# European-wide ecosystem responses and their vulnerability to intensive drought

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# Chapter 6

# General discussion

This thesis aims to provide a comprehensive understanding of the vulnerability of different vegetation types to drought in terms of the various responses of vegetation from a large-scale perspective. In face of the projections of devastating droughts for many regions of the world, mitigating drought impacts on ecosystems becomes crucial. Protecting and conserving ecosystems requires a thorough understanding of the vulnerability of each vegetation type in terms of their sensitivity to variations in drought conditions. Remote sensing provides a tool to simultaneously monitor a broad range of ecosystems under a wide range of drought conditions and environmental drivers.

This thesis reveals that the vulnerability to drought varied between vegetation types across Europe. Changes in canopy leaf area for different vegetation types, as detected by remote sensing, showed different sensitivities in response time, and response extent to drought (Chapters 2 & 3). Furthermore, remote sensing based methods were applied to study the drought strategies of different vegetation types, by including responses of three key parameters of vegetation, i.e. canopy leaf area, canopy water content and evapotranspiration. These parameters relate to important carbon and water regulation processes of plants during drought and were found to vary between vegetation types (Chapter 4). This variety of drought strategies can help plants to adapt in different ways to environments with water stress. At the same time, these strategies seem to cause different impacts on the mortality of plants (Chapter 5). Monitoring strategies of plants thus gives the opportunity to identify the mechanisms leading to mortality during drought (Chapter 5). Through remote sensing, the four studies in this thesis reveal the risks of drought to various ecosystems, and provide theoretical support for mitigating these risks, thus having wide implications for future drought management.

## 6.1 Increasing vulnerability of ecosystems with intensified droughts

With the projected intensified droughts in the future, vegetation could suffer increasing growth vulnerability. In general, forests exhibit relatively low vulnerability compared to other vegetation types based on the analysis of drought impact on canopy leaf area (Chapters 2 & 3). Especially for mixed forests, the canopy damage increases slowly when drought conditions become severe. However, irrigated crops are more vulnerable and experience a rapid increase in damage as drought conditions become severe. Notably, chapter 3 reveals an increasing vulnerability of different types of vegetation under intensified drought conditions. That is, the vegetation type does not always maintain a constant sensitivity towards drought, but exhibits non-linearly increasing damages with increasingly severe drought conditions. This indicates that if droughts become more severe in the future, such vegetation types will face a bigger challenge to maintain their stability.

A new method for coupling drought and vegetation damage (i.e., the anomaly in canopy leaf area) events was created in chapters 2 and 3. This method allows the one-to-one analysis of each characteristic of drought events and the corresponding characteristic of anomaly vegetation events. This realizes the analysis of the relationship between the occurrence time, duration, and severity of drought and anomaly vegetation events. Compared with previous studies - that only analyzed the correlation between drought and vegetation damage - this method more accurately captures the internal relationships between these two events and further deepens the understanding of their relationships. Based on this method between event characteristics, the vulnerability of vegetation in ecosystems was further quantified (Chapter 3). An analytical framework like this can facilitate a more accurate prediction of future vegetation damage in different ecosystems based on multiple quantified relationships between drought and vegetation damage events.

Using this framework, chapter 2 revealed the vulnerability of vegetation growth for different vegetation types across the Netherlands and Belgium, while chapter 3 evaluated the same vulnerability across Europe. We found that in general the different vegetation types exhibit similar growth-vulnerability patterns across countries and continents, gradually becoming more vulnerable to drought among forests-grasslands-crops. Across Europe, there are more types of vegetation, and the distribution range of a particular vegetation type is wider, resulting in a wider range of droughts and vegetation anomalies within the growth-vulnerability pattern. Therefore, it is easier to quantify these vulnerability patterns of vegetation across wide spatial ranges, i.e., it is easier to investigate the sensitivity of vegetation damage changes with changes in drought severity. For the extent of Europe, rainfed croplands showed a relatively low vulnerability compared to a mosaic of natural vegetation and cropland, while these vegetation types showed similar vulnerability in the Netherlands and Belgium. Mosaics of natural vegetation and cropland within the Netherlands and Belgium mainly include crops (such as corn, potato, and barley), grasslands and natural areas. Rainfed croplands also mainly include these crops and grasslands. Although the proportion of natural areas varies among these vegetation types, the impact on their vulnerability to drought is tiny. There are more crop types within Europe, and the changes in the proportion of natural area may be more significant, resulting in a larger impact of the variation in vegetation type composition within one ecosystem on vulnerability to drought. Overall, we found a clear and consistent pattern of the vulnerability of vegetation to drought across Europe, even though there are still variations in vegetation responses for different locations. This variation in vegetation response among locations is also significant within the national scope, even though that variation was more limited than at a European scale. The more narrow spatial range and likely more narrow range of environmental conditions probably explain this difference.

