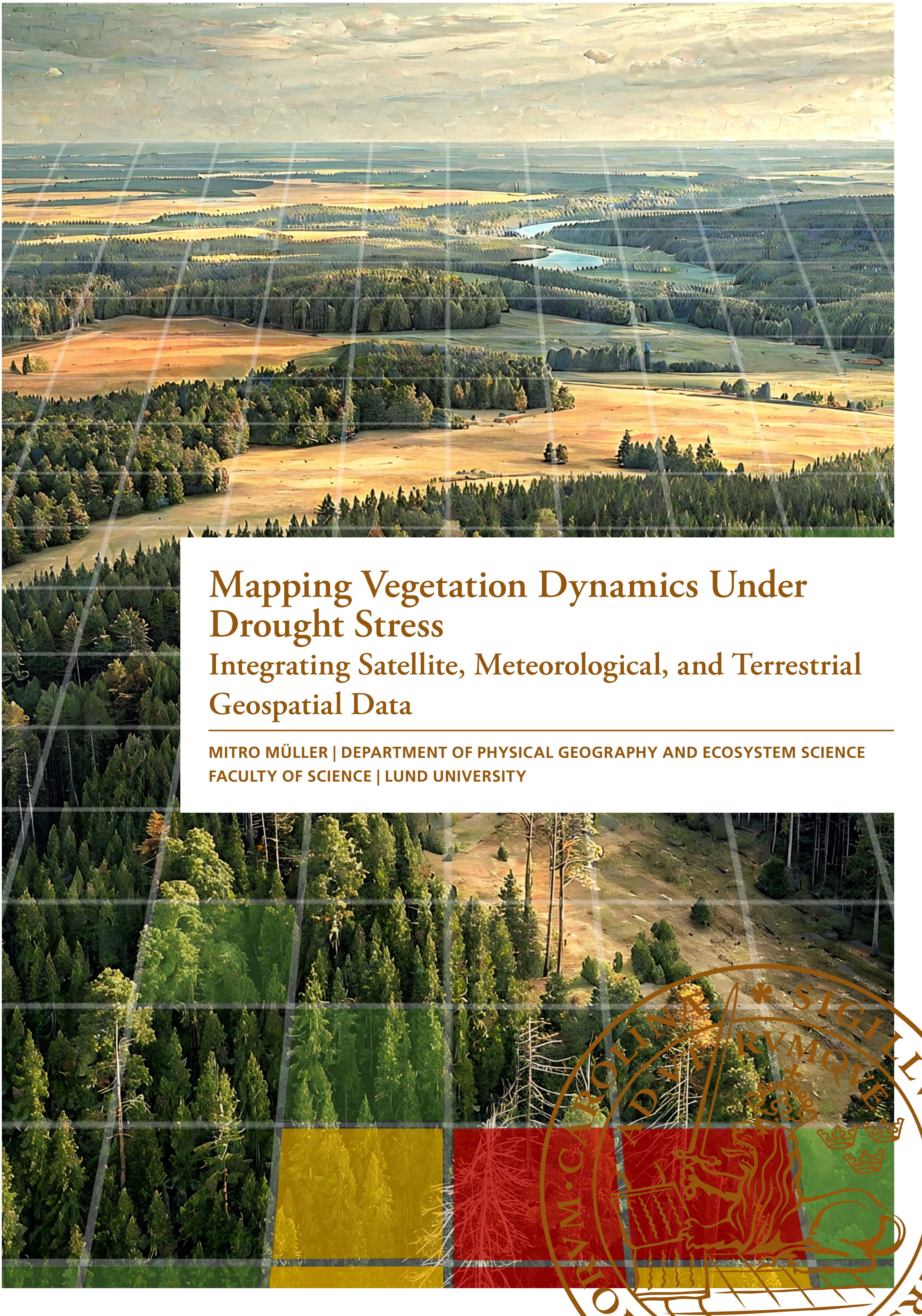
Mapping Vegetation Dynamics Under Drought Stress

Integrating Satellite, Meteorological, and Terrestrial Geospatial Data

Müller, Mitro

2025

Document Version:
Publisher's PDF, also known as Version of record



Mapping Vegetation Dynamics Under Drought Stress

Integrating Satellite, Meteorological, and Terrestrial Geospatial Data

MITRO MÜLLER | DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE
FACULTY OF SCIENCE | LUND UNIVERSITY

Mapping Vegetation Dynamics Under Drought Stress

Integrating Satellite, Meteorological, and Terrestrial Geospatial Data

Mitro Müller

DOCTORAL DISSERTATION

Dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Science at Lund University to be publicly defended on 9th of June, 2025, at 09.00 in Pangea Hall, of Department of Physical Geography and Ecosystem Science, Geocentrum II, Sölvegatan 12, Lund.

Faculty opponent
Professor Fabian Faßnacht

Organization: LUND UNIVERSITY, Department of Physical Geography and Ecosystem Science, Sölvegatan 12, Lund, Sweden

Document name: DOCTORAL DISSERTATION **Date of issue** 2025-06-09

Author(s): Mitro Müller **Sponsoring organization:**

Title and subtitle: Mapping Vegetation Dynamics Under Drought Stress: Integrating Satellite, Meteorological, and Terrestrial Geospatial Data

Abstract:

In an era of climate change, as the intensity and frequency of droughts are expected to increase, effective climate adaptation strategies become increasingly important for both natural ecosystems and society. Understanding vegetation's responses to drought and monitoring the impacts of drought on terrestrial ecosystems are essential for developing reliable decision-support systems. This thesis aimed to develop, test, and apply methodologies for detecting and quantifying the spatially explicit effects of drought on Swedish agricultural and forest ecosystems and their productivity. The thesis includes four research papers. Paper I focused on developing a change-detection framework that quantifies immediate and delayed drought-related vegetation changes in forest ecosystems and their recovery times. Results showed that using Sentinel-2 satellite data, successive stages of vegetation drought stress could be detected, and recovery times could be estimated. Paper II focused on identifying the drivers and mapping forest areas at high risk of disturbances from the European spruce bark beetle (Ips Typographus L.) due to drought-related effects. The forest stands predisposed to bark beetle attacks were accurately identified, and the methodology provided quantifiable information on the importance and dynamics of environmental features contributing to the predisposition risk. Paper III developed a causal inference framework to quantify the impacts of drought on crop yields while accounting for confounding variables. The methodology considered the effects of crop rotation and variations in local soil attributes, predicting regional and field level yields and identifying factors driving local variations in yield losses. Paper IV estimated the foliar and radial growth responses of Norway spruce (Picea abies (L.)) and Scots pine (Pinus sylvestris (L.)) trees to drought at a multidecadal level. Results indicate that the drivers of variance in annual radial growth were identified, with pine stands exhibiting higher drought resilience and faster recovery rates than spruce. Overall, this thesis demonstrates that effectively using multi-source geospatial data can identify and map the risks and effects of drought on forests and agricultural ecosystems over time and space, thereby enhancing our understanding of vegetation drought responses and resilience patterns. The methodologies presented in this thesis provide essential information for policy planning and decision-making supported by scientific knowledge, contributing to a shift towards more sustainable management practices in a changing climate.

