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

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Chapter 4

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

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Abstract

Food security is projected to be threatened by increasing co-occurring stresses (e.g., drought and salinity) under global climate change. To mitigate major impacts on food production, the tolerances and vulnerabilities of crops to these threats need to be characterized. The aim of this research is to assess the tolerances of crops to the combination of drought and salinity stress across plant functions under real-life settings. Using five traits, we evaluated the impacts of drought and salinity tolerance on a multitude of crops throughout the United States. We assessed the dominant stress as well as the onset of combined and individual effects of drought and salinity from March to October. We indeed observed that stress impacts strongly depended on time. In addition, we observed that crops were more sensitive to combined salinity and drought than to individual stresses, although stress impacts significantly varied between time and species. Of the individual traits, LAI was triggered first by stresses, followed by FVC and FAPAR, and Cw and Cab were the last to respond to stresses. In comparison to other species, almond demonstrated greater resilience to combined drought and salinity, whereas soybean and maize were more drought tolerant. In combination, our study provides a way of assessing the tolerance of various crops to co-occurrent stresses both independently and in combination. By allowing applications to other co-occurring stresses and vegetation types, our approach creates a quantitative foundation to inform sustainable food production.

4.1 Introduction

Crops are continuously exposed to a variety of abiotic stresses. Extreme occurrences including floods, droughts, and heat waves are forecasted to increase as a result of global climate change (Wang et al. 2022). These occurrences not only directly lower agricultural yield but also increase the susceptibility of crop production to future events (Zscheischler et al. 2018). Salinity and drought are two major factors that constrain crop yield and are expected to increase in frequency. By 2050, salinity is expected to affect half of the arable land, most of which is on dry or semi-arid land (Angon et al. 2022). More frequent droughts will further increase yield loss risk in the future, with rice, soybeans, wheat, and maize being particularly vulnerable (Leng and Hall 2019). Therefore, food security is expected to be more threatened by the co-occurrence of stress (i.e. salinity and drought) under global climate change. Although singular stress impacts on crops have been extensively studied, co-occurrence stress impacts are still considered challenging due to their complexity (Mehrabi et al. 2022). Thus, to mitigate major impacts on food production, the tolerances and vulnerabilities of crops to these threats need to be characterized.

Traditionally, the tolerance of crops is estimated for a limited number of crop types in highly controlled small-scale experiments. Maas and Grattan (1999) published a list of salt tolerance of 81 crops based on the electrical conductivity of the saturated paste (EC_e) under simulated conditions. However, there is evidence showing that the tolerance of some crops to salinity had been underestimated in such conditions (van Straten et al. 2021). Apart from isolated drought or salinity stress, several studies evaluated the tolerance of combined drought and salinity stress of various crops. In contrast, in wheat, the combination of mild salinity and drought stress was found to cause a stronger inhibition of wheat yield compared with singular stress (Paul et al. 2019). However, in these pot experiments, there was a large difference among various wheat cultivars concerning their tolerance to combined drought and salinity stress (Paul et al. 2019). Suarez et al. (2019) estimated the salt tolerance of grape rootstock in a simulated water stress environment for four years. They came to the conclusion that it was difficult to forecast the combined impacts of salinity and water stress based on the quantification of isolated effects of salinity or water stress from tests. Therefore, it is important to evaluate the simultaneous response to co-occurring stressors in real-life scenarios for a wide range of crop types.

Plant traits can serve as indicators for assessing crop health and crop responses, given that plant traits are associated with various plant functions involving leaf biochemistry and biophysics processes as well as photosynthetic processes. Leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (FAPAR), and the fraction of vegetation cover (FVC) are critical traits related to primary productivity, vegetation structure, photosynthesis, and transpiration (Asner et al. 2003; Fang et al. 2019; Weiss et al. 2016). Leaf chlorophyll content (Cab) is closely related to the process of photosynthesis and resource management strategy (Croft et al. 2017). Leaf water content (Cw) is a trait related to transpiration, stomatal conductance, and the respiration process and has been linked to drought impacts on crops in many studies (Bowman 1989; Zhu et al. 2017). LAI, FAPAR, and Cab have been shown to have a strong correlation with crop yield and are thus used to estimate final yield (Dente et al. 2008; Doraiswamy et al. 2005; Ghimire et al. 2015; López-Lozano et al. 2015). Therefore, to enhance our understanding of actual agricultural tolerances, and associated plant functioning, it is crucial to evaluate the performance of functional traits in real-life.

Remote sensing has a great potential for monitoring stresses on a large scale, if current challenges are met (Jiao et al. 2021; West et al. 2019). In particular for agricultural applications, satellites with multispectral sensors in high-resolution, such as Sentinel-2, allow stress detection based on retrieved plant traits (Weiss et al. 2020). Two common approaches to retrieving plant traits relevant for analyzing plant stress effects rely on statistical and physical modeling (Bayat et al. 2016). Statistical approaches involve parametric regressions based on the relationship between spectral bands/vegetation indices (VIs) and functional traits as linked to vegetation stress. Moreover, physical modeling approaches, such as radiative transfer models (RTM), show promising potential to retrieve plant traits related to stress from remote sensing (Wocher et al. 2020). Traits including LAI, FAPAR, FVC, Cw, and Cab retrieved from remote sensing have been applied to evaluate the response of vegetation to either drought or salinity stress (Bayat et al. 2016; Zhang et al. 2020). Instead of relying on individual traits to evaluate crop resistance mechanisms, remote sensing has demonstrated a way to monitor crop responses to stresses based on a multi-trait approach (Berger et al. 2022). Therefore, compared to most destructive methods with restricted capacity to detect mechanisms of stress in crops, remote sensing is a crucial tool that can simultaneously monitor plant functional traits across a wide range of crop types. Moreover, with remote sensing, such monitoring can be achieved over large spatial scales, at high temporal resolution, and in real-life agricultural settings. However, despite attempts to assess the impact of drought and salinity stress on crops using remote sensing traits, these studies are often limited in terms of the number of traits, crop types, and individual stress factors considered.

This study addresses the challenge of simultaneously evaluating the response of diverse crops to the co-occurrence of drought and salinity stress in real-life settings at a large scale. To achieve this, we generated a comprehensive co-occurrence map of drought and salinity across the entire United States. To isolate the effects of stress, we employed a pair-wise method to compare stressed and unstressed observations while eliminating the impacts of other factors including soil, climate zone, and region. Based on five retrieved traits including LAI, FVC, FAPAR, Cw, and Cab using Sentinel-2 observations, we characterized the response of eight crops to various drought and salinity stress conditions, as well as their interactions with other impacting factors throughout the growing season. We also analyzed the onset of stress (drought, salinity, and their combination) on five traits for each crop individually. Ultimately, our study provides valuable guidance to local farmers and governments by supplying timely information on crop responses to co-occurring stresses, both individually and collectively.

4.2 Methodology

According to the U.S. Drought Monitor (USDM), drought attacked the USA on a national scale throughout 2021 (NCEI and NOAA 2021). Around half of the contiguous USA experienced different strengths of drought from January onwards, and the west and middle of the USA which are typically used for farming crops suffered more severe drought (NCEI and NOAA 2021). In this study, we integrated multiple techniques to evaluate the response of diverse crops to salinity and drought stress at various levels simultaneously across the contiguous USA. In a previous paper (Chapter 3), we developed a novel approach to evaluate the expression of five crop traits under salinity and drought stress conditions in the Netherlands for only two crops. In this study, by adopting a pair-wise method to assess trait expressions concerning drought, salinity, and their combined impacts compared to non-stressed conditions, we captured stress impacts more precisely for a much larger range of crops and spatial conditions (Figure 4.1 and Figure S4-1).

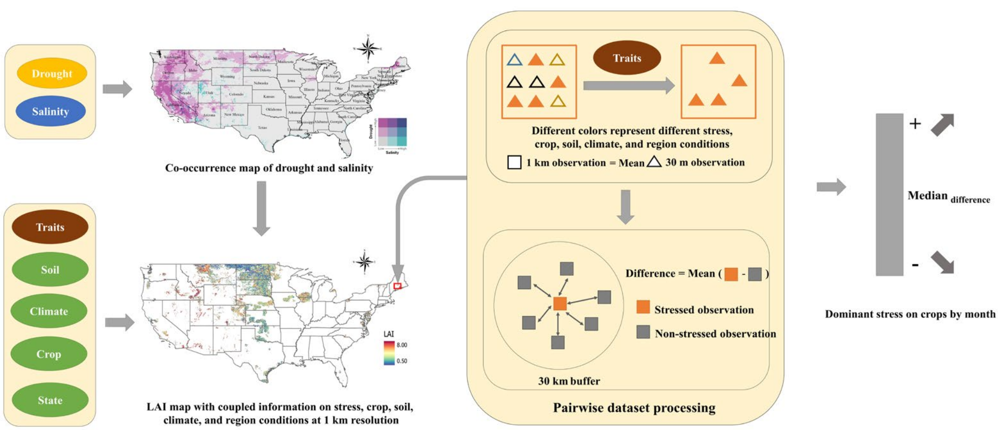

Figure 4.1 Conceptualisation of the technical workflow.

4.2.1 Study area and stress map

4.2.1.1 Drought map

A drought map of the contiguous USA in 2021 was generated based on the standardized precipitation evapotranspiration index (SPEI) drought index. The monthly SPEI with 3-month sliding time windows was collected from The West Wide Drought Tracker (https://wrcc.dri.edu/wwdt/about.php) (Abatzoglou et al. 2017). We extracted SPEI-3month data from March to October to coincide with various crop growth periods. Next, SPEI-3month maps for each month were combined to create the drought map for 2021. Then, the drought map with NAD 1983 Contiguous USA Albers projection was resampled to 30m resolution by using nearest neighbor interpolation. We define -8 and -12 as cumulative SPEI thresholds for no drought (-8 to 0), moderate drought (-12 to -8), and severe drought (< -12) in the whole growth season (McKee et al. 1993; Tao et al. 2014) (Figure 4.2a).

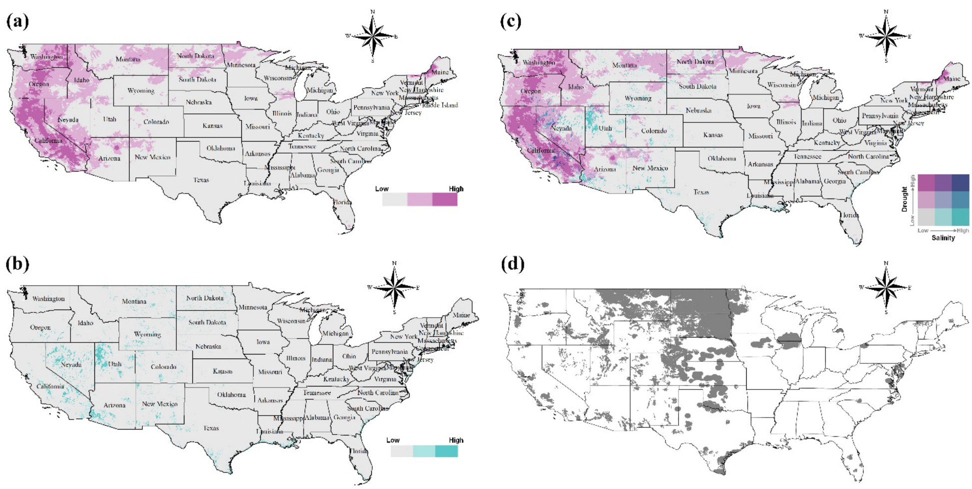

Figure 4.2 a) Drought map in the contiguous USA in 2021. b) Salinity map in the contiguous USA in 2021. c) co-occurrence map of drought and salinity in the contiguous USA in 2021. d) Map of stress-no stress pairs at 1km resolution.

4.2.1.2 Salinity map

A soil salinity map of the United States was generated from Gridded National Soil Survey Geographic Data (gNATSGO) (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcseprd1464625). We extracted the attribute Electrical Conductivity (EC) data for the topsoil with a 30m map unit raster. Based on EC, we developed the soil salinity map using the lookup function. Afterwards, the soil salinity map was reclassified to three levels namely no-salinity (0 $dS \cdot m^{-1}$ to 4 $dS \cdot m^{-1}$), moderate salinity (4 $dS \cdot m^{-1}$

to 8 dS·m^{-1}), and severe salinity (> 8 dS·m^{-1}) according to estimated salinity effects on crop growth (Richards 1954) (Figure 4.2b).