The increased vulnerability in different vegetation types also induces specific mortality probabilities (Chapter 5). European needleleaved evergreen forests showed high mortality during the drought of 2018. They seem to be more sensitive to increases in drought severity compared to broadleaved deciduous forests. Specifically, the high mortality sensitivity of needleleaved evergreen forests to increased drought severity indicates they are more likely to die due to drought compared to other forests, which will affect the composition of trees in the forest. In areas with frequent droughts, trees that are more likely to survive in drought may gradually occupy a dominant position in the evolution of forests. Indeed, increasing mortality under warming climate could change the species composition, structure and spatial distribution of biomes, disrupting the steady state maintained by the forest for centuries (Allen et al., 2015; Brodribb et al., 2020; Hammond et al., 2022). Even so, all forest types showed an increasing mortality in varying degrees with an increase in drought severity. This is consistent with previous studies which found that mortality increases with increasing drought intensity (Senf et al., 2020). This accumulating emerging evidence indicates that with the intensified droughts and warming under climate change, forest mortality will accelerate across many biomes (Hammond et al., 2022), thus posing a greater threat to forest survival.

## 6.2 Drought strategies detection through remote sensing

Chapters 2 and 3 mainly focused on the impacts caused by drought on vegetation canopy leaf area. In dry years, the changes in canopy leaf area compared with normal years can reflect the ability or inability of each vegetation type to maintain its productivity and structural stability. Therefore, the inhibition of vegetation growth by drought was revealed in these two chapters by investigating the abnormalities in LAI development. In addition to the negative effects on vegetation growth, drought also brings threats to the survival of vegetation. Vegetation growth and survival are sometimes decoupled during drought, since there may be a trade-off between growth and survival, due to limited possibilities for carbon investment: Vegetation may sustain growth regardless of water stress, or it may preferentially allocate resources to develop drought-resistant traits and processes for survival rather than maintain growth. Therefore, the change in canopy leaf area is only one aspect of the resource allocation and adjustment strategy of vegetation when facing of drought, and related to the carbon allocation strategy.

The overall drought vulnerability of specific ecosystems also requires the characterisation of the physiological responses of vegetation in other aspects. In times of drought, vegetation exerts water regulation by adjusting both the amount of water retained within the vegetation and the amount of water lost to the environment. During past drought events, hydraulic collapse was shown to widely impact forests and to be a critical cause of tree death (Arend et al., 2021). In response, we extended the approach used in chapters 2 and 3, with two additional parameters related to water strategies (i.e., canopy water content and evapotranspiration) detected through remote sensing to assess vegetation strategies to drought in chapters 4 and 5. This framework integrates key physiological processes related to vegetation mortality mechanisms, and the dynamic changes of these processes as monitored by remote sensing. This provides the possibility for large-scale remote sensing monitoring of vegetation strategies in future drought.