Key words: climate change, drought, forest, agriculture, remote sensing, change detection, time series analysis, machine learning

Language English **Number of pages**: 57

ISBN (print)**:** 978-91-89187-53-5

ISBN (PDF): 978-91-89187-54-2

Recipient’s notes Price Security classification

Signature Date 2025-04-16

Mapping Vegetation Dynamics Under Drought Stress

Integrating Satellite, Meteorological, and Terrestrial Geospatial Data

Mitro Müller

LUND
UNIVERSITY

Faculty of Science

Department of Physical Geography and Ecosystem Science

ISBN (print) 978-91-89187-53-5

ISBN (PDF) 978-91-89187-54-2

Printed in Sweden by Media-Tryck, Lund University

Lund 2025

Media-Tryck is a Nordic Swan Ecolabel certified provider of printed material. Read more about our environmental work at www.mediatryck.lu.se

MADE IN SWEDEN

Table of Contents

Popular summary

The frequency and intensity of drought periods are predicted to increase in the future. This makes efficient climate adaptation and drought preparedness strategies important for natural ecosystems and society. However, the spatial and temporal heterogeneity of drought trends and the limited spatial coverage of meteorological stations pose challenges for current drought monitoring efforts. Therefore, methods capable of monitoring drought impacts on vegetation at high temporal and spatial resolution are crucial for developing climate-wise decision-support systems.

This thesis investigated the integration of multiple data sources and novel modelling methods to detect drought impacts on vegetation and map vulnerable areas over large extents in Swedish forests and agricultural regions. Climate datasets can describe climate forcing driving drought periods but struggle to describe micrometeorological heterogeneity in complex, terrain-rich landscapes. Geospatial data can help to identify vulnerable areas by characterising biotic and abiotic factors related to vegetation drought resilience. Still, most data cannot detect vegetation responses to drought in a spatially and temporally consistent manner. However, satellite remote sensing enables monitoring of vegetation state in pre-, during, and post-drought conditions. The integration of all these data sources allows for better data-driven decision-making.

Time series analysis of satellite data allowed the identification of drought responses, quantification of impacts, vegetation drought resilience, and recovery time in Swedish forests and agricultural regions. High temporal resolution was a prerequisite for detecting successive stages of vegetation stress related to drought progression. Changes in the physiological functions of vegetation, latency in response times, and variations in carbon allocation strategies were observed across multiple tree and crop species. Overall, this thesis demonstrates that by combining remote sensing, multi-source geospatial data, machine learning and methodologies aimed at understanding model behaviour, regions sensitive to drought and the factors contributing to the vegetation drought vulnerability can be identified.

Forests and agriculture are economically valuable, but they also provide various ecosystem services. As climate change progresses, it is important to consider the susceptibility of these ecosystems to future droughts and to understand when, where, and how management efforts can improve vegetation's drought resilience. The results of this thesis highlight the great potential of drought impact detection and mapping methods, demonstrating how they can help direct management actions more efficiently and facilitate decision-making that considers the changing climate.

Populärvetenskaplig sammanfattning

I framtiden väntas torkperioderna bli allt vanligare och mer intensiva. Detta gör att effektiva strategier för klimatanpassning och beredskap mot torka blir viktiga för både det naturliga ekosystemet och samhället. Den spatiala och tidsmässiga heterogeniteten i torkans trender i kombination med ett underskott av meteorologiska mätstationer innebär dock utmaningar övervakningen av torka. Därför är metoder som kan mäta effekterna av torka med hög tids- och spatialupplösning viktiga för att utveckla klimatsmarta beslutsstödsystem.

Denna avhandling undersökte integrationen av ett flertal olika datakällor och nya modelleringsmetoder för att undersöka torkans effekter och för att kartlägga utsatta områden i svenska skogs- och jordbruks-områden. Klimatdata kan belysa meteorologiska faktorer som driver torkperioder, men har svårt att klarlägga mikrometeorologisk heterogenitet i komplexa terrängrika landskap. Geospatial data kan i sin tur hjälpa till att identifiera sårbara områden genom att karakterisera biotiska och abiotiska faktorer relaterade till vegetationens tolerans mot torka, men har inte förmåga att mäta vegetationens reaktion på torka på ett spatialt och tidsmässigt konsekvent sätt. Fjärranalys med satellitdata möjliggör dock övervakning av vegetationens tillstånd både före, under och efter torka. Integrationen av alla dessa datakällor möjliggör därmed ett bättre datadrivet beslutsfattande.

Tidsserieanalys av satellitdata gjorde det möjligt att identifiera vegetationens reaktioner på torka samt att kvantifiera effekterna, motståndskraften och återhämtningstiden för svenska skogar och jordbruksregioner. Hög tidsupplösning var en viktig förutsättning för att upptäcka successiva stadier av vegetationsstress relaterad till torkans utveckling. Resultat relaterat till att upptäcka förändringar i vegetationens fysiologiska funktioner, latens i svarstider och variation i kolallokeringsstrategier mellan arter erhölls. Sammantaget visar denna avhandling att regioner som är sårbara för torka, samt faktorer som påverkar vegetationens tolerans för torka bättre kan identifieras genom att kombinera fjärranalys, geospatial data från ett flertal källor, maskininlärning och ytterligare metoder som syftar till att förstå modellbeteende.

Skogs- och jordbruksmark är ekonomiskt värdefulla, men de tillhandahåller också en mängd olika ekosystemtjänster. I takt med att klimatförändringarna fortskrider är det viktigt att beakta dessa ekosystems känslighet för torka i framtiden och att bättre förstå när, var och hur förvaltningsåtgärder kan förbättra motståndskraften mot torka. Resultaten av denna avhandling belyser metoder som har stor potential att upptäcka och kartlägga effekterna av torka på vegetationen, och hur de vidare kan bidra till att mer effektivt rikta förvaltningsåtgärder och underlätta beslutsfattande som tar hänsyn till det förändrade klimatet.

List of Papers

I **Müller, M.**, Olsson, P.-O., Eklundh, L., Jamali, S., & Ardö, J. (2024). *Response and resilience to drought in northern forests revealed by Sentinel-2*. International Journal of Remote Sensing, 45(15), 5130-5157. https://doi.org/10.1080/01431161.2024.2372076

II **Müller, M.**, Olsson, P. O., Eklundh, L., Jamali, S., & Ardö, J. (2022). *Features predisposing forests to bark beetle outbreaks and their dynamics during drought.* Forest Ecology and Management, 523, 120480. https://doi.org/https://doi.org/10.1016/j.foreco.2022.120480

III **Müller, M.**, Thapa, S., Bouras, E-H., Olsson, P-O., Jamali, S., Eklundh, L., Ardö, J. *Using Sentinel-2 data to quantify the impacts of drought on crop yields at local and regional scales in Sweden*. Manuscript under review at Agricultural and Forest Meteorology

IV **Müller, M.**, Ogana, F., Holmström, E., Drobyshev, I., Olsson, P-O., Ardö, J. *Foliar Dynamics and Radial Growth Under Drought: A Multidecadal Satellite Study of Norway Spruce and Scots Pine*. Manuscript in preparation

Author's contribution to the papers

I **MM** and JA conceptualised the study. **MM** designed the methodology and conducted data curation and formal analysis. JA was responsible for funding acquisition and project administration. JA, LE, SJ and PO supervised the project. **MM** wrote the initial draft. All authors contributed to reviewing and editing the draft.

II **MM**, PO, JA, SJ, and LE conceptualised the study. MM designed the methodology. MM and PO collected resources, curated the data, and conducted formal analysis. JA and PO were responsible for funding acquisition and project administration. JA, LE, SJ, and PO supervised the project. **MM** wrote the initial draft. All authors contributed to reviewing and editing the draft.

III **MM** conceptualised the study, designed the methodology and conducted a formal analysis. **MM**, JA and PO were responsible for resources. **MM** conducted data curation and wrote the original draft. JA, LE, SJ and PO supervised the project. All authors contributed to reviewing and editing the draft.

IV **MM**, EH and ID conceptualised the study. **MM,** EH, and FO were responsible for data collection and curation. MM designed the methodology and conducted a formal analysis. JA and PO supervised the project. **MM** wrote the initial draft. All authors contributed to reviewing and editing the draft.