4.2.1.3 Co-occurrence map of drought and salinity

The co-occurrence of drought and salinity map for the COUNS in 2021 was created by overlaying the drought map and soil salinity map (Figure 4.2c). Given separative three levels of drought (no drought, moderate drought, and severe drought) and salinity stress (no salinity, moderate salinity, and severe salinity) (section 4.2.1.1 and section 4.2.1.2), we obtained nine classes of stress combinations, namely no stress, moderate salinity only (MS), severe salinity only (SS), moderate drought only (MD), severe drought only (SD), moderate salinity and moderate drought (MS+MD), moderate salinity and severe drought (SD+MS), severe salinity and moderate drought (MD+SS), and severe salinity and severe drought (SD+SS). In some cases, there were limited salinity observations for specific combination conditions. Therefore, these observations were merged with the closest classification into an overall category. For instance, MS+MD and SS+MD were reclassified to the MD+Salinity category.

4.2.2 Crop dataset

4.2.2.1 Crop map

The crop map of the contiguous USA in 2021 was collected from the Cropland Data Layer program (CDL) in the United States Department of Agriculture (USDA) (https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php). The crop map is in 30m resolution with NAD 1983 Contiguous USA Albers projection.

4.2.2.2 Crop selection

To ensure the highest availabilities of pairs subjected to multiple levels of stress throughout the growing season, eight crops including alfalfa, almond, grape, maize, sorghum, soybean, spring wheat, and sugar beet, were selected out of over 70 crop types because they contained most pairs of observations with comparable stress combinations (Table S4-1). These eight crops were classified into three categories according to their tolerance for drought and salinity stress from the literature (Table S4-2).

4.2.3 Remote sensing traits retrieval

In this study, we derived geospatial maps of functional traits by using remote sensing. We used Sentinel-2 observations composited scenes in 60m resolution (sun azimuth, sun zenith, view azimuth mean, view zenith mean, B03, B04, B05, B06, B07, B08A, B11, and B12) with 10-days periods (from 11th to 20th) for each month from The Sentinel-2 Global Mosaic 2 (S2GM-2) service (https://s2gm.land.copernicus.eu/mosaic-hub). Then, all scenes were processed by the biophysical processor in the Sentinel Application Platform (SNAP) toolbox API for python to retrieve five traits namely LAI, FVC, FAPAR, canopy water content (CWC), and canopy chlorophyll content (CCC) for each observation. Trait tiles were purged of observations raised with quality flags. After that, maps for the contiguous USA for each trait were accomplished by mosaicking all trait tiles from March to October to capture the full phenology of each crop. CCC and CWC were divided by LAI to acquire the independent leaf counterparts Cab (=CCC / LAI) and Cw (=CWC / LAI). To eliminate outliers for Cab and Cw created by extremely low values of LAI, observations with LAI values lower than 0.5 were excluded from the calculation of Cw and Cab. In order to maintain consistency for all five trait maps, LAI, FAPAR, and FVC maps were additionally screened for observations of LAI values less than 0.5.

4.2.4 Pairwise dataset processing

We adopted a pairwise method to eliminate the impacts of potentially confounding factors as much as possible. To ensure capturing representative crop responses on the basis of high-resolution data (section 4.2.3), we defined our pixels at 1km resolution. For this purpose, the crop map in 30m resolution was resampled to 1km using majority interpolation. The drought and salinity maps were resampled to 1km using the nearest neighbor interpolation. Subsequently, a fishnet comprising attributes of stress conditions, soil type, climate zone, state, and crop type, was created in 1 km resolution. Next, within a 30 km buffer, each observation in a stressed condition at the 1km resolution fishnet was coupled with several non-stressed observations that met the same criteria (crop type, soil taxonomy, climate zone, and state). The threshold of the buffer was determined by a semi-variogram based on LAI considering the spatial correlations and the presence of multiple stress combinations. To calculate the corresponding trait value for the 1km resolution fishnet, we extracted observations in a 30m resolution map with the same five attributes as the fishnet using raster calculator. Then, the average trait value at 1km resolution was determined by the mean value of the traits in 30m resolution using the zonal statistic. Next, we quantified the difference between stressed and non-stressed observations for the five traits based on the available pairs in the 1km resolution fishnet (Figure 4.2d) using the field calculation. Finally, we calculated the mean difference in trait values of each stressed observation involved in multiple pairs with unstressed conditions according to its unique (stressed observation) ID.

4.2.5 Data analysis

To minimize the impact of outliers, the median value for each stress class for five traits was calculated across the growth period. Considering the planting and harvest time of crops differs in the southern and northern part regions of the contiguous USA, we evaluated the response of crops to salinity and drought stress on crop traits from March to October to capture the whole growing period for different crops. The main effect of factors -stress condition, time, soil type, climate zone, state, and crop types) and their two-way interaction effects on each trait were determined by an analysis of variance (ANOVA) with SPSS 27.0. Post-hoc tests were performed to determine the significance of individual levels within factors. Partial Eta Square was determined to indicate the effect size of different factors. Since the interaction effects with crop type were omnipresent and to understand those better, we subsequently ran ANOVAs for each crop individually (Table S4-4 and Table S4-5). For eight crops, ANOVAs on stress condition, time, soil type, climate zone, state, and their two-way interactions were conducted for each trait, respectively. Since the interactions of other factors with stress were consistently smaller than those with time, we focused on the two-way ANOVAs of stress and time in the results. In addition, to evaluate which type of stress - salinity, drought, and combined salinity and drought - has the strongest impact on crops, the dominant stress without considering different strengths of stress was determined based on the median value of each trait throughout the growing season. Meanwhile, the onset of stress was determined as the first time during the growing season when a negative impact was observed on an individual trait. The onset of drought, salinity, and combined stress for eight crops was estimated for all five traits.

4.3 Results

4.3.1 Crop response commonalities to stress

The two-way ANOVAs of stress and time revealed a strongly time-dependent impact of stress on the five traits, as expressed by strong interaction effects (Figure 4.3). Each trait varied significantly ($p < 0.05$) over time for soybean, maize, almond, alfalfa, sugar beet, and spring wheat. However, the impact of time was always insignificant for sorghum. Stress significantly ($p < 0.05$) impacted FAPAR, FVC, and LAI for all crops. Except in Cw for sorghum, and in Cab for soybean and spring wheat, other crops had significant ($p < 0.05$) differences in Cab and Cw in all stress conditions across the growing season. In addition, for all traits and crops, the impacts of stress varied significantly ($p < 0.05$) over time except in Cw and LAI for sorghum. Among all crops, we found that both the main effect and interaction effect were always significant ($p < 0.05$) in all five traits for maize, almond, alfalfa, and sugar beet, indicating that the impacts of drought and salinity on their performance depended on the moment in the growing season. Interestingly, sorghum had the highest number of insignificant effects of both the main effect of stress and time as well as their interaction effect for the five traits. In particular, Cw was not significant ($p < 0.05$) in either main effects or interaction effects, suggesting sorghum had a stronger resilience to drought and salinity over the whole growing season. Moreover, time and stress were similarly important (as expressed by the partial eta square value) across five traits for soybean, maize, almond, spring wheat, and sorghum. In general, time, stress, and time*stress explained more of the variance in the trait values for grape, almond, alfalfa, sugar beet, and sorghum compared to soybean, maize, and spring wheat, indicating stronger impacts on the first group of crops. Furthermore, the interaction effect between stress and time was more important or equally important as the separate main effects, indicating that the impact of stress showed complicated dynamics that highly depended on the moment of the growing season.

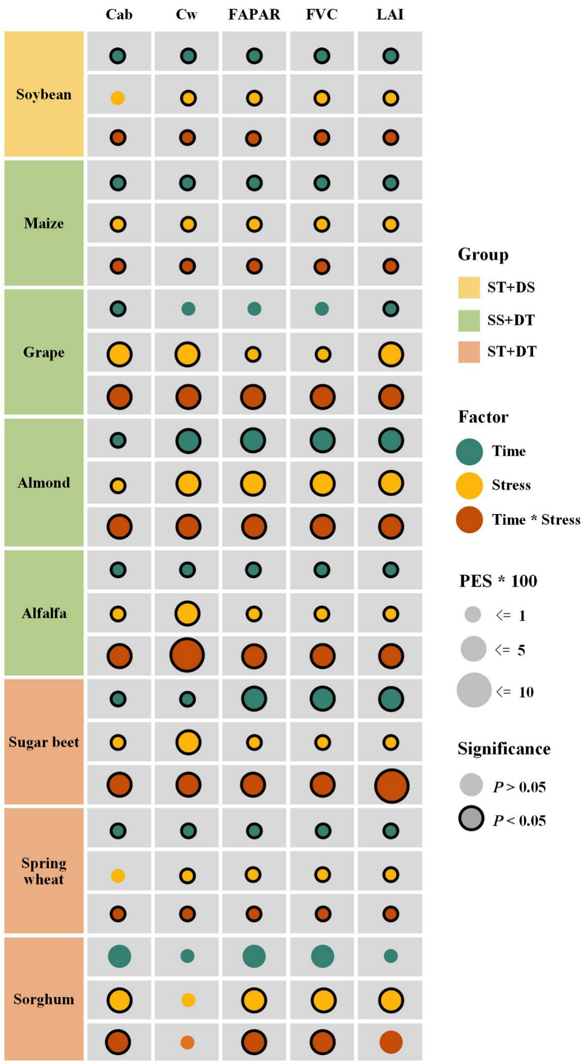

Figure 4.3 Results from two-way ANOVAs for different crop traits by stress, time, and their interactions, highlighting which effects are significant and which are not. ST+DS indicates salt-tolerant and drought-sensitive crops; SS+DT indicates salt-sensitive and drought-tolerant crops; ST+DT indicates salt-tolerant and drought-tolerant crops; PES indicates the partial eta square, i.e. the strength of the relationship.

4.3.2 Crop structural trait differences to stress in the growing season

Given the strong interaction effects of stress and time, the effects of salinity and drought on LAI, FVC, and FAPAR for crops from March to October were evaluated separately (Figure 4.4 and Figure S4-2). The patterns for FVC and FAPAR were similar to the pattern for LAI, even though the impacts of stresses were stronger for LAI throughout the growing season compared to FAPAR and

FVC. Therefore, they are presented in the supplementary information (Figure S4-3, Figure S4-4, Figure S4-7, and Figure S4-8).

Figure 4.4 The pattern of LAI, expressing the severest stress conditions in different months. ST+DS indicates salt-tolerant and drought-sensitive crops; SS+DT indicates salt-sensitive and drought-tolerant crops; ST+DT indicates salt-tolerant and drought-tolerant crops; in strength, low indicates a difference between stress pixels and control pixels smaller than 0.1 m^2 leaf per m^2 surface, moderate indicates a difference between stress pixels and control pixels between 0.1 m^2 leaf per m^2 surface and 0.5 m^2 leaf per m^2 surface, and high indicates a difference between stress pixels and control pixels greater than 0.5 m^2 leaf per m^2 surface; positive effect and negative effect indicate the direction of the pair-wise differences between stress pixels and control pixels.

The patterns of LAI, FVC, and FAPAR under drought and salinity stress varied strongly between different crops and at different moments (Figure 4.4, Figure S4-2, and Figure S4-3) as well as between different states (Figure S4-9, Figure S4-10, and Figure S4-11). For all crops, the combination of salinity and drought stress commonly had the biggest impact on the performance of LAI, FAPAR, and FVC over the whole growing season, even though occasionally in parts of the growing season positive effects on individual traits were observed. Drought stress alone had the lowest amount of impact among the three stress factors (and particularly affected sorghum). These results suggest that in general salinity was more important in determining crop performance than drought. Salinity stress showed negative impacts on all crops for LAI in all months. However, for FAPAR and FVC, salinity stress showed positive impacts on almond, alfalfa, and sorghum during the growing season (Figure S4-2).

The importance of individual and combined stresses varied among the different crops. In many crops, the combination of stresses really mattered. However, for almond and sorghum, there were only independent drought and salinity stress impacts on LAI, FVC, and FAPAR throughout the whole growing season. All crops except for grape and sugar beet responded consistently negatively to stresses for LAI from April to August. Thus, the responses of crops to drought and salinity differed between species and over time. Importantly, none of these patterns seemed to relate to their perceived tolerance to salinity or drought (Table S4-2).

4.3.3 Crop physiological traits difference to stress in the growing season

The patterns of Cab and Cw under salinity and drought stress varied between different crops and at different moments (Figure 4.5, Figure 4.6, Figure S4-5, and Figure S4-6) as well as between different states (Figure S4-12, and Figure S4-13). For all crops, the combined drought and salinity stress had the highest impact as the severest stress for Cab over the whole growing season. Drought stress alone was the most important stress factor in the least number of occasions. For almond and sorghum, only drought and salinity stress alone impacted Cab. Salinity stress tended to show positive impacts on soybean, almond, and sugar beet for Cab at the beginning and end of the growing season. Also, drought stress and the combination of salinity and drought stress showed negative impacts as well as positive impacts on crops for Cab without clear patterns in terms of the timing of the positive and negative effects. Crops including maize, almond, and alfalfa, responded negatively to stresses for Cab from April to August. All crops showed complex dynamic responses to stresses for Cab from March to October.