Based on the drought strategy framework we proposed previously, remote sensing estimates of LAI, NDII and ET were used to reflect changes in vegetation canopy leaf area, canopy water content and evapotranspiration in chapter 4. Based on these metrics, chapter 4 presents vegetation strategies composed of dynamic changes in three different physiological processes when different vegetation types face drought, including the adjustment time and extent of the three physiological processes response to drought. Corresponding to the findings of chapter 2 and chapter 3 that crops are relatively vulnerable to severe drought, crop strategies are also more sensitive to changes in drought severity, while forests are relatively insensitive. This is manifested as the severity of drought increases. At those conditions, crops may fail to retain biomass and water content at a certain point in time, but forests will maintain a relatively stable response despite the variation in drought severity. Furthermore, chapter 4 revealed that the adjustment of canopy water content and evapotranspiration sometimes deviates from the adjustments in canopy leaf area. Upon drought, some vegetation types tend to retain more biomass and allow for the loss of a certain amount of water content. For example, mixed forests showed late and low leaf area decrease but an early and high decrease in canopy water content under drought. Other vegetation types tend to retain their canopy water content and allow the reduction of canopy biomass. For instance, needleleaved deciduous forests showed a late and low decrease in canopy water content with an early decrease in canopy leaf area.

Faced with drought, various physiological processes within different vegetation types will undergo adjustments at different time points, forming unique response strategies of different vegetation types (Bartletta et al., 2016). The underlying mechanisms of mortality in different vegetation types are therefore various (Adams et al., 2017). For example, needleleaved evergreen forests will quickly adjust their evapotranspiration and try to maintain their canopy leaf area, while their canopy water content decreases in general. Once the water potential decreases beyond the hydraulic safety margin of trees, they will face hydraulic failure. Furthermore, this type of tree has a low ability to recover from such embolism (Anderegg et al., 2016). Broadleaved deciduous forests may drop leaves in drought while their leaves will try to maintain evaporation, and although they are more prone to embolism with reduced water content, they have a higher ability to recover from it (Anderegg et al., 2016; Johnson et al., 2012). Thus, needleleaved evergreen forests can actually suffer high mortality during drought despite their ability in maintain canopy leaf area. In conclusion, monitoring only one certain physiological process of vegetation cannot capture the impact of drought in a system's view, let alone gain a deeper understanding of the regulation processes related to vegetation mortality and the critical physiological response that is fatal to vegetation. In addition to the monitoring of canopy leaf area, the monitoring of other physiological responses of these two types of forests, such as water content and evapotranspiration, is particularly important for detecting future forest vulnerabilities.

Previous vegetation drought strategy research was commonly limited to local field measurement data which cannot realize large-scale strategy investigations, making it difficult to study drought strategies at ecosystem and continent scales. Remote sensing provides a technical means of large-scale real-time monitoring. However, in the past, it was only applied to monitor the changes in individual physiological responses of plants (Chakraborty et al., 2018; Clark et al., 2008; Lyons et al., 2021). These previous studies did not investigate vegetation strategies due to the lack of a drought strategy framework applicable to the field of remote sensing. Different from the current drought strategy framework (differentiating between drought avoidance, drought tolerance, and drought escape) and the hydraulic strategy framework (which distinguishes isohydric or anisohydric responses) that require a variety of in-situ measurements, the drought strategy framework developed in this thesis integrates key water and carbon regulation processes of vegetation during drought, enabling a more direct and simple assessment of vegetation strategies through remote sensing. The vegetation drought strategy as monitored by remote sensing allows for a comprehensive assessment of global drought impacts on key physiological processes of vegetation and provides a new perspective for related drought impact analysis. In addition, it can provide basic data at the ecosystem level for further research on vegetation mortality probability and mortality mechanisms during drought. In view of the impact of vegetation strategies on the mortality of various vegetation types (Chapter 5), the vegetation drought strategy detected by remote sensing can provide real-time and large-scale background parameters for future vegetation mortality prediction models, as well as be used as parameters for other Earth models to enhance model accuracy.

For further development of the framework and monitoring, high resolution remote sensing data sets which are applicable to the ecosystem level are desired for drought impact and ecosystem risk studies at large scale. For example, on a continental scale, the dataset SPEI used to evaluate drought conditions is usually limited to 25km (Sun et al., 2018). Likewise, the VOD data which represents the water content of vegetation is also limited to 25km resolution (Du et al., 2017; Moesinger et al., 2020). This resolution is not sufficient for analyzing vegetation response to drought at the ecosystem level. Therefore, a high-resolution SPEI dataset was calculated in this thesis based on an integrated precipitation data and potential evapotranspiration data from MOD16A2. At the same time, we calculated water content data at 1 km resolution based on Modis MOD09A1. Although this water content dataset enables ecosystem-level studies within Europe, high-resolution vegetation water content data on a global scale are still needed for future studies of ecosystem responses, such as developing new high-resolution VOD datasets or water content data derived from high resolution images like Sentinel.