Abbreviations

CIR	Chlorophyll Index Red-edge
CPI	Conditional Permutation Importance
GPP	Gross Primary Production
LAI	Leaf Area Index
LAIg	Green Leaf Area
LightGBM	Light Gradient-Boosting Machine
NDVI	Normalised Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIRv	Near-Infrared Reflectance of Vegetation
NMDI	Normalized Multi-band Drought Index
NPP	Net Primary Production
PDP	Partial Dependence Plots
PDSI	Palmer Drought Severity Index
POS	Peak of the season
PPI	Plant Phenology Index
RF	Random forest
RWI	Ring width index
SHAP	SHapley Additive exPlanations
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SWC	Soil Water Content
TPROD	Total Productivity Parameter
VI	Vegetation Index
VIS-NIR	Visual to Near-infrared Reflectance
VWC	Vegetation Water Content

Acknowledgements

First and foremost, I thank my supervisor Jonas Ardö, and my co-supervisors Lars Eklundh, Sadegh Jamali and Per-Ola Olsson for all the support and guidance throughout the project. Thank you for your encouragement and all the help over the years. I am profoundly grateful.

I acknowledge the Biodiversity and Ecosystem Services in a Changing Climate (BECC) for funding this doctoral thesis.

I thank all of my co-authors for their collaboration, insights, and valuable contributions to this research.

I thank all my past and present colleagues, as well as fellow PhD candidates in the Department of Physical Geography and Ecosystem Science, for the good times and the support they have provided throughout these years.

To my family, your patience and trust in me have provided the energy and meaning to continue learning and challenging myself. I am grateful to have you as part of my life.

Rationale and thesis structure

This thesis is rationalised by the immediate concern of climate change altering the frequency and intensity of extreme weather events that affect vegetation. While the global average surface temperature is approximately 1.3 degrees Celsius higher than it was in the late nineteenth century (Copernicus, 2024), the average surface temperature in Sweden has risen by 1.9 degrees Celsius (Schimanke et al., 2022). However, oceans have stored up to 90% of the excess heat (Cheng et al., 2024). This massive energy accumulation can drive extreme weather events such as droughts. Droughts are increasing forest mortality events worldwide (Hammond et al., 2022), impacting agricultural production (Orimoloye, 2022) and contributing to an increase in outbreaks of biotic disturbance agents (Netherer et al., 2019). In Sweden, forests have an important role both ecologically and in society's socio-economic interests. The majority of Swedish agriculture is rainfed, which exacerbates the risk that droughts pose to agricultural production. As climate change inevitably progresses, it will become increasingly important to shift the emphasis from mitigation measures towards active adaptation. This thesis has investigated the potential of combining satellite remote sensing, meteorological, and terrestrial geospatial data with novel modelling methods to enhance drought impact detection and quantification in Swedish forest and agricultural ecosystems.

The primary focus of **Paper I** is to develop a framework for tracking and quantifying the immediate and lagged impacts of drought on forests. **Paper II** focuses on mapping forest predisposition risk to bark beetle outbreaks as a secondary impact of drought and investigates the dynamics between predisposition risk and local environmental factors. In **Paper III**, the capacity to detect and quantify the impacts of drought on agricultural crop yields is investigated. **Paper IV** focuses on estimating the effects of drought on foliar and radial tree growth on a multidecadal scale and analysing the dynamics of tree carbon allocation.

This thesis begins with an introduction to the problem under study, followed by the aims and methods used to investigate the problem. The results and discussion sections first address the usefulness and limitations of satellite and other environmental data in detecting drought impacts. Finally, the capacity of methods developed to enhance the drought preparedness of societies, along with future possibilities for bridging the gap between the use of multi-source geospatial data, novel modelling methods, and understanding how drought impacts various types of forest and agricultural ecosystems are discussed.

Introduction

Climate change and terrestrial vegetation in Sweden

Climate change will present challenges and opportunities for Swedish forests and agriculture regarding productivity and sustainability. In Sweden, short growing seasons and excess water have been common factors limiting vegetation productivity (Bergqvist et al., 2022). Sweden's annual precipitation and temperature are predicted to increase, but the seasonal distribution of the precipitation is predicted to be uneven, resulting in wetter winters and drier summers in many areas (Salim & Zanchi, 2019). Consequently, soil water content (SWC) deficits are expected to occur more often, especially during the spring (Bastviken et al., 2015). Limited plant available water in the soil may blunt the benefits that warmer and longer growing seasons could offer.

The anomalously dry and warm spring and summer weather in 2018 heavily affected Sweden's forest and agricultural ecosystems. Approximately 25,000 hectares, corresponding to 2.6 million m^3 of forest, were damaged by fires (Skogsstyrelsen, 2018). Severe water stress greatly increases the effects of pests taking advantage of trees that are in poor physiological condition (Jactel et al., 2012; Netherer et al., 2015). Consequently, the largest documented outbreak of European spruce bark beetles (*Ips Typographus L.*) in Sweden was initiated in 2018, resulting in the loss of a total of 31 million m^3 of spruce trees from 2018 to 2020 (Schroeder, 2023). The cereal yields were reduced by up to 50% and livestock numbers were reduced due to a lack of affordable fodder and feed (Grusson et al., 2021). The risk of similar adverse ecological and socio-economical impacts may be much higher in the future.

By the 2030s, in Europe, the annual probability of droughts occurring that exceed the intensity of usual end-of-century drought events will be one in ten (Suarez-Gutierrez et al., 2023). In terms of excess heat, estimates are nearly ten times higher than the 1950–1999 average, and excess rain deficit distribution centers around values roughly twice as large as the recent past average. Boreal forest landscapes store approximately one-third of the entire terrestrial carbon pool, where most of the carbon is stored in soil organic matter and tree biomass (Adamczyk, 2021). Thus, understanding forest growth responses to changing climate plays an important role in the global carbon cycle (Hurteau, 2021). Additionally, forests and wood products hold a long history of cultural, economic, and ecological significance in Sweden, where approximately 70% of the land area is covered by forests (Lindstad, 2002).

Biodiversity in Swedish forest ecosystems is the basis for maintaining most of the other ecosystem services and is considered to be linked with human health, biomass production, decomposition and nutrient metabolism, and many technical innovations have risen from the study of nature-based solutions (Karlsson et al., 2022). The agricultural sector in Sweden is relatively small, but important for food security in Sweden. The warming climate may introduce productivity benefits if it is exploited effectively. Crop selection and scheduling are crucial challenges for agriculture to capitalise on changing climatic conditions (Wiréhn, 2018), and the need for irrigation may increase during dry years (Grusson et al., 2021).

Forests and agriculture have intricate relationships with the functioning of Swedish society, providing a multitude of ecosystem services. Addressing drought-related challenges and capitalising on possible opportunities requires adaptation strategies to increase the drought preparedness of society. Developing such strategies requires understanding the impacts of drought on vegetation, as these impacts may have further socio-economic implications within societies. Therefore, monitoring the state and drought resilience of northern high-latitude forest and agricultural ecosystems is of high importance. A better understanding of the drought resilience dynamics of both natural and managed ecosystems and pre-emptively identifying vulnerable areas is a fundamental step in increasing a society's drought preparedness and aiding in planning climate change adaptation strategies.

The drought phenomenon

Different definitions for drought have been formed according to disciplinary perspectives. Drought is an intricate phenomenon originating from a deficiency of precipitation, which results in a shortage of water for a certain activity or a group in the interest of the study (Wilhite & Glantz, 1985). During a drought period, the balance between rainfall and evapotranspiration in a particular area deviates from the long-term average balance or the state perceived as “normal” in this area. Droughts are expected to occur more frequently throughout Europe, and their intensity is expected to significantly increase in northern Scandinavia (Spinoni et al., 2017).