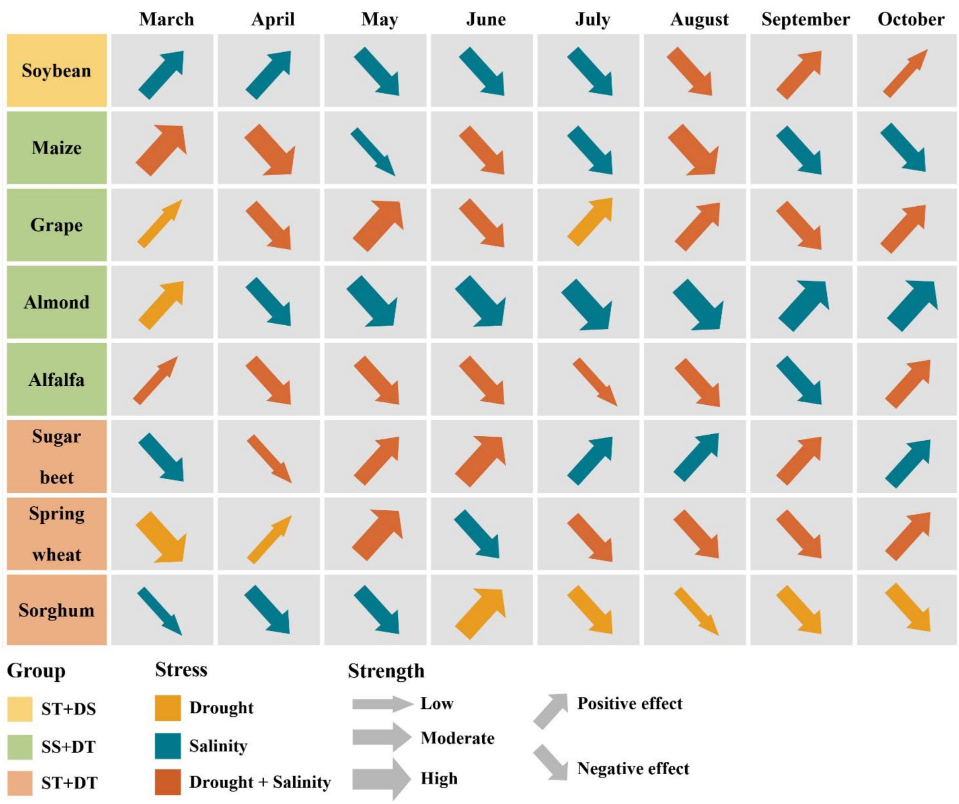

Figure 4.5 The pattern of Cab (Chlorophyll a/b), expressing the severest stress conditions in different months. ST+DS indicates salt-tolerant and drought-sensitive crops; SS+DT indicates salt-sensitive and drought-tolerant crops; ST+DT indicates salt-tolerant and drought-tolerant crops; in strength, low indicates a difference between stress pixels and control pixels smaller than 1 $ug.cm^{-2}$, moderate indicates a difference between stress pixels and control pixels between 1 $ug.cm^{-2}$ and 5 $ug.cm^{-2}$, high indicates a difference between stress pixels and control pixels greater than 5 $ug.cm^{-2}$; positive effect and negative effect indicate the direction of the pair-wise differences between stress pixels and control pixels.

Similar to Cab, Cw was mostly affected by the combination of salinity and drought stress over the whole growing season, while drought stress alone occurred in the least number of occasions as the most important stress factor among all crops. Interestingly, sorghum was the only crop that was most impacted by the independent effects of salinity and drought stress for Cw across the whole growing season. Drought stress always caused negative impacts on Cw, except for spring wheat and sorghum. In contrast, salinity stress and combined salinity and drought stress showed both negative and positive impacts on crops for Cw during the growing season, the direction of the impact as well as the most important stress factor varied strongly over time. Crops including maize, grape, alfalfa, and spring wheat responded consistently negatively to stresses for Cw in the later phase of the growing season, i.e., from July to October.

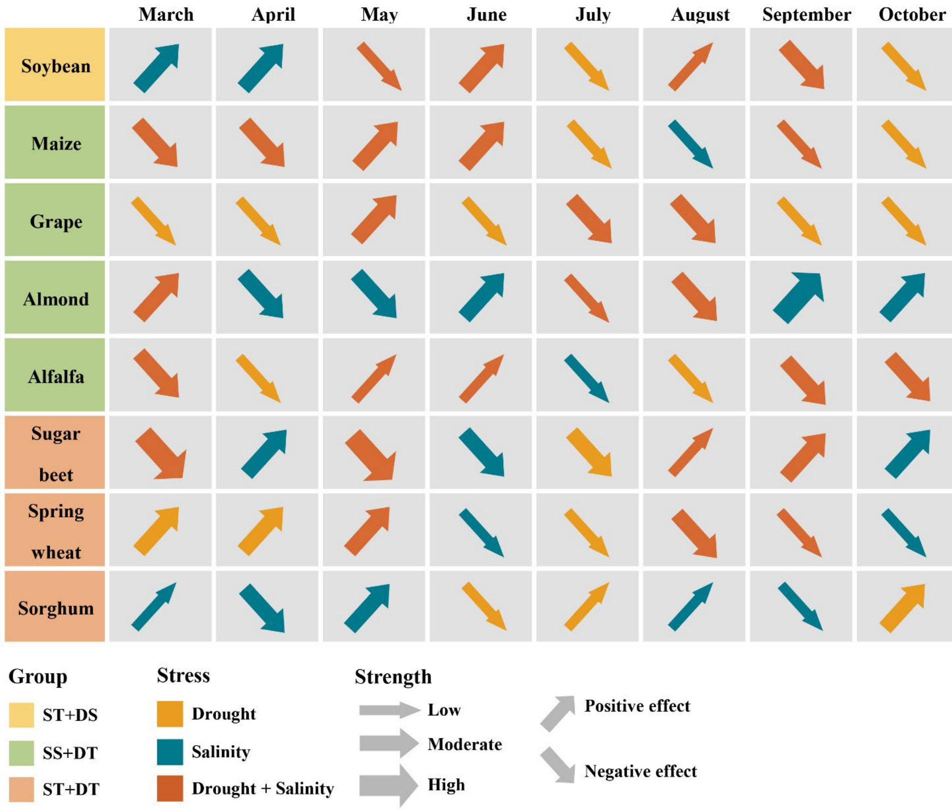

Figure 4.6 The pattern of Cw (concentration of water in leaves), expressing the severest stress conditions in different months. ST+DS indicates salt-tolerant and drought-sensitive crops; SS+DT indicates salt-sensitive and drought-tolerant crops; ST+DT indicates salt-tolerant and drought-tolerant crops; in strength, low indicates a difference between stress pixels and control pixels smaller than 0.001 g.cm^{-2}, moderate indicates a difference between stress pixels and control pixels between 0.001 g.cm^{-2} and 0.005 g.cm^{-2}, high indicates a difference between stress pixels and control pixels greater than 0.005 g.cm^{-2}; positive effect and negative effect indicate the direction of the pair-wise differences between stress pixels and control pixels.

4.3.4 The onset of drought and salinity impacts in the growing season

As crops responded in different ways to salinity and drought stress, the onset of stresses was analyzed to further compare the differences among crops and traits (Figure 4.7). We found for most crops that stress impacts were triggered in March and April, indicating on average crops suffered from stresses throughout most of the growing season. Although the onset of separate drought and salinity differed among crops as well as among traits, the onset of all crops to combined drought and salinity stress was similar to or later than drought for all traits except for Cab in alfalfa. Furthermore, among the five traits, LAI was the first trait to respond to stresses for all crops, except for almond under combined salinity and drought stress conditions. FAPAR and FVC showed similar onset timing to stress. On average, Cw and Cab were the last to respond to stresses, compared to other traits.

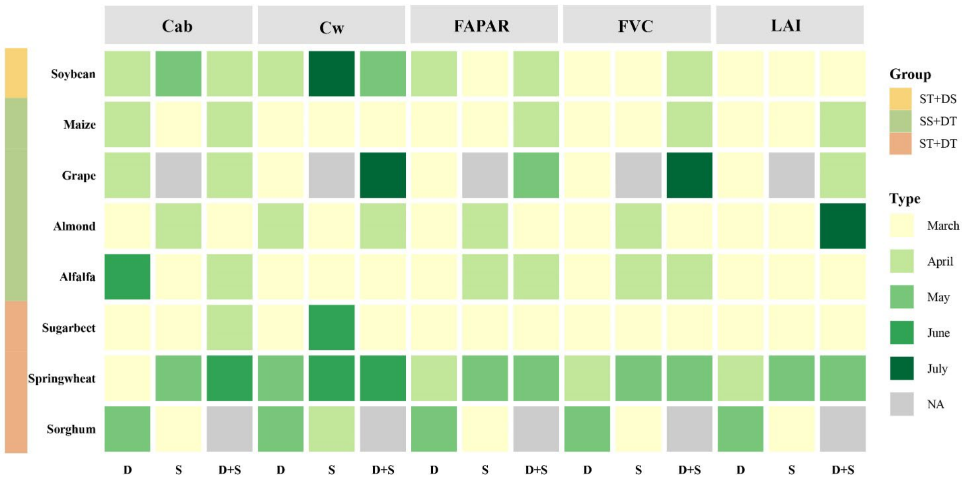

Figure 4.7 The onset of crop responses to stresses in the growing season. D indicates drought stress; S indicates salinity stress; D+S indicates combined drought and salinity stress; ST+DS indicates salt-tolerant and drought-sensitive crops; SS+DT indicates salt-sensitive and drought-tolerant crops; ST+DT indicates salt-tolerant and drought-tolerant crops.

4.4 Discussion

4.4.1 Crop responses to salinity and drought differ between species and growth stages

A key finding of our research is that the combined effects of drought and salinity stress on crop growth are more pronounced than the effects of drought or salinity stress individually. Consistent with our previous study (Chapter 3) and various small-scale experiments, co-occurring salinity and drought showed exacerbating effects on crop traits in most cases (Ors and Suarez 2017; Zhang et al. 2013).

While exacerbated impacts of co-occurring stresses are commonly observed, we additionally show how the impacts of stresses on crops vary strongly over the growing season (Figure 4.4, Figure 4.5, and Figure 4.6), a finding that would not be possible to obtain from small-scale experiments focusing on yield impacts only. Moreover, even the dominant stress on crop traits varied throughout the growing season. This indicates that the crop responses to drought and salinity are highly dependent on the moment. Such variation is consistent with physiological knowledge showing that the sensitivity to specific drivers depends on the growth stage (Saqib et al. 2013). For instance, previous studies showed that drought has a higher impact on maize during the reproductive phase (Daryanto et al. 2017), while the impacts of drought stress were strongest during the tuber bulking phase in potato (Chapter 3). Such impacts of (drought and salinity) stress are not commonly evaluated but are of crucial importance to evaluating those impacts and for taking mitigating measures. Our study shows how we can use remote sensing as a convenient tool to enable real-time dynamic monitoring and evaluating crop performance to regulate crop management.

Aside from the significant impact of the moment in the growing season, drought and salinity also affect crops differently depending on their species. A number of controlled experiments studies have shown that a variety of crops such as barley (Toker et al. 1999), reed (Sánchez et al. 2015), durum wheat (Houshmand et al. 2014), etc., respond differently to salinity and drought. Likewise, seven pepper accessions showed a wide variability of responses to salinity, drought, and their combination treatments (López-Serrano et al. 2017) These different responses of crops to drought and salinity likely link to their differences in tolerance to these stresses, which were shown in this study through the trait expressions of the various crops studied. For instance, almond -known to be sensitive to salinity and tolerant to drought- showed a higher sensitivity to salinity stress for LAI, FVC, FAPAR, and Cab during the growing season than to drought and or the combination of drought and salinity (Figure 4.4, Figure S4-2, Figure S4-3, and Figure 4.5), while sorghum responded more strongly to drought. Nevertheless, the responses of individual crops to salinity and drought stress were not fully consistent with expected tolerances based on controlled experiments. For instance, sorghum was expected to be tolerant to both drought and salinity (but mainly responded to drought) and almond was expected to be mainly sensitive to salinity. Thus, given the multitude of responses for different traits and crops that might not always be consistent with assumed tolerance to these stresses, our study shows that a comprehensive evaluation of responses to drought and salinity in a real-life agricultural setting across multiple crop types, growth conditions, and management is essential. In light of the projected future increase in drought and salinity stress, our remote sensing approach may be an appropriate tool to give timely guidance to government and local farmers.

