under various future scenarios, the local suitability area for salt-tolerant potato consistently expanded, with Kazakhstan, the Russian Federation, Ukraine, Hungary, and Romania emerging as crucial countries to enhance food production and accomplish SDG targets. In combination, the thesis shows from review to application how remote sensing techniques may be applied to detect stress responses and mitigate the impacts of those stresses on global crop production.

Despite proving the potential to detect stress responses of crops with functional traits by remote sensing, I found that the effectiveness of such monitoring varied across different plant species and growth stages (Chapter 2, Chapter 3, and Chapter 4). Consequently, there are several challenges left open that need to be addressed in future studies. One such challenge is the need for a better understanding of representative traits that can accurately reflect specific stress conditions at specific moments during the growing season (Chapter 2, Chapter 3, and Chapter 4). This challenge will be explained in more detail in section 6.1. Moreover, current remote sensing for agricultural applications still faces challenges regarding spatial-temporal resolutions and integration of multi-platform data. These limitations and the prospects to deal with them will be treated in section 6.2. Remote sensing is promising to effectively monitor the achievement of SDGs and ensure food security on a global scale, involving different stakeholders and policymakers (Chapter 5). My suggestion to implement these societal implications is treated in section 6.3. Overall, this comprehensive investigation explored various aspects of remote sensing-based monitoring of crop responses to stress, offering valuable insights into the viability of using remote sensing for improving food security and addressing sustainable development goals.

6.1 Open challenges regarding the Trait-based evaluation method

Plant functional traits are associated with various adaptation pathways to the environment, as they indicate a set of plant features that represent strategies for a variety of stress conditions (Andrew et al. 2022). Thus, plant functional traits allow us to quantify the extent of the adaptation to various environmental pressures (i.e., drought and salinity stress). Connecting vegetation function (including primary production) with environmental stress by trait-based evaluation methods has shown to provide significant promises (Zakharova et al. 2019). Functional traits are intimately linked to stress tolerance, carbon storage, water regulation, and climate regulation (Lavorel and Grigulis 2012). Thus, functional trait-based research plays a pivotal role in comprehending the structure and function of agroecosystems including crop productivity, agroecosystem dynamics, non-crop biodiversity, other biogeochemical cycles, and crop vulnerability to climate change (Martin et al. 2015). However, large-scale research on functional traits across a wide variety of crops remains quite limited. For instance, leaf economics trait information is unavailable for over 70% of the important agricultural species in the TRY database (Martin et al. 2015).

Even though trait-based methods show promising potential to evaluate stress impacts on plants, it remains challenging to identify a proper selection of appropriate traits that detect specific signals for different stresses (Griffin-Nolan et al. 2018). Specifically, diverse stresses may manifest similar symptoms in plants (He et al. 2020), while different plant strategies (to resist these stresses) might lead to different expressions of functional traits (even for the same stress). According to Chaves et al. (2009), most plant species tend to lower transpiration and avoid more severe stress by decreasing their leaf area both for drought and salinity stress. Functional traits such as specific leaf area (SLA), leaf dry matter content (LDMC), leaf area (LA), turgor loss point (TLP), relative water content (RWC), leaf chlorophyll content (Cab) are essential for plant drought tolerance (Kramp et al. 2022; Mwamahonje et al. 2021). Meanwhile, most of these traits are used to evaluate salinity stress impacts as well (Zhou et al. 2021). In addition, it was reported that any abiotic stress decreases leaf size (El-Moneim et al. 2020). Likewise, there is no significant difference in the expression of traits for drought vs. salinity in our study (Chapter 2, Chapter 3, and Chapter 4).