Despite the higher resolution application of remote sensing at an ecosystem scale in this thesis, accurate detection of vegetation strategies on species scale could still not be achieved. At the same time, the drought regulation strategy of vegetation is considered to depend on the individual species within a given ecosystem (Li et al., 2019; Martínez-Vilalta and Garcia-Forner, 2017; Vilagrosa et al., 2003). Research of drought strategies for different species will therefore likely produce a more accurate vegetation strategy map. In this case, the development and usage of hyperspectral data can help achieve the recognition of vegetation species, while high resolution remote sensing data can extract higher precision vegetation responses, making it possible to monitor vegetation strategies at wide extents at species level. For example, for large-scale applications, high-resolution vegetation parameters based on Sentinel are still needed and can be applied in the future analysis of vegetation strategies. At smaller scales, the application of airborne instruments in specific plots can help to capture the accurate vegetation strategies and provide validation to large scale monitoring. In addition, field survey data is also important in further drought strategy analysis. For instance, the on-site measurement of regional environmental data is helpful for the monitoring and analysis of the drought strategies of individual species in different locations, which can reveal the impact of regional conditions on vegetation regulation strategies.

## 6.3 Early warning signals for forest mortality

Based on the observed empirical relationship between drought severity and forest mortality (Chapter 5), forest mortality is expected to increase with increasing drought severity in the future (Senf et al., 2020). However, plants have regulatory capabilities during drought, and how these regulatory capabilities will affect mortality is not clear. By utilizing the potential of remote sensing to capture multiple aspects of plant strategies to drought, we were able to further analyze the impact of these strategies on tree mortality. We found that a large proportion of trees that had died in 2018 showed significantly abnormal changes in canopy water content. Therefore, the vegetation water regulation process is particularly important for the survival of vegetation during drought. In addition to the high mortality of trees with high reductions in canopy water content, forests with a high reduction in both canopy water content and leaf area also showed a relatively high mortality. These findings can provide early warning signals for forest mortality in future droughts. For example, a detection of early dropping leaves and early loss in water content of trees during drought warns of a high possibility of tree mortality and thus further follow-up inspection and timely implementation of protective measures is required for those trees.

Current early warning signals are mostly based on greenness-based indicators (Anderegg et al., 2019; Liu et al., 2019). However, greenness is not directly linked to mortality mechanisms of forests. Instead, the changes in vegetation greenness are related to changes in other physiological responses of vegetation. Thus, the change of greenness is not enough for providing a critical explanation of plant mortality. In addition, relying solely on greenness to provide vegetation mortality warnings may miss earlier warning signals and miss the best opportunity for rescue, such as an early decrease in vegetation water content. As hydraulic failure is one of the key mechanisms of tree mortality, the use of remote sensing to detect water content changes in forests during drought has attracted widespread interest (Anderegg et al., 2014; Asner et al., 2016; Martin et al., 2018). Our results reveal a critical influence of tree water content variability on the probability of the mortality through remote sensing. Furthermore, a high reduction of water content as well as leaf area in forests indicates a higher mortality probability than solely high reduction of water content. This indicates that various anomaly physiological responses of vegetation during drought, including water and carbon anomalies, may cause dual pressure on vegetation and increase mortality. Therefore, monitoring multiple physiological responses of vegetation during drought through remote sensing can better indicate the probability of mortality compared to single physiological response monitoring. However, abnormal changes in water content and canopy leaf area can only indicate a high probability of tree mortality, and more accurate tree mortality prediction still requires a more comprehensive analysis of tree physiological responses in the future.