4.4.2 Patterns in growth stage-dependent responses to stress

Although the responses of crops to drought and salinity differed between species and growth stages, there were commonalities among various crop types. In general, for all eight crops, LAI was triggered first by drought and salinity stress, followed by FVC and FAPAR, and Cw and Cab were the last to respond (Figure 4.7).

Therefore, it indicates that -depending on the growth stage- crops employ a different strategy to resist drought and salinity or vary in the sensitivity of traits to these stresses. Generally, our results suggest that most crops prefer to remove some leaves first before decreasing the vegetation cover as a whole to capture as much sunlight as possible, maintaining energy and nutrient uptake. When they cannot deal with water stress anymore, they reduce leaf chlorophyll content and leaf water content at last. This general sequence in trait responses -which we describe for the first time- with chlorophyll and leaf water responding when conditions get severe for a longer period of time, may explain why several studies concluded that chlorophyll content has a high correlation with drought or salinity stress (Schlemmer et al. 2005). Our results, showing that LAI responds first, explain why LAI -as the most well-known trait- provides a highly sensitive stress detection for vegetation (Li et al. 2022). Given their similar responsiveness, also FAPAR and FVC have the capability to determine and monitor stress impact on crop growth (Cammalleri et al. 2022; Mohammed and Algarni 2020).

Given that crops employ different strategies to resist drought and salinity stress (section 4.4.1) and given the growth-stage dependent trait responses to drought and salinity (this section), our study shows the importance of evaluating multiple traits simultaneously. Several studies focus on the spatiotemporal variation of individual traits, but the responses of crops from the beginning to the end of the growing season are rarely considered or compared. This limited coverage in time and traits may limit their findings to the restricted range of crop varieties and growth stages. Instead, in this study, we obtained a detailed description of crop tolerances to drought and salinity thanks to the combination of multiple measurements during the growing season and the assessment of multiple traits simultaneously. Such quantification is of importance for understanding crop responses to stress in real-life agricultural systems.

4.4.3 Local impacts on crop responses to salinity and drought stress

Despite the strong significance of all patterns described above, the effect sizes of the crop responses to salinity and drought stress were limited. Additionally accounting for the potential effects of differences in soil type, climate zone, and region between our observation pairs hardly improved our explanatory power of the effects of stress (Figure 4.3, Table S4-4, and Table S4-5), even though local conditions affected crop responses to stress (Figure S4-9, Figure S4-10, Figure S4-11, Figure S4-12, and Figure S4-13). The interaction effects of e.g. soil type or climate zone with stress were however significant in many cases (Table S4-5). This may be explained by the fact that soil moisture and soil salinity variations are known to be controlled by various factors, including soil type, climatic conditions, and local management policy (Ben Ahmed et al. 2012). Ben Rouina et al. (2007)

pointed out that the response of the olive tree to drought stress varied in soil type, due to the higher water-holding capacity in clay soils than in sandy soils. In most crops and for the five traits investigated, the impacts of soil type on the effects of stress were stronger than the impacts of climate zones or specific regions thereon. Together, they provide a partial explanation for the strong variation in crop responses to salinity and drought stress in the contiguous USA. However, even soil type did not affect the expression of impacts of salinity or drought stress as much as time did. This reinforces our assessment of the importance of time-dependent impacts of drought and salinity stress (section 4.4.1) and the generic patterns in the timing of the trait responses (section 4.4.2). In combination, our results indicate that a high variation in responses to drought and salinity is an outcome of the complex interaction of different crop responses and strategies over time in a broad spectrum of environmental conditions.

4.4.4 Future implications

The remote sensing approach developed and employed in this study to evaluate crop tolerance to combined salinity and drought stress by assessing multiple traits linked to crop performance also provides possibilities for application to other stress combinations (e.g., flood, heat, frost). Given the general nature of the traits used and of its generic assessment methodology, such applications are not only feasible for crops but for all kinds of vegetation types. Our approach is complementary to existing small-scale and experimental approaches by focusing on large-scale settings in local agricultural settings. Our approach shows that it is able to capture the high variation in crop performance in the contiguous USA at relatively high resolution. This suggests that it can be an interesting approach for local farmers or the government to timely assess crop health. In this way, it gives farmers an open-source tool to monitor crop growth conditions and adjust field management based on evidence. For larger to global scale applications, our approach allows evaluating food security and associated stress factors to may constrain food security, many of which are likely to become more prominent in the near future.

4.5 Conclusions

In this study, we evaluated the responses of multiple crops to salinity, drought, and their combination based on five functional traits across the entire U.S. continent throughout crop growing season in 2021 from remote sensing. We found that stress impacts were highly dependent on the moment in the growing season. Moreover, different crops showed divergent responses to these stresses over time. In general, crops were more sensitive to the combined effects of salinity and drought stress compared to the individual effects of salinity and drought stress. Most crops first reduced their primary production capacity through reducing LAI before reducing water or chlorophyll contents. In combination, we established a quantitative foundation for simultaneously assessing the responses of various crops to the occurrence of stresses, alone and collectively at large scale and under actual agricultural conditions. Consequently, we contribute to monitor food security and guide food production in a timely and non-destructive way by remote sensing.

4.6 Author contributions

Wen Wen: Conceptualization, Methodology, Investigation, Writing, and Reviewing. Joris Timmermans: Conceptualization, Methodology, Supervision, Writing, and Reviewing. Qi Chen: Methodology and Reviewing. Peter M. van Bodegom: Conceptualization, Methodology, Supervision, Writing, and Reviewing.

4.7 Supporting information

Table S4-1. Number of observation pairs in the final selection for crops during the growing season from March to October.

	March	April	May	June	July	August	September	October	Total
Soybean	405	1500	6994	13810	18402	22975	21824	12392	98302
Maize	911	2827	6227	10293	14460	16228	16341	9497	76784
Alfalfa	1678	4265	8144	8402	6932	6517	7702	5868	49508
Spring wheat	14	35	3298	11391	9093	6925	7695	5604	44055
Sugar beet	101	140	289	755	1014	1187	1153	1036	5675
Almond	405	728	709	705	707	705	699	739	5397
Grape	340	352	391	452	466	527	587	622	3737
Sorghum	9	12	58	111	176	180	144	127	817

Table S4-2. Crop stress-tolerance characteristics.

Crop	Drought tolerance (Idowu et al. 2012; Wei et al. 2018)	Salinity tolerance (Grieve et al. 2011)	Category
Soybean	drought-sensitive (DS)	salinity-tolerant (ST)	ST+DS
Maize	drought-tolerant (DT)	salinity-sensitive (SS)	SS+DT
Grape	drought-tolerant (DT)	salinity-sensitive (SS)	SS+DT
Almond	drought-tolerant (DT)	salinity-sensitive (SS)	SS+DT
Alfalfa	drought-tolerant (DT)	salinity-sensitive (SS)	SS+DT
Sugar beet	drought-tolerant (DT)	salinity-tolerant (ST)	ST+DT
Spring wheat	drought-tolerant (DT)	salinity-tolerant (ST)	ST+DT
Sorghum	drought-tolerant (DT)	salinity-tolerant (ST)	ST+DT

Table S4-3. Two-way ANOVA results by time series and stress interactions for different crop traits (sig.= significance with ** $p < 0.01$; * $p < 0.05$; ns = not significant).

Crops	Factors	LAI		FAPAR		FVC		Cab		Cw	
		sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared
Alfalfa	time	**	0.001	**	0.001	**	0.001	**	0.001	**	0.001
	stress	**	0.002	**	0.002	**	0.002	**	0.004	**	0.013
	time*stress	**	0.012	**	0.014	**	0.014	**	0.014	**	0.073
Almond	time	**	0.007	*	0.030	*	0.004	*	0.003	**	0.010
	stress	**	0.014	**	0.016	**	0.020	*	0.004	**	0.018
	time*stress	**	0.037	**	0.036	**	0.035	**	0.030	**	0.045
Grape	time	*	0.007	ns	0.003	ns	0.003	*	0.005	ns	0.001
	stress	**	0.010	*	0.004	*	0.005	**	0.012	**	0.010
	time*stress	**	0.048	**	0.028	**	0.033	**	0.027	**	0.028
Maize	time	**	0.000	**	0.001	**	0.001	**	0.001	**	0.001
	stress	**	0.001	**	0.001	**	0.001	**	0.001	*	0.000
	time*stress	**	0.003	**	0.002	**	0.002	**	0.002	**	0.002
Sorghum	time	ns	0.007	ns	0.014	ns	0.011	ns	0.010	ns	0.006
	stress	**	0.026	*	0.014	*	0.015	*	0.018	ns	0.001
	time*stress	ns	0.020	*	0.028	*	0.026	*	0.035	ns	0.009
Soybean	time	**	0.001	**	0.000	**	0.001	**	0.002	**	0.001
	stress	**	0.000	**	0.000	**	0.000	ns	0.000	**	0.000
	time*stress	**	0.001	**	0.001	**	0.001	**	0.002	**	0.001
Spring wheat	time	**	0.001	**	0.001	**	0.001	**	0.003	**	0.002
	stress	*	0.000	*	0.000	*	0.000	ns	0.000	*	0.000
	time*stress	**	0.002	**	0.002	**	0.002	**	0.002	**	0.001
Sugar beet	time	**	0.023	**	0.014	**	0.019	**	0.006	**	0.006
	stress	**	0.007	**	0.005	**	0.007	**	0.008	**	0.010
	time*stress	**	0.053	**	0.028	**	0.033	**	0.026	**	0.040

Table S4-4. Multi-way ANOVA for different crop traits including only main effects of time, stress, soil type, climate zone, and state (sig. = significance with ** $p < 0.01$; * $p < 0.05$; ns = not significant).

Crops	Factors	Cab		Cw		FAPAR		FVC		LAI	
		sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared
Alfalfa	time	**	0.004	**	0.011	**	0.002	**	0.004	**	0.002
	stress	**	0.002	**	0.011	**	0.001	**	0.001	**	0.001
	soil type	**	0.012	**	0.005	**	0.010	**	0.010	**	0.005
	climate zone	**	0.003	**	0.002	**	0.002	**	0.002	**	0.002
	state	**	0.006	**	0.009	**	0.005	**	0.005	**	0.004
Almond	time	**	0.039	**	0.055	**	0.081	**	0.084	**	0.067
	stress	**	0.005	**	0.010	*	0.003	**	0.007	**	0.006
	soil type	**	0.078	**	0.115	**	0.050	**	0.040	**	0.040
	climate zone	**	0.030	**	0.075	**	0.013	**	0.013	**	0.020
	state	--	--	--	--	--	--	--	--	--	--
Grape	time	**	0.013	**	0.016	**	0.047	**	0.051	**	0.087
	stress	**	0.014	**	0.015	**	0.006	*	0.004	*	0.004
	soil type	**	0.025	**	0.023	**	0.042	**	0.045	**	0.044
	climate zone	**	0.077	**	0.019	**	0.078	**	0.096	**	0.137
	state	ns	0.000	*	0.004	**	0.007	**	0.010	**	0.029
Maize	time	**	0.007	**	0.004	**	0.004	**	0.004	**	0.005
	stress	**	0.002	*	0.000	**	0.001	**	0.001	**	0.001
	soil type	**	0.003	**	0.008	**	0.003	**	0.003	**	0.004
	climate zone	**	0.001	**	0.001	**	0.001	**	0.001	**	0.001
	state	**	0.003	**	0.004	**	0.002	**	0.002	**	0.003
Sorghum	time	**	0.037	ns	0.015	**	0.053	**	0.044	**	0.037
	stress	*	0.009	ns	0.000	ns	0.001	ns	0.001	ns	0.000
	soil type	*	0.026	ns	0.008	ns	0.016	ns	0.013	*	0.020
	climate zone	ns	0.013	ns	0.008	ns	0.014	ns	0.012	*	0.028
	state	*	0.026	*	0.019	ns	0.015	ns	0.014	**	0.040
Soybean	time	**	0.011	**	0.006	**	0.004	**	0.004	**	0.007
	stress	**	0.001	ns	0.000	**	0.001	**	0.001	**	0.001
	soil type	**	0.001	**	0.001	**	0.003	**	0.004	**	0.005
	climate zone	**	0.000	**	0.000	**	0.000	**	0.000	*	0.000
	state	**	0.002		0.001	**	0.001	**	0.001	**	0.001

Spring Wheat	time	**	0.014	**	0.002	**	0.004	**	0.003	**	0.006
	stress	**	0.002	ns	0.000	**	0.000	**	0.001	**	0.001
	soil type	**	0.005	**	0.003	**	0.002	**	0.003	**	0.005
	climate zone	**	0.001	ns	0.000	**	0.002	**	0.002	**	0.002
	state	**	0.002	*	0.001	**	0.002	**	0.001	**	0.003
Sugar beet	time	**	0.073	**	0.029	**	0.051	**	0.066	**	0.089
	stress	ns	0.001	**	0.015	*	0.002	*	0.002	*	0.003
	soil type	ns	0.002	*	0.004	**	0.006	**	0.006	**	0.006
	climate zone	*	0.002	**	0.004	**	0.004	**	0.004	**	0.010
	state	**	0.009	**	0.005	**	0.009	**	0.008	**	0.016

Table S4-5. Multi-way ANOVA for different crop traits including main effects of time, stress, soil type, climate zone, and states and the interactions of stress and time with other factors (sig. = significance, ** $p < 0.01$; * $p < 0.05$; ns = not significant).