Salinity (in the first growing phase) affects plants in a comparable way as droughts, namely through water stress/osmotic stress. Therefore, additional traits are required to make these distinctions. For example, salinity also has clear impacts with regard to toxic stress/ion stress (Munns 2002). Thus, the traits related to toxic stress tolerance may provide a breakthrough to distinguish salinity stress from drought stress. In melon plants, the levels of phenylalanine, histidine, proline, and the Na^+/K^+ ratio emerge as key distinguishing traits for salinity tolerance (Chevilly et al. 2021). Moreover, the Na^+/K^+ ratio is one of the most important traits in controlling salinity tolerance in rice (Kanawapee et al. 2012) while Na^+/K^+ was not significantly affected in wheat (Garcia et al. 1997; Pires et al. 2015). In addition, physiological traits related to chlorophyll fluorescence might be another option to distinguish drought and salinity stress impacts, as these stresses are found to have varying effects on photosynthetic performance (Lazarevic et al. 2021). Meanwhile, Lazarevic et al. (2021) pointed out that the plant growth stage during which the stress impacts the plant is another factor that needs to be taken into account when choosing a set of traits to differentiate plant tolerance mechanisms between drought and salinity stress. Likewise, the impact of drought and salinity on crop traits is found to be highly dependent on the moment in the growing season (Chapter 3 & Chapter 4). Moreover, although LAI, FAPAR, and FVC exhibit comparable patterns in response to drought and salinity stress, Cab and Cw appear to have distinct patterns from other traits (Chapter 3 & Chapter 4). Thus, distinct traits representing different stress strategies are varied in species, between stress strengths as well as between growth stages.

Given trait multifunctionality, traits may not line up with environmental gradients as expected when only taking the tolerance of individual stress into account (Sack and Buckley 2020). Indeed, plant stresses frequently occur in combination, and thus a functional trait confers tolerances to multiple stresses simultaneously. In general, co-occurrence stresses (e.g. salinity and drought stress) exert a more pronounced negative impact on plant growth (Chapter 3 & Chapter 4), photosynthesis, ionic balance, and oxidative balance, compared to the effects of either stress alone (Angon et al. 2022). However, it is important to note that in certain cases, salinity may have a more pronounced negative effect than drought stress, while in other instances, drought stress may outweigh the impact of salinity (Angon et al. 2022; Ibrahim et al. 2019; Zhou et al. 2021). In addition, Sack and Buckley (2020) indicated that the relative importance of multifunctional traits is highly contingent on the environmental context such as stress levels and their interactions under the co-occurrence stress environment. LAI, FAPAR, and FVC exhibited the most significant reductions under severe drought stress conditions for both maize and potato crops, underscoring their heightened sensitivity to drought compared to salinity (Chapter 3). Moreover, the interaction effects of stress (e.g., drought and salinity) and environmental factors (e.g., soil type and climate zone) were significant in many cases (Chapter 4), indicating that the severity of stress and its impact on crops were affected by diverse environmental conditions. Therefore, when assessing plant tolerance to co-occurrence stress using a traits-based approach, it is important to consider a number of variables, including the plant species, the severity and duration of each stress, and the specific physiological responses of the plant to the combined stress conditions.

Network theory presents an effective approach toward resolving the relationships among multiple plant traits and their significance (He et al. 2020). The concept of plant traits networks (PTNs) provides a multidimensional framework for comprehensively evaluating the responses of plants across diverse lineages, life forms, ontogenetic stages, and environmental conditions (He et al. 2020). In plant trait networks, certain economic traits were found more important than other traits. Particularly in dryland ecosystems, where nutrients and water are scarce, plants prioritize those links between their economic traits that increase the effectiveness of storing carbon and nitrogen and thus enhance their resilience against shortages and their competitiveness (Wang et al. 2023b; Wilcox et al. 2021). However, this is not valid for all conditions. For example, herbaceous plants emphasize the connections between structural traits to increase leaf structural resilience and to lessen physical damage from drought, whereas woody plants favor connections between economic traits to resist drought stress (Wang et al. 2023b). Although various studies have analyzed the key traits for plant functioning based on PTNs, the application to agriculture systems is still unclear and there is no comprehensive framework established to quantify the relative significance of each trait function under co-occurrence stress environmental circumstances. Even so, our results on multiple crops suggest that these herbaceous crops exhibit a prioritization of reducing their structural traits including LAI, FAPAR, and FVC, before undergoing reductions in water or chlorophyll contents (Chapter 4). This demonstrates leaf water content and leaf chlorophyll content are considered to be key traits for agricultural crops to maintain crop health and resilience to drought and salinity stress at an early stage.