Multiple climatological and hydrological parameters are often needed to characterise a drought, but most definitions relate drought to the reduction in the amount of precipitation received over an extended period (Mishra & Singh, 2010). Still, droughts occur in areas characterised by low rainfall, as well as in areas characterised by high rainfall. In a review by Wilhite and Glantz (1985), more than 150 published definitions for the term "drought" were found. To clarify existing differences in views between disciplines, they were able to group the definitions into four types of droughts: meteorological, agricultural, hydrological, and socio-economic. Meteorological droughts are often defined by site-specific thresholds set for a number of days without rain or a period when rainfall is below a specified amount. Agricultural drought connects meteorological drought to impacts seen in cultivated crops. Hydrological drought focuses on effects recorded on surface or subsurface hydrology like notable decreases in stream flows or aggregate runoff. Socio-economic drought refers to a situation when the demand for an economic good exceeds the supply due to before mentioned definitions that are more weather-related. Thus, the drought period's estimated onset and termination date may vary largely based on the chosen definition.

The drivers of extreme weather periods can have land-atmosphere feedbacks enhancing each other. Two primary physiological stressors that cause vegetation mortality are edaphic drought (soil drought) and atmospheric aridity, both of which can exacerbate drought severity through feedback loops (Zhou et al., 2019). When a reduction in SWC causes evaporation to decrease, the sensible heat flux and vapour pressure deficit in the atmosphere will increase. This, in turn, increases the evaporative demand of the atmosphere, causing a further decline in soil moisture levels (Figure 1).

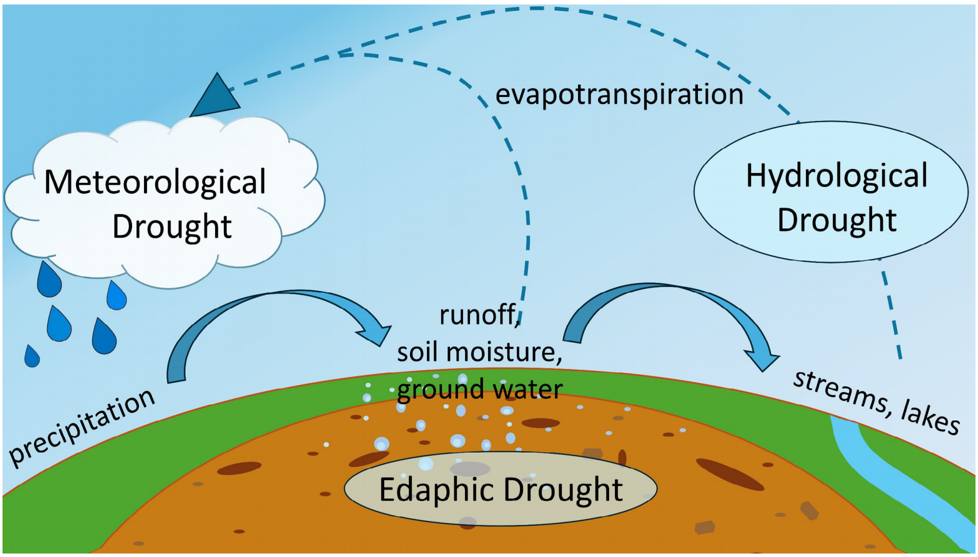


Figure 1. Simplified presentation of how multiple climatological and hydrological factors drive the progression of droughts and interact with each other. The lack of precipitation during a meteorological drought eventually causes soil water content to decrease. When edaphic drought is prolonged, water transportation to streams, lakes and groundwater will also decrease. This hydrological drought, in turn, will reduce evapotranspiration and can further intensify the meteorological drought.

In 2018, Europe experienced one of the most severe and long-lasting summer droughts combined with extreme heatwaves ever recorded (Schuldt et al., 2020). From May to August, a high-pressure system centred over Fennoscandia was linked to record-breaking temperatures across land areas, lack of precipitation, and unusually low stream flows (Bakke et al., 2020). In Sweden, the average temperature over the May to August period was 2.8°C warmer than the 1981–2010 climatological average (Wilcke et al., 2020). Heatwaves intensified the evaporation rate (Copernicus European Drought Observatory, 2018), resulting in particularly long-lasting and substantial SWC deficits in southern Sweden (Lindroth et al., 2020).

In this thesis, meteorological variables are used to define drought periods, primarily focusing on linking meteorological drought to its effects on terrestrial vegetation. The impacts on society are discussed. Data collected during the 2018 extreme drought period are extensively used to study the impacts of drought on terrestrial vegetation.

Role of local environmental factors

The most important abiotic factors affecting vegetation drought resilience are microclimate, water availability, and soil nutrients, and the most important biotic factors are vegetation structure and leaf economic and hydraulic plant traits (Kopp Hollunder et al., 2022). The term microclimate refers to the range of climatic conditions in nearby locations that substantially affect ecological processes such as plant regeneration and growth, soil respiration, nutrient cycling, and ecological patterns within plant communities (Chen et al., 1999). By generating shade, transferring water, and evapotranspiration, the vegetation feeds back to the microclimate, influencing the environment's temperature and vapour pressure deficit (Wright & Francia, 2024). The diversity of vegetation, its functional groups and other characteristics determine how it interacts with the local microclimate.

Interception and evaporation determine the amount of water supplied to the ground surface. This water is removed by overland flow, infiltration to the soil matrix, transferred to more long-term groundwater storage or returned to the atmosphere through evapotranspiration. Topographic gradients strongly influence the rate at which soil water moves downslope and how groundwater fluxes behave (Condon & Maxwell, 2015). Soil characteristics, particularly variations in soil texture, are significant factors affecting soil moisture variation (Yeakley et al., 1998). Soil infiltration rate and field capacity (the maximum amount of available water held in the soil after gravity-induced drainage) strongly depend on the soil texture (van Wesemael et al., 2003). These properties further determine the permanent wilting point, which is the highest water content level of a specific soil, at which indicator plants will wilt and fail to recover afterwards (Tolk, 2003). However, it is challenging to precisely determine the actual effect of soil texture due to its intricate interconnections with topography, as soil texture often correlates with its position in relation to local topography (Price, 2011). Areas with steep upper slopes are likely characterised by coarser and thinner soils, which can transfer water rapidly. Contrastingly, areas with low slope gradients are more likely to have soils with finer particle sizes and thicker soils, leading to a lower capability to transfer water.

Vegetation resilience to drought

Every known living organism requires water to survive. Though water is a simple molecule, its complex properties seem to fit better into the requirements for carbon-based life than any other molecule (Chaplin, 2001). Water is essential for chemical reactions, thermal regulation, and cellular functions of plants. Through photosynthesis, plants can convert radiative energy into a form that living organisms can use. Photosynthesis is limited by the presence of light and the amount of green biomass, which in turn requires water to survive. Gross primary productivity (GPP) is the rate at which carbon compounds are produced by photosynthesis; however, plants use some of this energy for metabolism and respiration. The net primary production (NPP) is the net amount of biomass stored in plants.

Reduction of SWC influences nutrient cycling and uptake and increases soil salt concentration, leading to a decrease in soil water potential in comparison to plant cells (Zargar et al., 2017). This lack of available water impacts cellular features and processes that are vital for the plant's functioning, such as turgor pressure, metabolic reactions, influx and efflux, ion transport, nutrient metabolism, cellular development, and the translocation of solutes. Plants take up most of their mineral nutrients from the soil through the cellular membranes of their roots and shoots. The rate at which plants can uptake important minerals may decrease when the soil dries (Bista et al., 2018). These internal interferences then negatively affect the plant's capability to uphold photosynthesis.