Crops	Factors	Cab		Cw		FAPAR		FVC		LAI	
		sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared	sig.	Partial Eta Squared
Alfalfa	time	ns	0.000	*	0.000	*	0.000	*	0.000	*	0.000
	stress	ns	0.000	ns	0.000	ns	0.000	ns	0.000	ns	0.000
	soil type	**	0.000	**	0.002	**	0.003	**	0.003	**	0.002
	climate zone	*	0.002	**	0.001	ns	0.000	ns	0.000	*	0.000
	state	**	0.001	**	0.002	**	0.002	**	0.002	**	0.002
	time*stress	**	0.006	**	0.026	**	0.009	**	0.004	**	0.006
	time*soil type	**	0.013	**	0.026	**	0.018	**	0.022	**	0.018
	time*state	**	0.014	**	0.027	**	0.019	**	0.020	**	0.022
	time*climate zone	**	0.007	**	0.013	**	0.007	**	0.008	**	0.008
	stress*soil type	**	0.008	**	0.002	**	0.006	**	0.007	**	0.006
	stress*climate zone	*	0.001	**	0.001	*	0.001	ns	0.001	ns	0.001
	stress*state	**	0.006	**	0.003	**	0.005	**	0.006	**	0.005
Almond	time	**	0.012	**	0.008	**	0.005	**	0.007	**	0.019
	stress	**	0.008	**	0.011	**	0.007	**	0.013	**	0.013
	soil type	**	0.017	**	0.025	**	0.017	**	0.016	**	0.017
	climate zone	**	0.022	**	0.013	**	0.019	**	0.025	**	0.035
	state	--	--	--	--	--	--	--	--	--	--
	time*stress	**	0.020	**	0.027	**	0.018	**	0.018	**	0.022
	time*soil type	**	0.060	**	0.094	**	0.061	**	0.056	**	0.043
	time*state	--	--	--	--	--	--	--	--	--	--
	time*climate zone	**	0.055	**	0.064	**	0.046	**	0.047	**	0.066
	stress*soil type	*	0.005	**	0.006	**	0.008	**	0.009	**	0.010
	stress*climate zone	**	0.008	**	0.006	*	0.004	**	0.009	**	0.010
	stress*state	--	--	--	--	--	--	--	--	--	--
Maize	time	*	0.000	**	0.000	ns	0.000	ns	0.000	*	0.000
	stress	*	0.000	*	0.000	ns	0.000	ns	0.000	*	0.000
	soil type	**	0.001	**	0.003	**	0.001	**	0.002	**	0.002
	climate zone	*	0.000	ns	0.000	ns	0.000	ns	0.000	*	0.000
	state	**	0.001	**	0.002	**	0.001	**	0.001	**	0.001
	time*stress	**	0.002	**	0.001	**	0.001	**	0.001	**	0.001
	time*soil type	**	0.032	**	0.018	**	0.021	**	0.021	**	0.033
	time*state	**	0.015	**	0.016	**	0.011	**	0.011	**	0.018
	time*climate zone	**	0.005	**	0.003	**	0.004	**	0.004	**	0.005
	stress*soil type	**	0.001	ns	0.000	**	0.001	**	0.001	**	0.002
	stress*climate zone	ns	0.000	**	0.001	*	0.000	*	0.001	**	0.001
	stress*state	**	0.001	*	0.001	**	0.001	**	0.001	**	0.002
	time	**	0.010	*	0.005	**	0.011	**	0.010	*	0.007
	stress	*	0.004	ns	0.002	ns	0.002	*	0.003	**	0.007

Grape	soil type	**	0.038	**	0.018	**	0.042	**	0.045	**	0.061
	climate zone	**	0.041	**	0.010	**	0.029	**	0.026	**	0.030
	state	ns	0.000	*	0.003	*	0.002	*	0.003	**	0.010
	time*stress	**	0.013	*	0.011	*	0.011	**	0.013	**	0.018
	time*soil type	**	0.102	**	0.043	**	0.054	**	0.054	**	0.061
	time*state	*	0.005	*	0.004	**	0.006	**	0.007	*	0.004
	time*climate zone	**	0.065	**	0.034	**	0.072	**	0.082	**	0.142
	stress*soil type	ns	0.001	*	0.001	ns	0.000	ns	0.000	ns	0.000
	stress*climate zone	**	0.009	**	0.008	ns	0.001	ns	0.001	ns	0.001
	stress*state	ns	0.000	ns	0.000	ns	0.000	ns	0.000	ns	0.000
Sorghum	time	*	0.021	ns	0.014	*	0.025	*	0.024	*	0.024
	stress	ns	0.007	ns	0.001	ns	0.003	ns	0.006	ns	0.002
	soil type	*	0.022	ns	0.006	*	0.020	*	0.019	**	0.035
	climate zone	ns	0.003	ns	0.004	ns	0.003	ns	0.005	ns	0.003
	state	*	0.015	ns	0.007	ns	0.010	ns	0.013	ns	0.008
	time*stress	**	0.049	ns	0.012	*	0.036	*	0.035	*	0.033
	time*soil type	ns	0.032	ns	0.029	*	0.059	ns	0.056	ns	0.034
	time*state	ns	0.016	ns	0.011	ns	0.016	ns	0.022	ns	0.033
	time*climate zone	ns	0.021	ns	0.008	ns	0.038	ns	0.035	ns	0.031
	stress*soil type	*	0.021	ns	0.010	ns	0.010	*	0.016	*	0.018
	stress*climate zone	ns	0.002	ns	0.001	ns	0.001	ns	0.000	ns	0.000
	stress*state	ns	0.001	ns	0.001	ns	0.001	ns	0.002	ns	0.006
Soybean	time	*	0.000	*	0.000	*	0.000	*	0.000	**	0.000
	stress	ns	0.000	ns	0.000	ns	0.000	ns	0.000	ns	0.000
	soil type	*	0.000	**	0.001	ns	0.000	*	0.000	ns	0.000
	climate zone	ns	0.000	**	0.000	ns	0.000	ns	0.000	ns	0.000
	state	**	0.000	*	0.000	*	0.000	*	0.000	*	0.000
	time*stress	**	0.001	**	0.001	*	0.001	**	0.001	**	0.001
	time*soil type	**	0.013	**	0.011	**	0.009	**	0.009	**	0.010
	time*state	**	0.007	**	0.005	**	0.005	**	0.005	**	0.006
	time*climate zone	**	0.002	**	0.001	**	0.002	**	0.002	**	0.002
	stress*soil type	ns	0.000	ns	0.000	ns	0.000	ns	0.000	*	0.000
	stress*climate zone	*	0.000	*	0.000	*	0.000	**	0.000	*	0.000
	stress*state	*	0.000	*	0.000	*	0.000	*	0.000	**	0.000
Spring wheat	time	**	0.001	**	0.002	**	0.001	**	0.001	**	0.003
	stress	ns	0.000	*	0.000	ns	0.000	ns	0.000	*	0.000
	soil type	**	0.001	**	0.003	ns	0.000	*	0.001	**	0.001
	climate zone	**	0.001	ns	0.000	ns	0.000	ns	0.000	*	0.000
	state	*	0.000	*	0.000	*	0.000	*	0.000	*	0.001
	time*stress	**	0.003	**	0.001	*	0.001	*	0.001	*	0.001
	time*soil type	**	0.011	**	0.010	**	0.008	**	0.007	**	0.011
	time*state	**	0.007	**	0.003	**	0.007	**	0.007	**	0.011
	time*climate zone	**	0.005	**	0.002	**	0.004	**	0.004	**	0.005
	stress*soil type	*	0.001	*	0.001	ns	0.000	ns	0.000	ns	0.001
	stress*climate zone	ns	0.000	ns	0.000	ns	0.000	ns	0.000	ns	0.000
	stress*state	**	0.001	ns	0.000	*	0.001	*	0.001	**	0.001

Sugar beet	time	ns	0.002	*	0.003	ns	0.003	ns	0.001	ns	0.001
	stress	ns	0.001	ns	0.001	**	0.004	*	0.003	**	0.004
	soil type	*	0.003	*	0.003	ns	0.002	*	0.002	ns	0.001
	climate zone	ns	0.001	**	0.003	*	0.002	*	0.002	**	0.007
	state	ns	0.001	**	0.005	*	0.003	*	0.003	**	0.006
	time*stress	*	0.007	**	0.009	**	0.010	**	0.011	**	0.012
	time*soil type	**	0.015	**	0.020	**	0.017	**	0.019	**	0.017
	time*state	**	0.014	**	0.012	**	0.020	**	0.020	**	0.019
	time*climate zone	**	0.007	*	0.005	**	0.012	**	0.012	**	0.012
	stress*soil type	*	0.002	ns	0.001	ns	0.001	ns	0.001	**	0.004
	stress*climate zone	ns	0.001	ns	0.001	ns	0.001	ns	0.001	*	0.003
	stress*state	ns	0.001	*	0.002	*	0.003	**	0.003	**	0.005

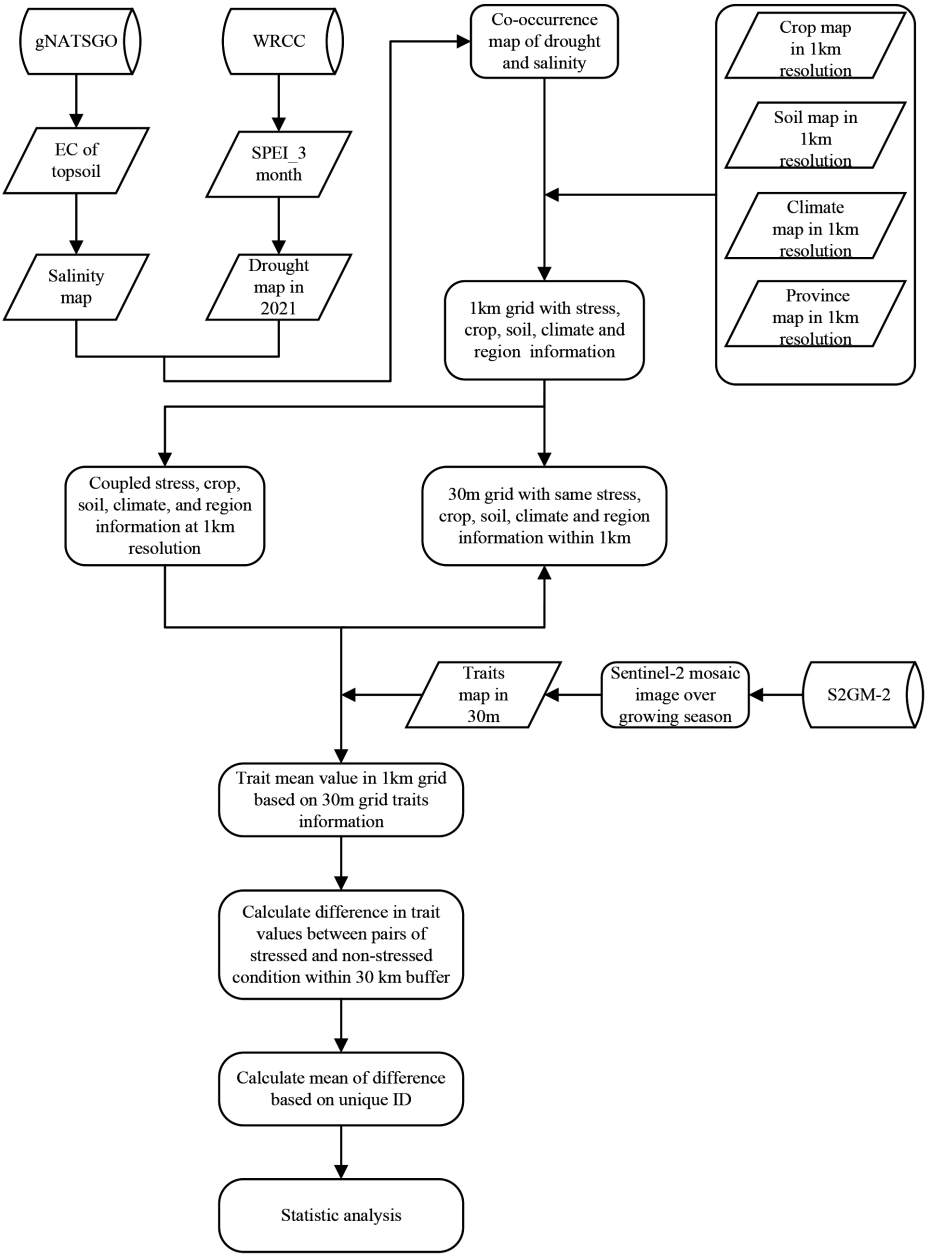

Figure S4-1 Technical workflow of pairwise dataset processing.