Overall, the trait-based method has proven to be a promising way to evaluate plant tolerances to diverse stresses. Hence there is a great opportunity for creating a system that can monitor crops in real-time across a wide variety of crops at various scales (local, regional, national, and global). This system requires however a spatial and temporal resolution that is presently not offered by traditional monitoring platforms. To address this need, the integration of remote sensing technologies, such as satellites, offers a compelling solution to extend the implementation of trait-based methods in agriculture. By leveraging remote sensing capabilities, timely and comprehensive monitoring of agricultural systems can be achieved, enabling a more effective and efficient evaluation of crop responses to stresses on a broader spatial and temporal scale.

6.2 Prospects of remote sensing for agricultural applications

Remote sensing has become increasingly relevant in the field of sustainable agriculture and emerged to improve food security in developing countries with its global coverage characteristics (Berger et al. 2022). With enhanced spatial, temporal, and spectral capacities based on various launched platforms and sensors, remote sensing studies, focused on agricultural applications, have increased significantly (Weiss et al. 2020). Although remote sensing technologies show significant advantages compared to traditional methods, there are constraints that remain to limit their application in agriculture.

High-resolution maps for stresses and crops are still not fully available at a global extent. While high-resolution stress maps (e.g. drought and salinity) have been generated using remote sensing observations, they focus mostly on regional or continental extents. For example, Aadhar and Mishra (2017) created a drought map for South Asia based on the Standardized precipitation index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). AghaKouchak et al. (2015) reviewed the progress of monitoring drought using satellite remote sensing observations, highlighting the limitations including data continuity, unquantified uncertainty, sensor changes, community acceptability, and data maintenance in drought monitoring by current satellite missions for the application at different regions. And while specific countries have developed their local-scale programs to track crop systems, such as the Netherlands (Key Register of Parcels (BRP), https://www.pdok.nl/introductie/-/article/basisregistratie-gewaspercelen-brp-) (as used in Chapter 3) and the United States (Cropland Data Layer program (CDL), https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php) (as used in Chapter 4), similar maps at different locations are not widely accessible. This significantly limits the monitoring of crop performance under salinity and drought stress, and the quantification of food security in developing countries. To address this issue, high-resolution crop maps need to be created. Compared with other maps (e.g., stress map, landcover map, etc.), crop mapping asks for higher spatial resolution (e.g., 10m ~ 30m) considering the diversity of crop types and fragmented cultivation plots. Although there is a program Global Agricultural Monitoring Initiative-Best Available Crop Specific Masks (GEOGLAM-BACS) that generates crop type map at 0.05 degree on a global scale, it only contains four main crop types (wheat, maize, rice, and soybeans) and have certain limitations (Becker-Reshef et al. 2023). Additionally, differences in phenology, cultivation practices, cloud cover, and weather across different regions pose challenges to the quality and quantity of satellite images for crop mapping (Wu et al. 2023). As new-generation satellite spectrometers (e.g. HysIRI spectrometer) characterized by high spatial resolution (8-30 m) and spectral resolution (~10 nm) are being launched, future applications in precision farming and environmental monitoring are promising to be enhanced in the coming years (Lassalle 2021). With such crop maps, coupled with (remote sensing derived) maps of environmental stresses, approaches such as those developed in this thesis may be further refined and globally applied.