Rather than drought impacts on vegetation being single events, they can result in compounding and secondary impacts (de Brito, 2021). In forests, severe water stress greatly increases the risk of insects exploiting the poor physiological condition of the trees (Jactel et al., 2012; Netherer et al., 2015). The most significant insect disturbance agents in temperate and boreal forests are the various species of bark beetles (Sommerfeld et al., 2021). More than 25% of Europe's current Norway spruce (*Picea abies* (L.)) total growing stock may be at risk of bark beetle outbreaks, due to the European spruce bark beetle primarily targeting Norway spruce (Hlásny et al., 2021). In agriculture, crop losses are often followed up by a shortage of feed for livestock and consequent early slaughtering of animals (Knutzen et al., 2023). The presence of the secondary impacts further complicates the quantification of the total impacts of drought on vegetation and how they influence society.

Significant differences in drought resilience and the latency of stress reactions can exist within functional groups, individuals, or even individual species (Robakowski et al., 2020; Sánchez-Pinillos et al., 2022). Although the effects of the 2018 drought were observed throughout the Nordic countries, differences were observed in how the drought impacted the NPP of forests in different regions (Lindroth et al., 2020). There is a clear relationship between vegetation water relations and carbon balance, where vegetation temporal responses to drought are expected to be crucial for risk prediction, as deteriorating hydraulic function is a likely cause of drought-induced mortality (Martinez-Vilalta et al., 2019). As leaves and needles are essential for photosynthesis, changes in them are often considered to correlate highly with changes in GPP. However, it is not known what proportion of the drought-induced decrease in GPP is commonly attributable to stomatal closure and how much is attributable to other non-stomatal characteristics, such as decreased electron transport activity, carboxylation rate, reduced active leaf area (LAI), and decreased mesophyll conductance or their combination (Gourlez de la Motte et al., 2020). Also, changes in GPP and NPP in response to drought will likely vary with soil and vegetation species- and community-specific properties.

Whether direct or indirect, the magnitude of drought effects on vegetation is related to the intensity of the drought and the ecosystem's sensitivity to drought exposure. The sensitivity of a species or an ecosystem is governed mainly by the physiology of the species, community structure, ecosystem-level processes and their adaptability to changes in the earth’s physical systems and processes (Stein et al., 2011). The concept of ecosystem resilience was proposed by Holling (1973) as a way to quantify a system's capacity to withstand disruptions and changes. Later, Westman (1978) suggested that resilience should consider the degree, manner, and restoration rate of the initial structure and function following a disturbance event. During droughts, the plant water status is governed by the soil water supply and the evaporative demand of the atmosphere. However, many plants are physiologically able to exercise control over metabolic responses to water deficit. Controlling the water flux through leaf and root surfaces by altering resistances to water flow. Thus, the water status in the mesophyll cells of the plant leaves might not actually track changes in SWC or evaporative demand in the short term. Plants can compensate for the lack of water by modulating their stomatal aperture and, in the longer term altering their leaf and stomatal development, with an aim to equalize water availability and use by controlling stomatal conductance (Hamanishi et al., 2012). Overall, physiological traits and adaptation strategies of plant species can cause large variations in their sensitivity to drought and the latency of their stress reactions. Still, there is a lack of knowledge regarding how plants respond and adapt to drought on a daily or weekly scale (Joshi et al., 2022).

Integration of multi-source geospatial data

Investigating dependencies between climatic variables and ecosystem productivity is of interest in a multitude of research fields. Automated weather stations are a relatively low-cost solution, with varying capabilities to record changes in environmental variables for decades (Tanner, 1990). Additionally, the micrometeorological eddy covariance method can measure the exchange between the ecosystem and atmosphere in terms of gas, energy, and momentum (Liang et al., 2020). However, the network of measurement stations is still far from covering the whole globe in detail, and they cannot produce spatially continuous data on changes in biogeophysical processes.

The increased availability of reanalysed meteorological data, terrestrial geospatial data, and satellite data with extensive spatial coverage can enhance the monitoring of vegetation states and drought resilience across varying spatiotemporal scales. This provides alternatives to traditional field-based measurements. Indices utilising meteorological datasets have been created to estimate the spatiotemporal variation of relative dryness and to monitor drought. Among the most widely used drought indices are the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the Standardized Precipitation Index (SPI) (Mckee et al., 1993), and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). Differentiating from the other two, SPEI can consider the role of atmospheric evaporative demand at different time scales.

Apart from meteorological data, variables influencing the local microclimate (Greiser et al., 2018), soil nutrients (Adeniyi et al., 2024), and SWC (Ågren et al., 2021) variation can be described using topographical and soil data sets. Similarly, information on land use and cover (Zhang & Li, 2022), vegetation composition (Nasiri et al., 2023) and vegetation height (Tolan et al., 2024) are distributed as geospatial data sets. However, when data is produced on a regional or national level, it may not be updated often. Although they would include valuable information on local environmental factors that impact vegetation drought resilience, their usability in monitoring intra- and inter-annual changes, like phenology, plant growth or vegetation disturbances, is often limited. Phenology describes the key events in the life cycle of organisms, such as plant greening, senescence and reproductive events, and often strongly responds to meteorological variables (Dronova & Taddeo, 2022). However, available in-situ phenology observations are often sparse in space and time, making it challenging to generalise evidence from the plant level to broader geographic extents. Regarding phenological cycles and vegetation health state, satellites can provide data sets covering years or even decades, collected with a known interval in a consistent manner over space and time (Younes et al., 2021).

Satellite remote sensing methods are based on transferring electromagnetic radiation, facilitating access to resources that overcome the spatial limitations of in-situ measurements and the temporal limitations associated with many other geospatial data sources. The interaction of electromagnetic radiation with the land surface strongly depends on the wavelength and the interacting medium's geometrical, electrical, magnetic, and conductive properties (Marzano, 2014). This thesis will focus on the use of optical satellite sensors, which can enable the differentiation of spectral signatures of objects present in the satellite images. Thus, disturbances causing deviations from the known spectral signature can also be detected.

Detection and mapping of drought impacts

The Swedish Council of Experts on Climate Adaptation stated that successful climate adaptation requires shifting the focus from problems to solutions and from planning to implementation (Nationella expertrådet för klimatanpassning, 2022). They emphasised the importance of developing systems enabling proactive measures. Though research on drought impacts and resilience indicators in Nordic boreal forests has advanced, studies remain context-specific, highlighting ongoing limitations in generalisable indicators. Therefore, further development of methods that can account for dependencies related to vegetation age, diverging resilience trends, species-specific drought responses, spatial variability, and the integration of long-term data is still necessary to identify varying drought response patterns in the landscape. Recent developments in satellite remote sensing and machine learning offer detailed yet complex solutions for monitoring the spatiotemporal variation of land surface biogeophysical parameters (Prodhan et al., 2022).

To monitor the impacts of droughts on forests, it is crucial to identify the typical seasonal trajectories of forest types or species to enable the detection of states deviating from the norm due to drought stress. Satellite remote sensing can help meet the need for indicators of species diversity and vegetation structure and aid in detecting responses of phenological metrics to stressors over vast, heterogeneous regions (Dronova & Taddeo, 2022). These indicators can provide information on vegetation resilience, recovery of vegetation cycles, and the identification of stable microrefugia. GPP is often used as an indicator of ecosystem vitality and resilience against drought stress and to monitor the duration of ecosystem recovery time (Yu et al., 2017). Optical satellites can detect changes in vegetation characteristics, focusing mainly on canopy cover, biomass, and other biophysical attributes of forests and agricultural crops. Vegetation structure and health are often estimated using satellite data derived from visual to near-infrared (VIS-NIR) vegetation indices (VI). However, these measurements frequently saturate over dense forests or overlook changes in vegetation functioning that occur before significant changes in foliar biomass occur (Vicca et al., 2016). Nordic boreal forests are commonly dense, and new buds account for only a small fraction of total tree biomass, and the shoots grow slowly. Accordingly, Jönsson et al. (2010) showed that the widely used Normalised Difference Vegetation Index (NDVI) poorly detects phenological phases in coniferous forests. Also, in areas where the number of satellite observations within a year is low or unevenly distributed over the year, characterising vegetation phenology and monitoring vegetation state can be especially challenging (Mas & Soares De Araújo, 2021).