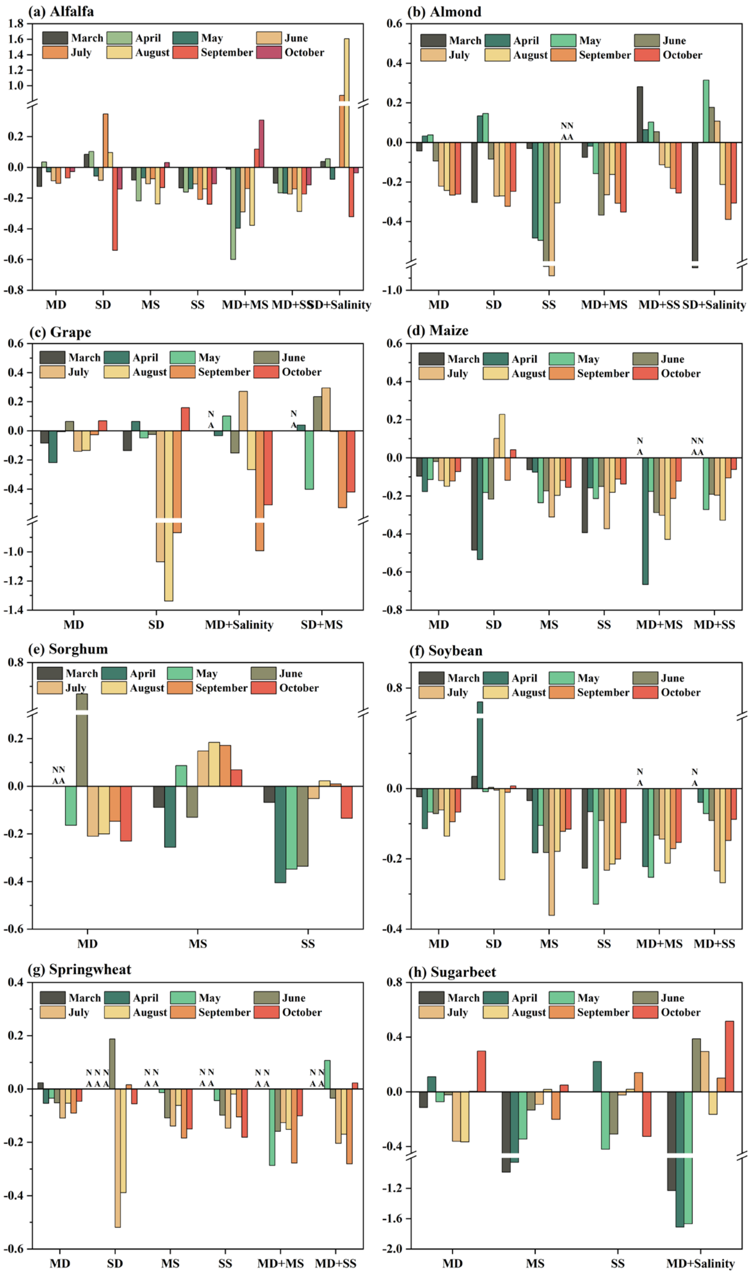

Figure S4-2. Expressions of LAI under various stress conditions for eight crops from March to October in 2021. MS, moderate salinity only; SS, severe salinity only; MD, moderate drought only; SD, severe drought only; MD+MS, moderate drought and moderate salinity; SD+MS, severe drought and moderate salinity; MD+SS, moderate drought and severe salinity; SD+SS, severe drought and severe salinity; MD+Salinity, moderate drought and salinity; SD+Salinity, severe drought and salinity; NA, the stress condition is not applicable to that month.

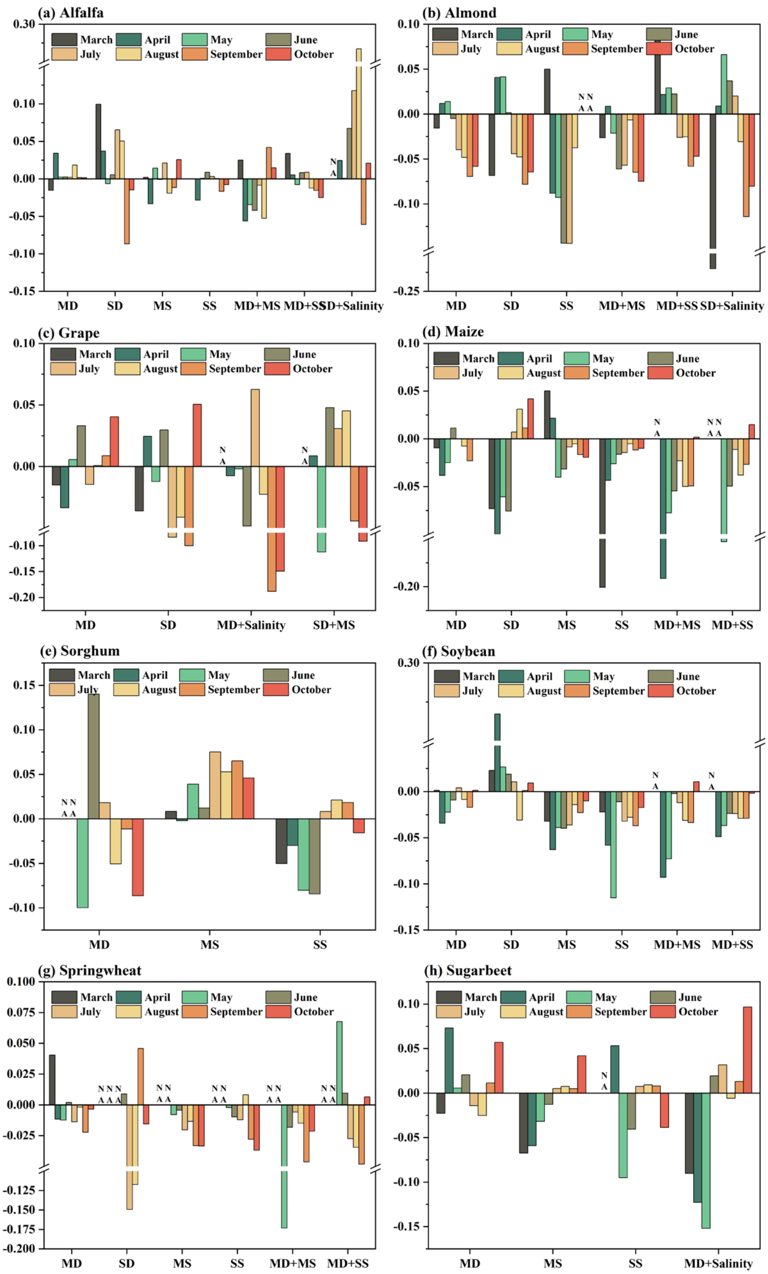

Figure S4-3. Expressions of FAPAR under various stress conditions for eight crops from March to October in 2021. MS, moderate salinity only; SS, severe salinity only; MD, moderate drought only; SD, severe drought only; MD+MS, moderate drought and moderate salinity; SD+MS, severe drought and moderate salinity; MD+SS, moderate drought and severe salinity; SD+SS, severe drought and severe salinity; MD+Salinity, moderate drought and salinity; SD+Salinity, severe drought and salinity; NA, the stress condition is not applicable to that month.

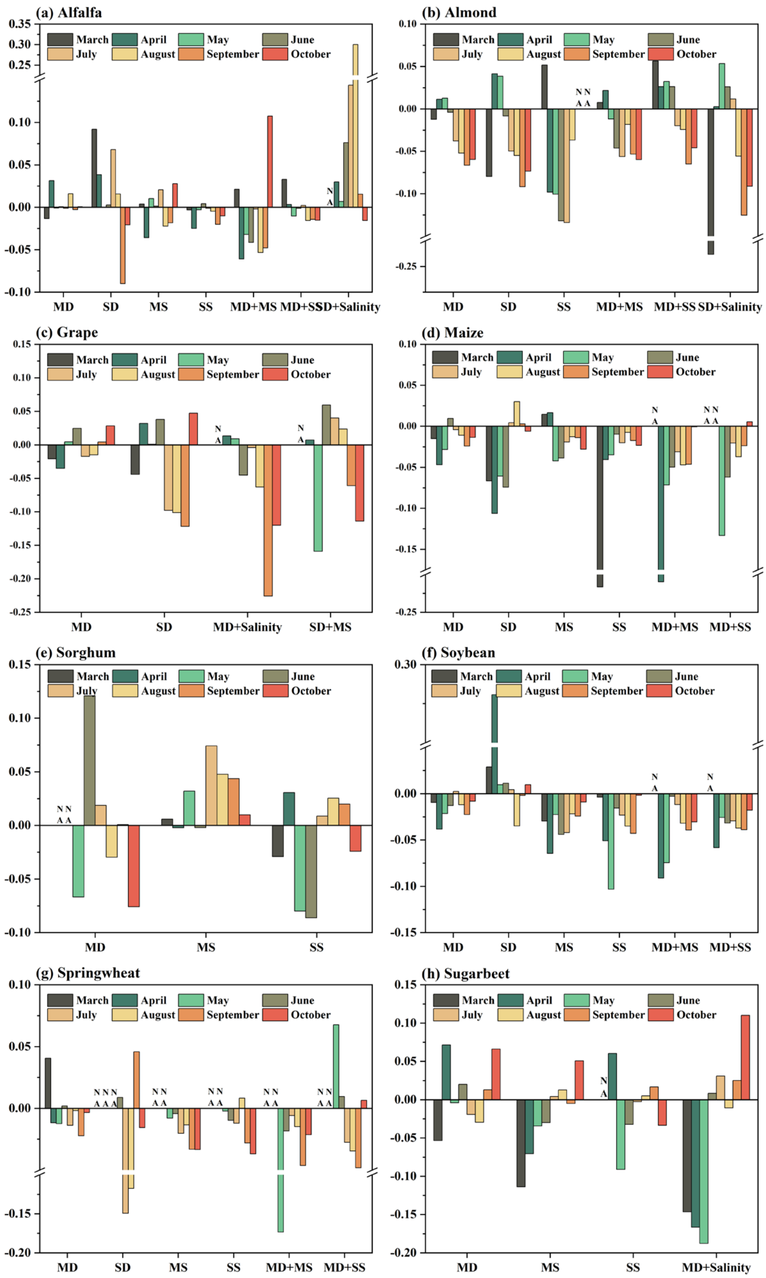

Figure S4-4. Expressions of FVC under various stress conditions for eight crops from March to October in 2021. MS, moderate salinity only; SS, severe salinity only; MD, moderate drought only; SD, severe drought only; MD+MS, moderate drought and moderate salinity; SD+MS, severe drought and moderate salinity; MD+SS, moderate drought and severe salinity; SD+SS, severe drought and severe salinity; MD+Salinity, moderate drought and salinity; SD+Salinity, severe drought and salinity; NA, the stress condition is not applicable to that month.