Remote sensed traits show potential for evaluating crop responses to stress. Various trait retrieval methods have been investigated to detect plant responses to stress by optical remote sensing observations (Verrelst et al. 2015). Most approaches are developed based on parametric regressions, specifically employing spectral bands, vegetation indices (VIs), and spectral ratios to establish correlations with functional traits associated with plant stress (Berger et al. 2022). However, the number of traits that can be directly retrieved from remote sensing imagery is limited. For instance, osmotic traits were found to be promising to detect drought and salinity stress, but so far neither parametric approaches nor physically based methods (i.e., radiative transfer models (RTMs)) have been able to retrieve these traits with remote sensing. Instead, in our approach we relied on traits that could be quantified by RTMs. PROSAIL is a well-known RTM that integrates a leaf optical properties model (PROSPECT) (Jacquemoud and Baret 1990) and a canopy bidirectional reflectance model (SAIL) (Verhoef 1984). PROSAIL has been widely to estimate canopy biophysical, and structural traits in agriculture at different scales (Chaabouni et al. 2021). For future research, it would be interesting to evaluate whether additional traits such as osmotic traits may be derived from RTMs. Additionally, it becomes possible to retrieve biochemical traits based on a modified RTM. For instance, Zhu et al. (2014) developed a modified PROSPECT model integrating the specific absorption coefficient of the copper ion to retrieve copper ion traits. Therefore, by integrating RTMs with local experimental results of indirect traits' optical properties, it is projected to be more effective in retrieving stress-related traits. With the launch of multi-sensor satellites (e.g. Sentinel-2) with a short revisit period, the spatial-temporal resolution has been enhanced. This thesis evaluates crop response to stress only based on satellite remote sensing (Chapter 3 & Chapter 4). Apart from satellite remote sensing, other remote sensing technologies including microwave data and unmanned aerial vehicles (UAVs) play a crucial role in providing valuable insights for agricultural applications. Active microwave radiometers have predominantly been employed for the characterization of various biophysical traits, water content, leaf area index (LAI), vegetation height, aboveground biomass, crop type mapping, and monitoring crop growth (Vereecken et al. 2012). Meanwhile, UAV-based remote sensing (UAV-RS) shows high potential to complement and validate satellite remote sensing thanks to its high spatial resolution and high frequency, and economical friendly (Wang et al. 2023a). Zhou et al. (2020) quantified soybean traits under drought stress based on UAV imagery to identify drought tolerance genotypes.

Another new development involves the integration of remote sensing data from multiple platforms and sensors. Through this integration, a more comprehensive and detailed understanding of the intricate interaction of stress combinations and affected crop traits can be obtained (Berger et al. 2022). The synergistic utilization of optical and microwave data enables the detection of more accurate and additional land surface properties and traits. Also, microwave observations can be interpreted and corrected using optical data and the resulting parameters (Vereecken et al. 2012). Numerous approaches have been proposed to integrate remote sensing data from multiple platforms, encompassing microwave data (both active and passive), as well as optical data spanning from visible, near-infrared, and thermal spectra (Vereecken et al. 2012). However, there are several factors that need to be considered for this integrated framework application. Data collected from various sensors for the same location often exhibit redundancy. This redundancy arises from the distinct characteristics and physical diffusion mechanisms inherent in different sensors (Le Hegarat-Mascle et al. 2000; Li et al. 2021). As a result, multiple sensors may capture similar or overlapping information, leading to a significant amount of time consumption to fuse remote sensing data. This time-consuming process can potentially limit the efficiency of data analysis and interpretation. Moreover, the integration framework involves data from various platforms/sensors, each with distinct spatial and spectral resolutions, acquisition frequencies, and calibration procedures. This heterogeneity necessitates meticulous data preprocessing and calibration to ensure compatibility and consistency during integration (Mura et al. 2015).