In contrast to forests, where trees close their stomata to preserve their leaf water potential when the amount of water in the soil falls below a specific threshold, grasses typically do not stop growing until the SWC falls below their permanent wilting point (Vicca et al., 2016). Thus, changes might happen rapidly when the permanent wilting point is reached. Time-series analysis on croplands can be challenging because crop rotation between consecutive years will obstruct the comparison of satellite signals from the same field before and during a meteorological extreme event. At the same time, crop- and site-specific climate change adaptation strategies are required because the severity of drought impacts varies by location (Sjulgård et al., 2023). Local soil, topography, management, crop species, and drought occurrence in relation to crop growth stages influence the drought resilience of the crops (Mohammadi et al., 2023). Since yield drivers can have extremely non-linear effects on farmers and commodity markets, method development should concentrate on capturing them during non-standard years (Schauberger et al., 2020). However, analysis based on remote sensing data alone is often insufficient for the mechanistic interpretation of phenological cycles and asynchronies caused by stressors. This is why integrating ancillary environmental and geographic data is needed (Dronova & Taddeo, 2022). Simultaneously, drought monitoring and forecasting initiatives that rely solely on historical meteorological data may face increasing uncertainties in the future, as they will be unable to effectively account for extreme meteorological anomalies (Park et al., 2019).

Machine learning algorithms can learn directly from data without relying on user-defined rules and can uncover nonlinear patterns in large and diverse geospatial datasets (Vulova et al., 2025). However, collecting sufficient data on vegetation changes to train machine learning models can be challenging. The integration of multi-source geospatial data can provide a basis for collecting data from vast geographical areas. While remote sensing observations have been used to quantify drought impacts from an ecosystem perspective, methods for detecting early drought impacts remain limited, and uncertainties are often unquantified (Aghakouchak et al., 2015). Advancements in satellite sensors' spatial, spectral, and temporal resolutions introduce new opportunities for monitoring drought and vegetation states (Misra et al., 2020). Despite the opportunities created by the availability and integration of novel modelling techniques and data sources, explaining how machine learning models reach specific conclusions has been challenging. To overcome this limitation, recent advances in “explainable AI” techniques have enhanced the interpretability of outputs and results produced by machine learning algorithms, thereby increasing the transparency of the models' decision-making processes (Lundberg et al., 2020).

The conditional permutation importance (CPI) was developed to refine existing model feature importance methods (Debeer et al., 2021; Debeer & Strobl, 2020). CPI can account for dependencies among features, aiming to avoid misleading results caused by interdependent predictors. Thus, further improving interpretability and accuracy in variable importance assessments. An alternative way to study the importance of interdependent variables is TriPlot analysis (Pekala et al., 2021). The TriPlot method combines information on the importance of individual variables, the correlation structure between predictors, and the importance of groups of variables formed based on their correlations. Though these methods can quantify the importance of features, they do not provide information on how each variable influenced each prediction.

The use of SHapley Additive exPlanations (SHAP) has gained significant popularity as a technique for explaining machine learning models in geospatial applications or for extracting insights about real-world scenarios (Roussel, 2024). SHAP is a model-agnostic method, meaning it can be applied to any machine learning model to quantify the contribution of each model variable to a specific prediction, where the sum of the contribution of each variable equals the final prediction (Lundberg & Lee, 2017). This means that SHAP values can explain individual predictions by quantifying how much each feature contributed to a specific output, aiding to understand the model reasoning behind a single prediction. Summarising the SHAP values of all local explanations provides information on the global importance of features, characterising the average model behaviour and contribution of each variable. Another widely used model explanation method is Partial dependence plots (PDP), which offer a solution to plot the model prediction function, allowing the relationship between the outcome and predictors to be visualised in low-dimensional graphical renderings (Greenwell, 2017). Both SHAP values and the PDP plots can be useful in explaining the output and decision-making process of the machine learning models, previously considered “black box models.”

Combining multiple geospatial data sources can provide new opportunities for characterising and monitoring changes on the Earth’s surface (See et al., 2024; Vila-Viçosa et al., 2020). Meteorological, terrestrial geospatial, and satellite data combined with novel modelling and model interpretation methods could enable the development of techniques capable of quantifying drought impacts on terrestrial vegetation. This approach would also provide information on the importance and dynamics of environmental factors that control the severity of drought impacts in a local context. In a changing climate, effective adaptation measures will become increasingly valuable. Novel drought monitoring methods can aid in better directing management efforts and provide information for decision-making.

Aims and objectives

The overall aim of this thesis is to develop, test and apply methodologies for the detection and quantification of spatially explicit drought effects on Swedish agricultural and forest ecosystems and their productivity. The thesis provides information on the potential and challenges associated with integrating multi-source geospatial data for monitoring drought impacts on terrestrial vegetation.

Four studies were carried out with the following specific goals to accomplish this:

1. Develop a change-detection framework to quantify immediate and delayed drought-related vegetation changes in forest ecosystems and their recovery times.
2. Identify drivers and map forest areas with a high risk of European spruce bark beetle disturbances as a secondary effect of drought.
3. Develop a causal inference framework considering crop rotation and local environmental factors when quantifying climate-driven changes in agricultural crop yields between selected periods.
4. Estimate the foliar and radial growth responses of Norway spruce and Scots pine trees to drought at national and multidecadal scales by combining satellite, meteorological, soil wetness, and dendrochronological data.

Methods

Overview

Sweden's southern regions, where direct and secondary drought impacts have commonly been more severe than in the country's northern regions (Ou, 2017), have a higher coverage of the research areas included in this thesis (Figure 2). Drought conditions and the impact of local environmental factors were described using geospatial and meteorological data sets (papers I, II, III & IV). Sentinel and Landsat are two crucial remote sensing programs that provide multispectral data to track changes in terrestrial vegetation and phenological patterns of vegetation (Mas & Soares De Araújo, 2021). Studies including the investigation of intra-annual temporal changes (Papers I and III) used Sentinel-2, while one examining multidecadal changes (Paper IV) used Landsat satellite data.

Sentinel-2 is a satellite mission recording wide-swath (290 km), high-resolution (four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution), multi-spectral images with a push-broom sensor (European Space Agency, 2015). Sentinel-2A, Sentinel-2B, and Sentinel-2C satellites were launched in June 2015, March 2017, and September 2024, respectively. This thesis used atmospherically corrected and orthorectified bottom-of-atmosphere reflectance Sentinel-2 images (Level-2A). At mid-latitudes, revisit times ranged from two to three days during the study periods determined in this thesis.

The global consolidated Landsat Collection 2 archive covers over 50 years (Crawford et al., 2023), making it especially useful when monitoring long-term vegetation changes (Morin-Bernard et al., 2023). This thesis used the Landsat 4 and 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 and 9 Operational Land Imager (OLI) sensors radiometrically calibrated and geolocated multispectral data are provided as surface reflectance images (Level 2).