The three physiological processes in our thesis reflect the water and carbon management of vegetation in general, while they only provide part of the early warning signals for tree mortality. Apart from these physiological processes, several other factors may also affect tree mortality. Tree height, for example, is thought to be a strong predictor of tree mortality during extreme drought. Some researchers believe that taller trees have greater hydraulic vulnerability and thus show higher mortality during drought (Stovall et al., 2019). However, this is still a controversial conclusion, with some researchers believing that the high mortality of big trees depends more on the composition of trees in the forest and the idiosyncratic host-tree selection of bark beetle (Stephenson and Das, 2020). Drought-induced insect infestation is indeed an important cause of tree death, and especially coniferous forests are particularly vulnerable to beetle attacks. Therefore, early warning of infestations of insects is also important for forest protection. Forests with low tree species richness can be more likely to be attacked (Jaime et al., 2022). The composition of forest stands may help to identify vulnerable plots and provide help for early warning of bark beetle infestations. Early detection of bark beetle infestations was explored by remote sensing such as using sentinel-2 data to map the bark beetle infestation at the green-attack stage (Fernandez-Carrillo et al., 2020; Stephenson and Das, 2020). In combination, these assessments may provide assistance for mortality prediction and forest management.

The combination of high-resolution detection (to identify individuals with high mortality probability) with large scale real-time remote sensing detection (to continuously characterize vulnerability at large scale) is important for early warning of forest insect infestations in the future (Hlásny et al., 2021). Early warning signals of tree mortality detected by remote sensing at large scale can rapidly locate forest areas at risk during drought. However, due to the limitation of the resolution of remote sensing data, it is still impossible to identify the mortality probability of individuals in forests. The mortality pattern of trees has a high spatial heterogeneity, and the response of individual trees cannot be represented by the regional response of large-scale forests due to the different geographical environments around them (soil, microorganism, water content) (Dorman et al., 2015; Lines et al., 2010). Therefore, after locating high-vulnerability areas, more detailed high-resolution tracking and field measurement surveys can further locate individuals at risk of mortality as mentioned previously. For example, one may use above mentioned Sentinel data or other high-resolution images like Worldview, Geoeye or drones to track unhealthy tree individuals. In addition to allowing prevention of pest outbreaks, this systematic early warning framework can be widely used in the prevention of forest tree mortality during drought due to other death mechanisms. For instance, it may allow early detection and subsequent inspection of trees that may die from water failure or carbon starvation. This systematic investigation from top to bottom allows effectively combining the advantages of large-scale monitoring and high-resolution monitoring, providing effective tools for tailored forest management. Therefore, such early warning and investigation systems are expected to be developed in future research.

## 6.4 Societal implications

To ensure a sustainable future for humankind, significant advances need to be made to reduce the impacts of the rising global water scarcity with the rising temperatures in the future. By 2030, the Sustainable Development Goals (SDGs) aim to reduce water scarcity by significantly increasing the efficiency in water use across all sectors. The conservation of high-risk biomes should also be strengthened in future drought management (SDG 6)(United Nations, 2018). In this study we show that under more severe drought conditions, the canopy of irrigated crops and rainfed tree/shrub croplands is highly vulnerable, which indicates that their biomass and crop yield will be more affected by drought. Thus, in future drought management, information on drought vulnerability of these crop types should be incorporated, to allow for more efficient drought mitigation measures. In particular, we emphasize the combination of a quick response time and large growth damage of these crops to drought. Following this, the management in these crops requires especially quick and efficient actions. In this case, preparation for protection in advance should be strengthened in these crop types, such as developing more water-efficient allocation systems and cultivating drought-resistant crop species to improve the resistance of these crops (IPCC, 2019).