In addition, by combining remote sensing data with artificial intelligence techniques like Machine Learning (ML), it is possible to identify and predict crop trait changes with stress. Lassalle (2021) reviewed six categories of machine learning algorithms including Partial Least Square Regression (PLSR), Random Forest (RF), Linear or Quadratic Discriminant Analysis (LDA/QDA), Support Vector Machines (SVM), Neural Networks (NNs), and Elastic net (ENET) regression. These algorithms were utilized to monitor plant stress using hyperspectral remote sensing. Ion traits including Na^+, Cl^-, K^+, and Ca^{2+} concertation were determined for wheat with salinity stress by employing PLSR on canopy reflectance data (El-Hendawy et al. 2019b). ML has demonstrated a strong performance in detecting crop stress signals at an early stage using hyperspectral data (Zarco-Tejada et al. 2018). These algorithms have also shown their relevance in distinguishing between different stresses that have similar effects on plant reflectance (Lassalle et al. 2019). Furthermore, certain machine learning algorithms are capable of handling nonlinear relationships between stress intensity and the spectral response of plants, thus providing new opportunities for quantitative monitoring (Lassalle 2021). Finally, the integration of ML and RTM has shown promise in accurately and rapidly mapping crop traits across extensively cultivated regions (Danner et al. 2021). This way, this combination of techniques highlights the potential to quantity and monitor stress-related crop traits at the global scale (Berger et al. 2022; Verrelst et al. 2019).

Finally, combining crop growth models with remote sensed traits enables timely and accurately predict stress impact on food security in crop production. Crop growth models simulate the relationship between crop physiological processes and the environment, aiming to assess the potential impacts of climate change on crop growth and yield in different regions (Kasampalis et al. 2018). Gaining early insights into the impacts of extreme weather events on crops can assist farmers and decision-makers in minimizing risks and enhancing food security. However, current crop growth models have certain limitations. They lack spatial scale information and suffer from the absence or inaccuracy of relevant data such as soil conditions and weather parameters (Kasampalis et al. 2018; Palosuo et al. 2011; Wallach et al. 2006). To enhance yield predictions by crop models, remote sensing technology can provide the missing spatial information required by crop growth models. Variables in the crop growth model can be replaced or adjusted using remote sensing data through data assimilation (Maas 1988). A review conducted by Jin et al. (2018) highlighted the capability of assimilating remote sensing data to enhance the accuracy of predictions and estimations in crop growth models, ultimately leading to improved understanding and management of agricultural systems. Hence, more accurate predictions of crop growth and yield may in the future be achieved by integrating remote sensing data with crop models, thereby improving agricultural production and ensuring food security.

6.3 Implications to sustainability goals

Remote sensing can significantly contribute to achieving the Sustainable Development Goals (SDGs) by providing data to track the progress of key indicators and assess policy efficiency. Specifically, three major gaps in SDGs indicators are expected to be filled by integrating remote sensing data, including environmental indicators, multi-resolution spatial indicators, and indicators coupling environmental and societal or economic data (Cochran et al. 2020; Griggs et al. 2014; Scott and Rajabifard 2017). With respect to securing SDG 2 (zero hunger), remote sensing earth observations can strengthen the monitoring of food security by providing crop growth models with timely input variables to better predict crop production. Already several international monitoring systems, such as the GEOGLAM, have been developed to track crop growth and evaluate the progress toward achieving SDG 2(Singh Parihar et al. 2012). The GEOGLAM Crop Monitor provides monthly assessments of crop conditions for wheat, maize, rice, and soybeans in 49 countries (Anderson et al. 2017), and thereby creates the ability to use its products within SDG indicators (e.g. target 2.C) (Anderson et al. 2017; Whitcraft et al. 2019). In addition, the Crop Monitor for Early Warning