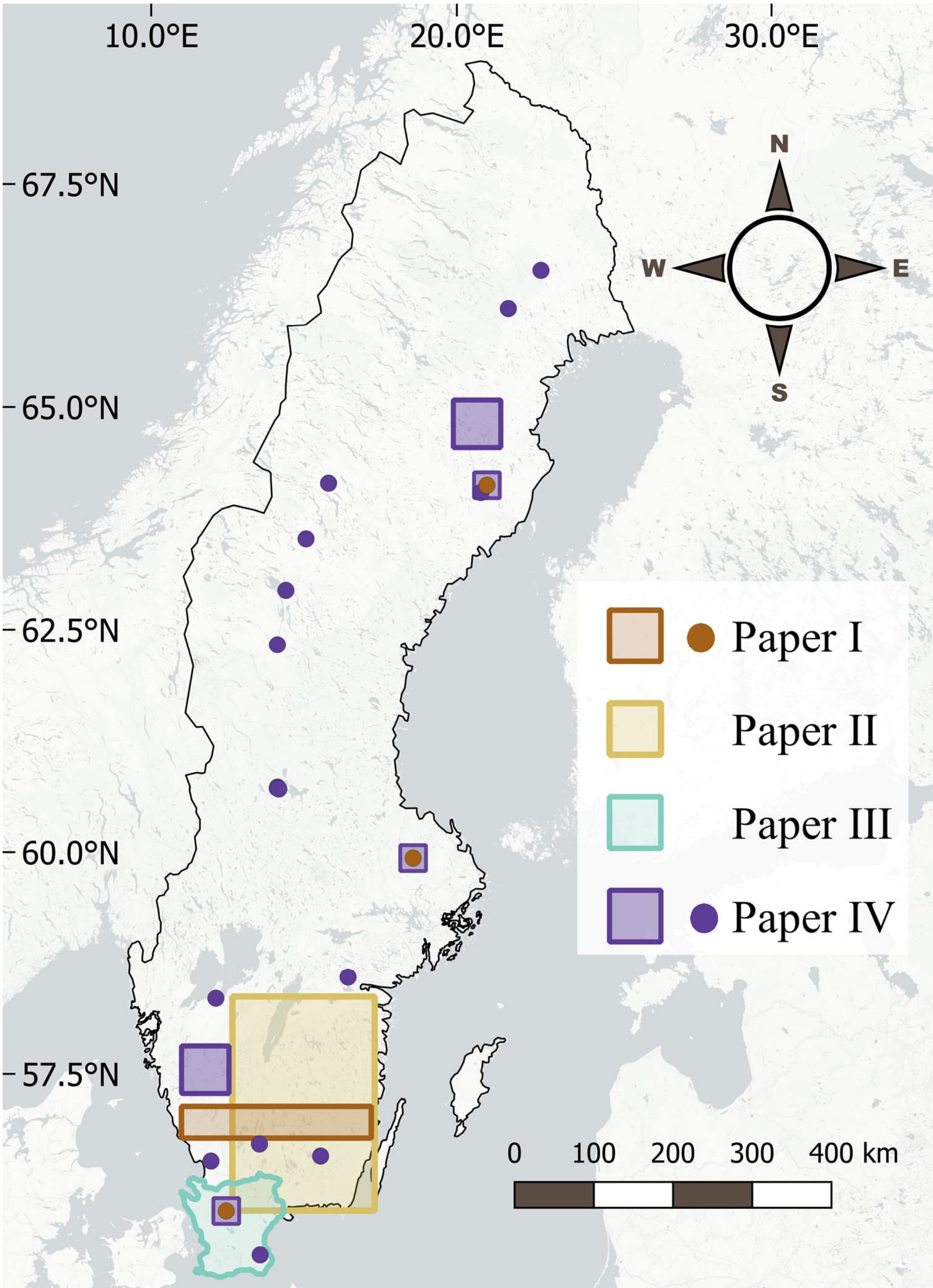


Figure 2. The study areas of each research paper of this thesis.

Paper I

This study explores the capability of Sentinel-2 data to monitor vegetation stress phases related to drought progression and to quantify both short- and long-term impacts on forest growth. We calculated three VIs across six forest types, comparing pre-, during-, and post-drought conditions to investigate vegetation drought responses and drought resilience patterns in Swedish forests. For the 2015–2022 period, we calculated the normalized multiband drought index (NMDI) (Wang & Qu, 2007) for detecting vegetation water content (VWC) changes, the chlorophyll index red-edge (CIR) (Gitelson, 2003) for detecting chlorophyll content changes and the plant phenology index (PPI) (Jin & Eklundh, 2014) for detecting changes in green leaf area (LAIg). VIs chosen aim to detect successive stages of vegetation stress related to the progression of the drought, where drought decreases the plant-available water in the soil, which impacts the VWC and may alter biochemical processes and eventually LAIg.

VI data cubes with daily time steps were composed for three eddy covariance sites. As the vegetation phenological cycles can be roughly identified using Fourier-based approaches (Garonna et al., 2014), a time-series model was fitted using Weighted Harmonic analysis of time series to gap fill and minimise noise at each point in the site time series. For the eddy covariance sites, we calculated daily reference VI values using data from 2015 to 2017, representing an average period without extreme climate events. In this study, resilience concepts of Δamplitude and elasticity (Westman, 1978) were used, where Δamplitude represents the intensity of disturbance or systems' resistance to it, and elasticity represents the recovery time to reach the pre-disturbance stage (Figure 3). The Δamplitude was estimated by calculating the VI percentage difference between the reference period and the drought year of 2018. Post-disturbance recovery was also considered. First, the immediate and carry-over effects were measured on an annual scale by calculating Δamplitude between the reference and post-reference peak of season (POS). Then, the within-year drought response was presented by a daily Δamplitude time series limited to the 2018 growing season at each ICOS sites. The response times of each forest type and the earliest detectable drought response, compared to the date of meteorological drought onset, were measured using breakpoint detection (Jamali et al., 2015) with a daily temporal resolution. SPEI with 0.1° spatial and weekly temporal resolution (SPEI-T) was calculated to define the drought onset date at the ICOS sites.

Additionally, we calculated the annual peak of the season (POS, VI maximum) rasters for a transect with a strong gradient in average annual precipitation. For the transect area, we prepared data on average annual precipitation for 1988–2017 (Andersson et al., 2021) and statics average soil moisture maps (Ågren et al., 2021) to represent the local variation in the long-term plant-available water. High spatial resolution SPEI (SPEI-S) with 0.05° spatial and monthly temporal resolution was downloaded (Gebrechorkos et al., 2023) to study dynamics between annual average precipitation, drought intensity and forest drought resilience at the TR. Then, changes in the density distribution of the POS VI values between reference, drought, and post-drought years were examined at the transect. Multiple regression analysis was used to investigate differences in disturbance intensity across various forest types within regions with differing levels of average annual precipitation and drought intensity. To determine how the local water availability affects the VI responses, differences in statistical populations of each forest type in regions with varying soil moisture availability were examined.