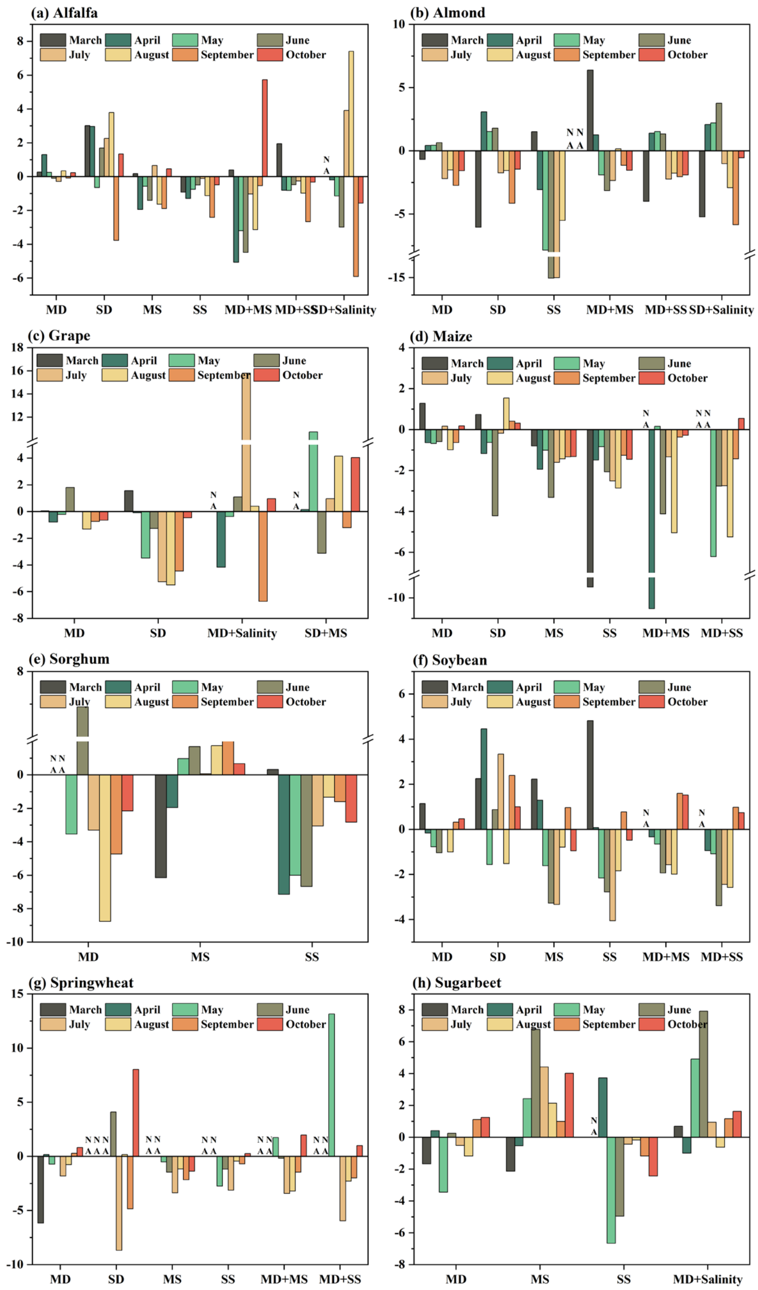

Figure S4-5. Expressions of Cab under various stress conditions for eight crops from March to October in 2021. MS, moderate salinity only; SS, severe salinity only; MD, moderate drought only; SD, severe drought only; MD+MS, moderate drought and moderate salinity; SD+MS, severe drought and moderate salinity; MD+SS, moderate drought and severe salinity; SD+SS, severe drought and severe salinity; MD+Salinity, moderate drought and salinity; SD+Salinity, severe drought and salinity; NA, the stress condition is not applicable to that month.

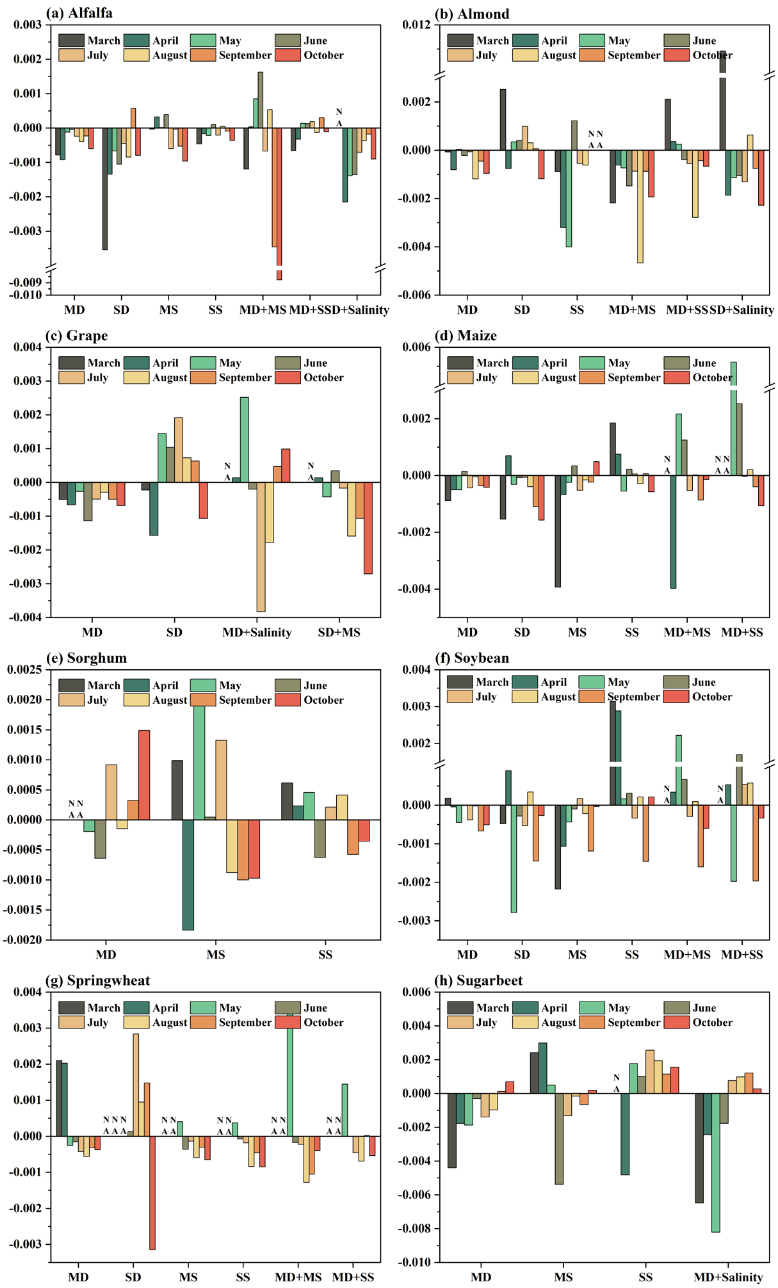

Figure S4-6. Expressions of Cw under various stress conditions for eight crops from March to October in 2021. MS, moderate salinity only; SS, severe salinity only; MD, moderate drought only; SD, severe drought only; MD+MS, moderate drought and moderate salinity; SD+MS, severe drought and moderate salinity; MD+SS, moderate drought and severe salinity; SD+SS, severe drought and severe salinity; MD+Salinity, moderate drought and salinity; SD+Salinity, severe drought and salinity; NA, the stress condition is not applicable to that month.

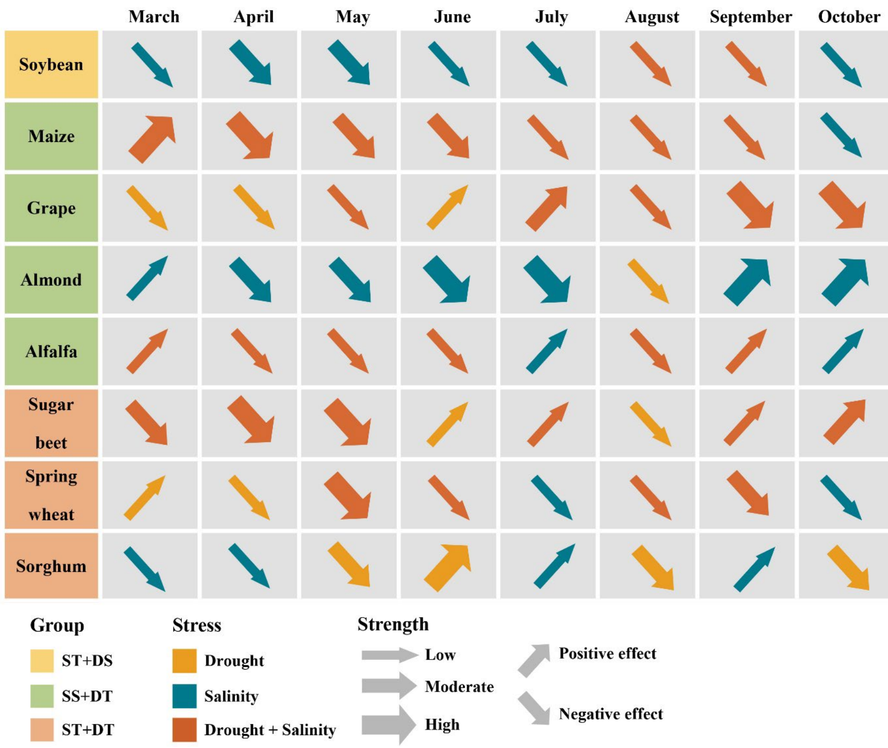

Figure S4-7. The pattern of FAPAR, expressing the severest stress conditions in different months. ST+DS indicates salt-tolerant and drought-sensitive crop; SS+DT indicates salt-sensitive and drought-tolerant crop; ST+DT indicates salt-tolerant and drought-tolerant crop; in strength, low indicates a difference between stress pixels and control pixels smaller than 0.05 (unitless), moderate indicates a difference between stress pixels and control pixels between 0.05 and 0.1, high indicates a difference between stress pixels and control pixels greater than 0.1; positive effect and negative effect indicate the direction of the pair-wise differences between stress pixels and control pixels.

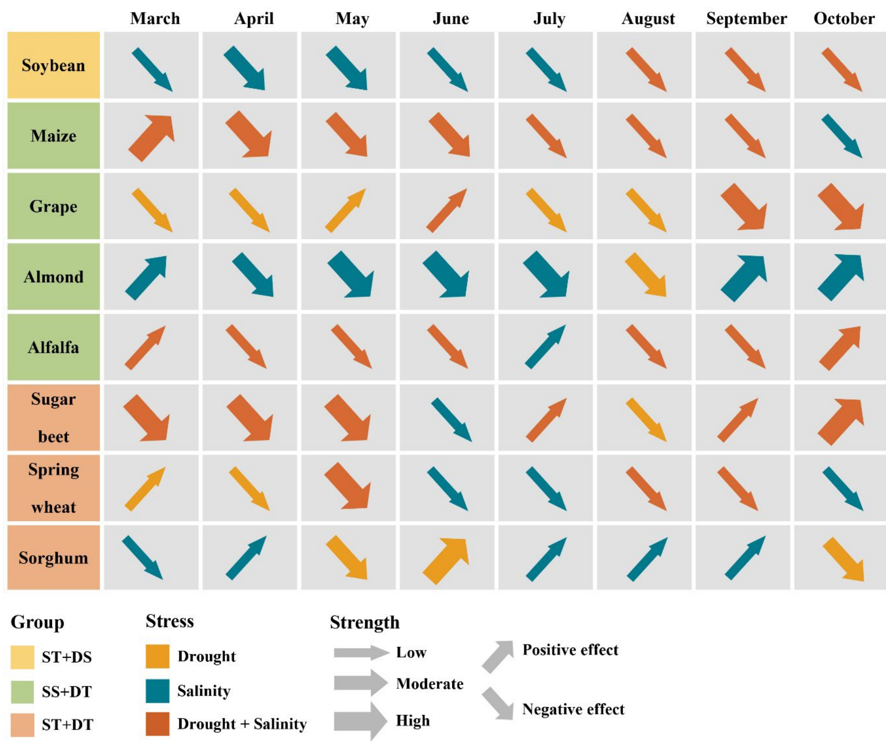

Figure S4-8. The pattern of FVC, expressing the severest stress conditions in different months. ST+DS indicates salt-tolerant and drought-sensitive crop; SS+DT indicates salt-sensitive and drought-tolerant crop; ST+DT indicates salt-tolerant and drought-tolerant crop; in strength, low indicates a difference between stress pixels and control pixels smaller than 0.05 (unitless), moderate indicates a difference between stress pixels and control pixels between 0.05 and 0.1, high indicates a difference between stress pixels and control pixels greater than 0.1; positive effect and negative effect indicate the direction of the pair-wise differences between stress pixels and control pixels.