(CM4EM) within GEOGLAM monitors the risk of food insecurity in over 80 countries, and serves as an early warning tool for agriculture monitoring, enhancing resilience to climate-related extreme events (Becker-Reshef et al. 2020). Through this, CM4EM is possible to detect crop growth in a drought-stressed environment and provide timely updates on food production challenges (Becker-Reshef et al. 2020). This way, CM4EM contributes towards not only SDG 2 (target 2.1), but also SDG 1(target 1.5), SDG 3 (target 3.D), and SDG 13 (target 13.3) (Becker-Reshef et al. 2020). However, these international monitoring systems focus solely on droughts without incorporating the effects of salinity. Co-occurring drought and salinity give rise to a more pronounced -inhibitory- impact on crop growth (Chapter 3 & Chapter 4) than their individual impacts. Given the increasing possibility of co-occurring drought and salinity stress with climate change, there is a compelling need to take these co-occurring stresses into account and enhance our understanding of crop monitoring on a global scale. By integrating the evaluation of salinity impact on crops with the current GEOGLAM framework, it provides crucial open-source benefits to diverse stakeholders engaged in agricultural research, policy, and practice. Notably, in arid and semi-arid regions where water scarcity and soil salinization pose formidable barriers to sustainable crop production, leveraging the GEOGLAM program with the integration of salinity evaluation can prove instrumental in developing targeted strategies for resilient agriculture.

As part of the SDGs, improving agricultural resilience and food production within limited arable land under global climate change is a significant challenge to addressing food security. In this regard, saline agriculture poses a promising future to enhance the utilization of salt-affected areas. Specifically, saline agriculture is considered to significantly contribute to achieving several SDGs, including food security (SDG 2), freshwater resources utilization (SDG 6), sustainable livelihoods (SDG 8), climate change adaption (SDG 13), and life on Land (SDG15) (Negacz et al. 2021; Singh 2021). The most promising areas for saline agriculture are Africa, the Middle East, Central Asia, the United States, and Australia (Negacz et al. 2022). Additionally, Kazakhstan, the Russian Federation, Australia, Iraq, and Lesotho exhibit significant potential to address their food shortage challenges and work towards achieving sustainable development goals through the cultivation of salt-tolerant potatoes (Chapter 5). Given these regions with different soil properties, climate conditions, and water availability, salt-tolerant variates of major crops (e.g. potato) in addition to halophytes (e.g. Salicornia europaea) are accessible options for broader application at the global scale, particularly for developing countries (Chapter 5). However, given the high frequency of co-occurrent stress (e.g. salinity and drought), saline agriculture needs to further take the risk of co-occurring impacts (e.g., with drought) into account. Therefore, this asks for understanding and managing the combined effects of stress on crop productivity, soil health, water availability, and overall system resilience to ensure sustainable and effective agricultural practices in saline environments. With the impact of climate change, there will be an expansion of suitable areas for saline farming in response to the increase in salinity. Salt-tolerant potato, as a part of saline farming, is proven 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 (Chapter 5). By quantifying the contribution of saline farming to sustainable development in the face of impending climate change threats on a global scale, it provides valuable insights into optimizing the utilization of salt-affected soils. Consequently, it establishes a foundation for the promotion and widespread implementation of saline farming practices, bolstering food security and fortifying agricultural resilience at the global scale.

6.4 Concluding remarks

Remote sensing has shown promise in monitoring crop growth and health using vegetation indices (VIs) and plant functional traits, although the results may vary depending on spectral wavelengths and stress intensity. Plant functional traits derived from remote sensing data can serve as proxies for monitoring the effects of drought and salinity stress on crop health, as they align closely with vegetation processes. A novel approach was developed to quantify the impact of drought, salinity, and their combination on multiple crops at a large scale using remote sensing traits. The impact of stress varies across species, growth stages, and stress conditions. The interaction between drought and salinity stress is complex, and their combined effect generally exacerbates the impact on crops compared to individual stress. Most crops tend to reduce their primary production capacity before experiencing reductions in water and chlorophyll content. In order to mitigate the impact of salinity on crop productivity and improve food production, salt-tolerant potato -as a proxy of saline agriculture-, can contribute to enhancing the use of salt-affected areas and support the achievement of SDG2. This thesis provides a promising perspective on the application of remote sensing in agriculture systems to monitor food production with stress and improve agricultural resilience.