In forest management, more attention should be paid to needleleaved evergreen forests and mixed forests due to their higher mortality during drought. For instance, more resources could be allocated for monitoring and managing these forests, including the distribution of more economic support and building comprehensive management system targeted to the protection of these forests. Needleleaved evergreen forests are especially vulnerable to drought-induced bark beetle infestation (Ayres and Lombardero, 2000; Berthelot et al., 2021; Gan, 2004). Over the last decades, the bark beetle outbreaks in the northern hemisphere have reached unprecedented levels, causing a large number of deaths in coniferous forests. Thus, the prevention of outbreaks and timely management of infected trees are crucial in these forests. In addition, the mortality probability of trees is associated with their different strategies. Therefore, increasing the diversity of hydraulic strategies in forests can effectively increase ecosystem resilience during drought (Anderegg et al., 2018). Different drought strategies can be represented by different tree species. Thus, the changing of the species composition in forests such as preserving more drought-resistant tree species can help to change the resistance of the whole forest system (Bradford et al., 2022; Griess et al., 2012). Thinning has also been considered as one of the useful methods to mitigate the effects of droughts on forests, since thinning temporarily reduces competition in areas with severe soil water deficits and changes forest composition, which can increase the resistance of a forest against drought and bark beetles (Allen et al., 2010; Sohn et al., 2016).

Although many European countries have adopted legislation that requires monitoring, control, and intervention to mitigate the effects of natural disturbances on forests, more systematic and comprehensive monitoring of forests is still needed (Hlásny et al., 2021). The communication between government and management personnel with scientific researchers should be strengthened to enable utilizing these technological and innovative advantages to better manage forests. For example, developing and applying above mentioned systematic early warning framework at a national level will make the prevention of forest mortality more systematic and targeted, avoid wasting of management resources, and provide a theoretical basis for accurate control measures. In particular, for the management of infestations, this fast-tracking and positioning of infected trees can help to process or remove infected trees as early as possible, thus preventing the large-scale expansion of pests and diseases in the forest, and minimizing the loss of forests caused by drought-induced pest outbreaks.

It is important to have forest management personnel on site who possess the professional knowledge for the protection of forests under extreme weather conditions. For example, training employees in forest management with the knowledge of early warning signals of drought stress on vegetation like the early decrease in leaf area and leaf water content. This will facilitate the early implementation of active prevention and control of drought impacts and other drought-related infections. At the same time, a comprehensive monitoring and management network is also important for forest protection. Local communities often have a deeper understanding of local environmental conditions and forest conditions. Therefore, strengthening the communication with local communities, and engaging in dialogues with other stakeholders can help to improve the efficiency of control measures. By actively exchanging relevant management policies and knowledge with the public, public awareness of protection can be enhanced, which is beneficial for individuals to play a positive role in protection.

## 6.5 Conclusions

This thesis addressed the potential of remote sensing applications to assess ecosystem vulnerability and mortality probability. Remote sensing-based vulnerability analysis reveals particularly vulnerable ecosystems, providing a theoretical basis for implementing different priority management measures for ecosystems with different vulnerabilities under future drought. In addition, drought strategies detected from remote sensing provide continuous data in time and space for future research on drought impact and risk predictions, which will benefit from the establishment of a drought strategy framework for global ecosystems. Based on drought strategies detected from remote sensing, probability analysis of forest mortality provides early warning signals for drought management in forest systems.

Remote sensing offers a wide range of analytical advantages for drought impact analysis. However, due to limitations in the spatial resolution of current remote sensing data, the responses of individual species in ecosystems cannot be assessed. Different species are usually considered to have various response strategies in response to drought. In future research, a combination of species data detected by hyperspectral data and vegetation response data extracted from high-resolution remote sensing data will allow to monitor and analyze vegetation drought strategies at the species level. Thus, high-resolution remote sensing data are still needed for future ecosystem response analysis. This will help to further accurately reveal global vegetation drought strategies, and at the same time provide real-time global data parameters for Earth system models, providing a basis for the development of future drought vegetation prediction models.

In summary, this thesis reveals that in the face of drier environmental conditions in the context of climate change, ecosystems will be more vulnerable and face more severe survival challenges. In particular for forest ecosystems, accumulating evidence suggests that mortality increases as drought becomes more severe, which may change the structure and function of forests. Therefore, it is critical to conduct effective ecosystem conservation and management to prepare for future droughts. In the face of multi-faceted water pressures during drought, prioritizing the protection of more vulnerable ecosystems and implementing hierarchical management will help to maximize resource utilization and ecosystem preservation. At the same time, strengthening the dynamic monitoring of ecosystem during drought, especially combining the advantages of remote sensing, will provide critical information for earlier disaster prevention and timely ecosystem protection.

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