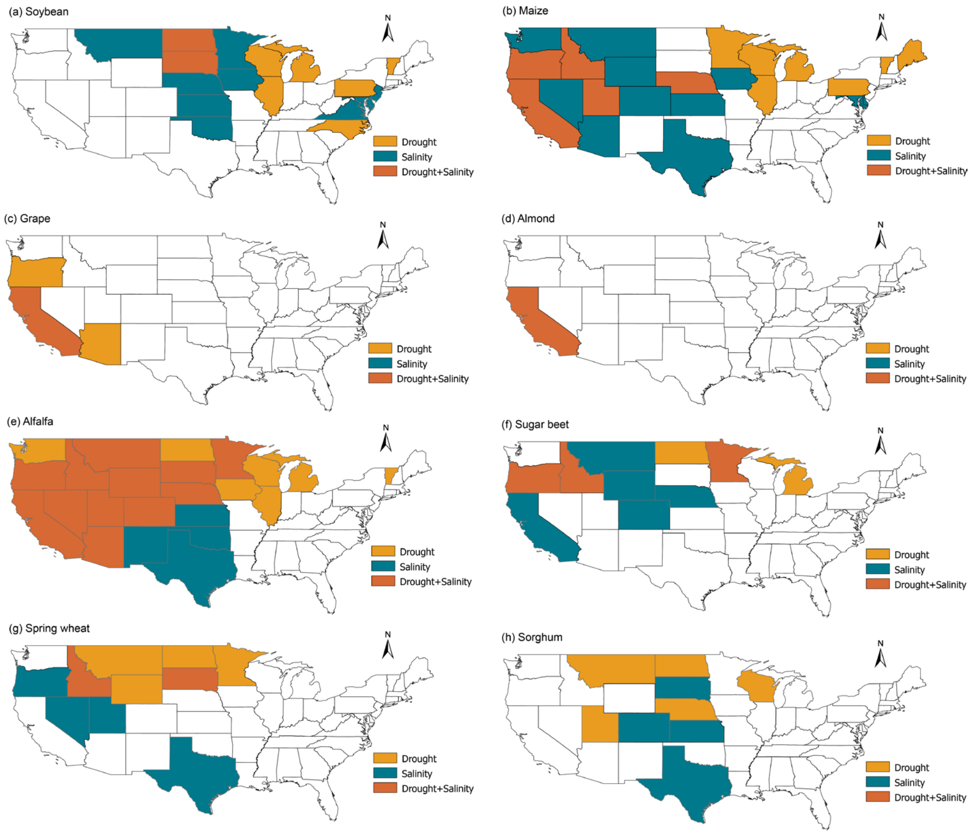

Figure S4-9. The spatial variation of LAI by states for eight crops.

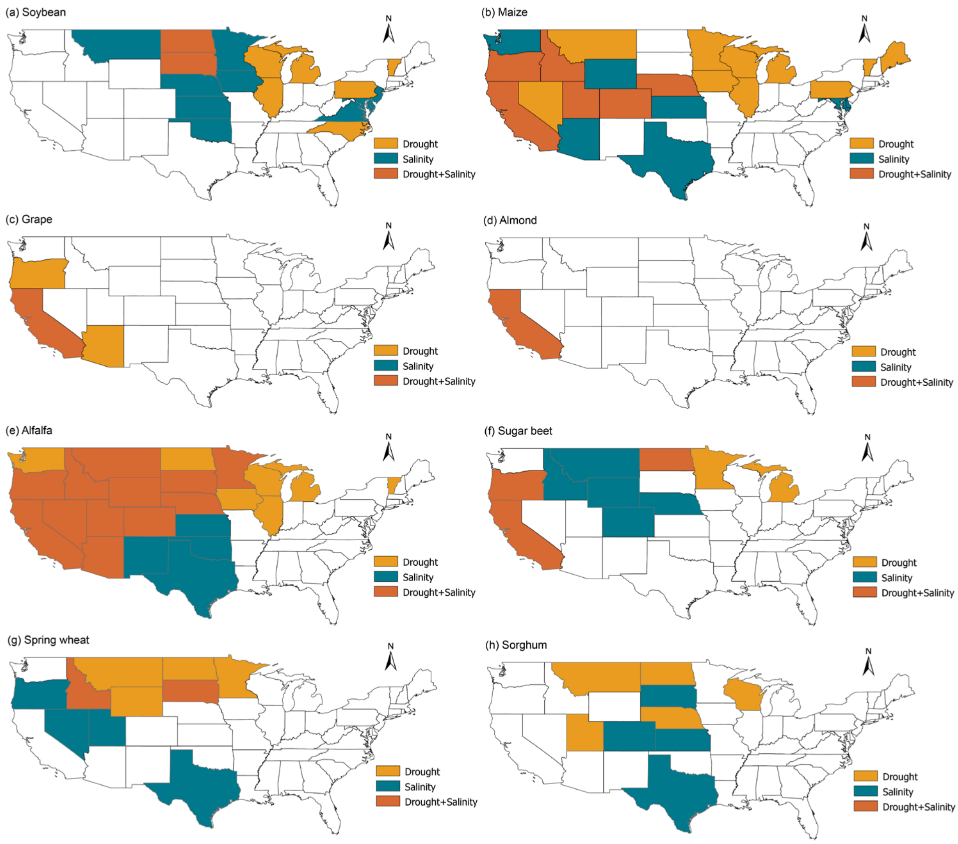

Figure S4-10. The spatial variation of FAPAR by states for eight crops.

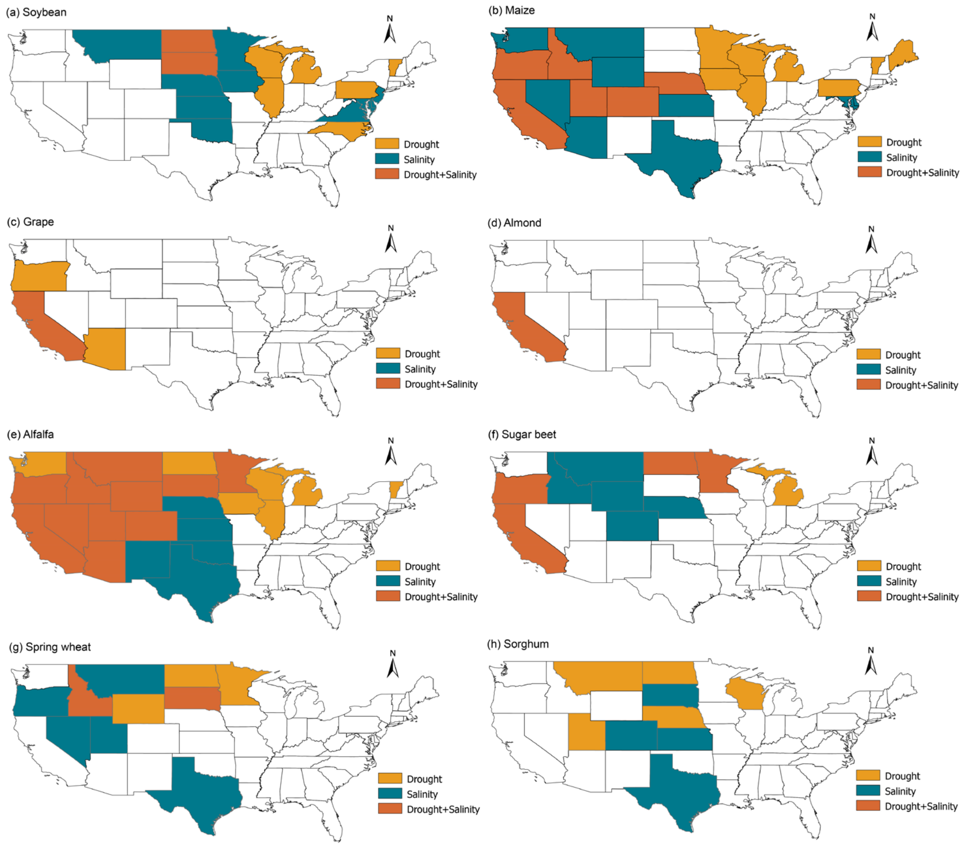

Figure S4-11. The spatial variation of FVC by states for eight crops.

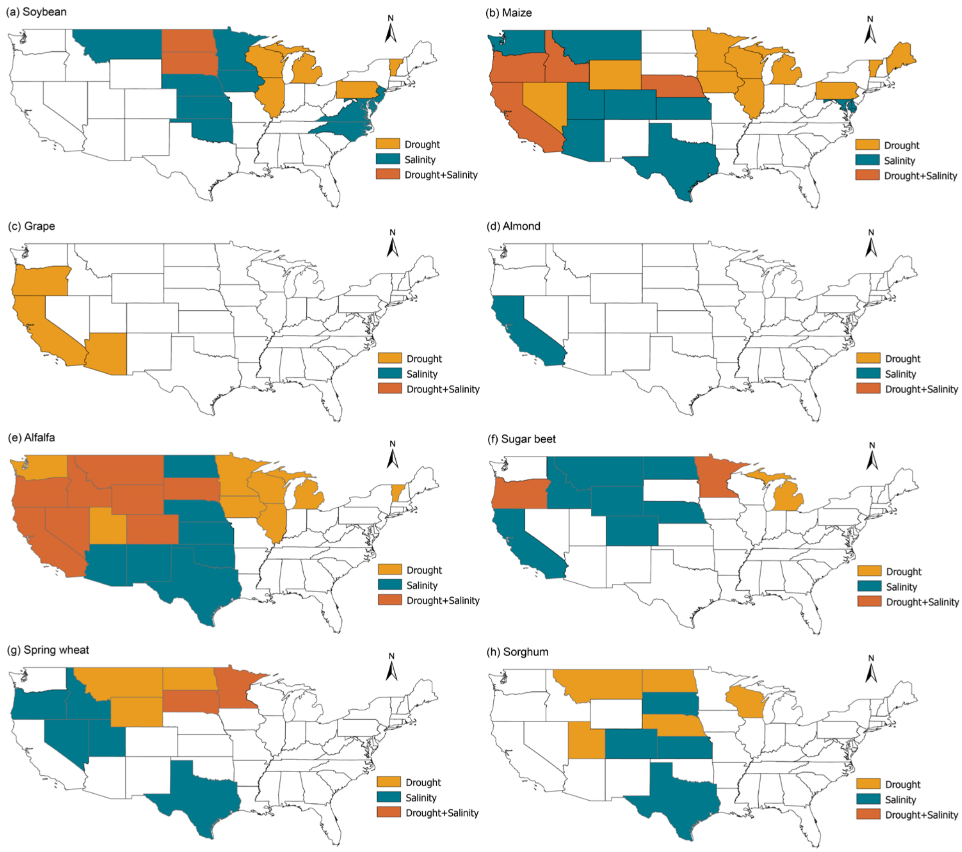

Figure S4-12. The spatial variation of Cab by states for eight crops.

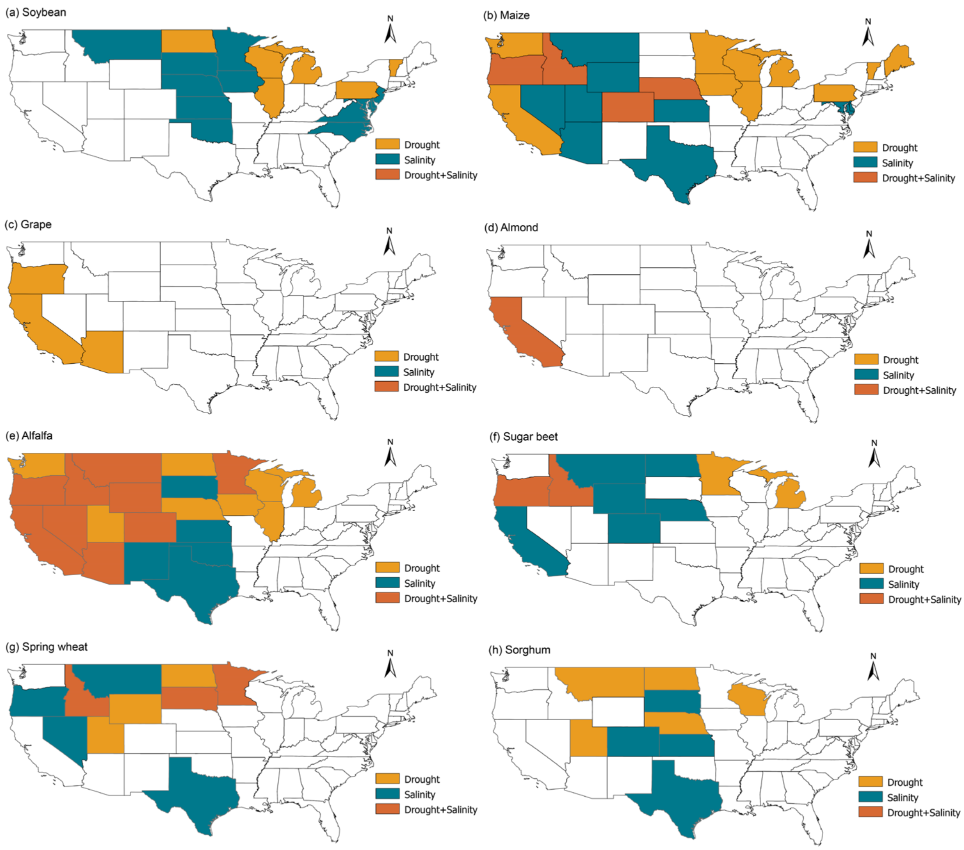

Figure S4-13. The spatial variation of Cw by states for eight crops.