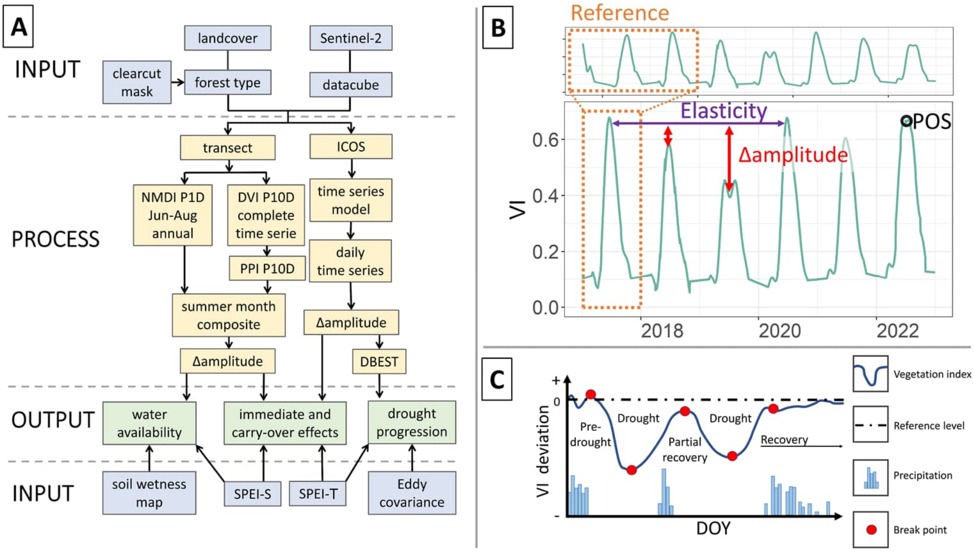


Figure 3A Flowchart presents input data, processes taken and their order, and outputs of which the study results were concluded. Figure 3B The resilience concepts and the definition of the reference period are visually presented. The orange dashed line outlines the reference period. Red lines show the Δamplitude, the disturbance intensity, quantified by comparing VI values against the reference period average. The purple line represents elasticity, which is the time required for recovery to reach the pre-disturbance stage. The black circle illustrates the peak of a single growing season, defined as the annual VI maximum. Figure 3C The theoretical relationship between VI deviations from the reference caused by drought and the detected breakpoints.

Paper II

The aim of this study is to investigate how different environmental factors affect the risk of bark beetle (*Ips typographus* L.) attacks during a drought year and in subsequent years when weather conditions were more normal but bark beetle populations were higher than during the drought year. We utilised geospatial data and random forest (RF) models (Breiman, 2001) on a large dataset of bark beetle presence data to quantify the importance of environmental features that predispose Norway spruce forests to bark beetle outbreaks and interpret the patterns identified by the models.

Information on bark beetle presence was derived from data collected by harvester machines equipped with Global Navigation Satellite System receivers (GNSS), including coordinates for 639,997 individual trees removed due to the presence of bark beetles. The harvester data included only information about removed trees, and we had insufficient field inventory observations for healthy stands to achieve a balanced dataset. Therefore, areas within an estate with trees harvested elsewhere were considered healthy, relying on the idea that, for cost efficiency, the estates were examined for attacked trees before the harvester was brought to the property. Rasters with 10 × 10 m grid resolution were created, where each pixel entailing a harvested tree or an inventory recording of bark beetle presence was classified as attacked by the bark beetle. The number of attacked and healthy observations was balanced using stratified random sampling, using forest and soil type coverage as grouping variables.

A literature review was conducted to identify candidate environmental features predisposing forest trees to bark beetle attacks. Then, geospatial data serving as proxies for these features were downloaded. We aimed to decompose the joint interactions between features, selecting the most important features to decrease the number of dependent features in the data. Environmental features in unison control the local predisposition risk of forest stands, and the independence of these features can rarely be expected in a natural environment. We used CPI and TriPlot analysis for feature selection aiming to mitigate collinearity between continuous variables. Finally, bark beetle presence data was converted to binary rasters with a 10 × 10 m spatial resolution and combined with geospatial data of selected environmental features. One raster was produced for the drought year 2018 and one for the 2019-2020 period, both covering a 48,600 km^2 area in southeastern Sweden. Lastly, the information from the binary rasters and data on the environmental features were combined. Resulting in a total of 24,433 records for the drought year and 75,447 records for the normal period. The data were split, with 80% allocated for training and 20% for validation data for both study periods.

We used the RF learning algorithm because it has been widely used for classification tasks, is computationally reasonably cheap, and is not susceptible to overfitting or outliers (Wei et al., 2015). We trained two binary classification models: one for the drought period and one for the normal period. The primary goal was to quantify and interpret patterns the models uncovered; thus, prediction accuracy was not compared with additional machine learning methods. Still, reliable interpretation of the results requires a good underlying model, so the RF hyperparameters were tuned by conducting a 10-fold cross-validation using a sample grid of defined hyperparameter values (Kuhn, 2008). The best models were selected based on their average ability to identify the attacked pixels accurately. Models predicted a probability of class membership, not a discrete label. This was considered as quantified information on the risk of attack. When evaluating model performance, a 50% cut-off limit was used for predicted probabilities to facilitate the computation of a confusion matrix.

The primary focus was set on analysing SHAP values to quantify the contribution of each feature to a particular prediction. Thus, the forest stand's predisposition to bark beetle attacks could be estimated while simultaneously deriving information on how environmental features control the local predisposition risk under drought and during periods of more normal weather conditions but with higher bark beetle populations (Figure 4).

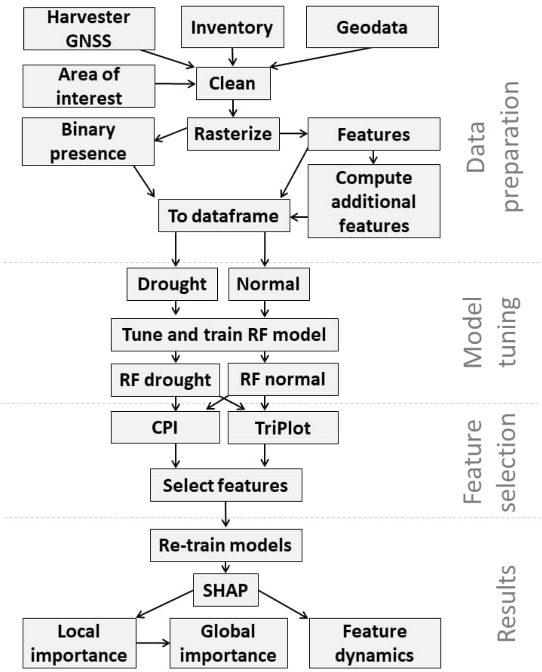


Figure 4. Summary of processing steps taken from harvester, inventory and geospatial datasets to results. The data preparation section summarises data sources and pre-processing steps. The model tuning and feature selection sections describe steps to choose optimal model hyperparameters and predictor variables. Results sections show how final RF models were trained, SHAP values calculated, and how results were derived from the SHAP values.

Paper III

This study aimed to develop a causal inference framework for comparing crop yield responses under extreme drought and more normal weather conditions, as the impacts of drought on crop yields vary by location, necessitating crop- and site-specific adaptation measures to climate change (Sjulgård et al., 2023). This is important because crop rotation between consecutive years hinders the comparison of satellite signals from the same field before and during a meteorological extreme event, and variations in soil properties can influence the comparisons made between different fields. Furthermore, the drivers of yield loss variation between fields during extreme drought were investigated.

We acquired information on the types of crops grown at each agricultural field in Scania County in 2017 and 2018 (Jordbruksverket, 2015). In Scania, the summer of 2018 was extremely hot and dry, and on a national scale, cereal yields were reduced by up to 50% (Grusson et al., 2021). On the other hand, weather conditions in 2017 summer were close to the long-term average (SMHI, 2017). We focused on common production crops, including winter wheat, spring wheat, winter barley, spring barley, oats, and grasses for grazing and hay. This resulted in 58,860 and 57,951 fields for the years 2017 and 2018, respectively. Annual statistics of total crop yields in Scania were downloaded (Official Statistics of Sweden, 2023), and annual yield data from 64 fields with spring barley and 88 fields with winter wheat were included.

Daily precipitation and temperature (Andersson et al., 2021) and SPEI at a 3-month time scale and monthly temporal resolution (Beguería et al., 2024) were downloaded. Information on topsoil texture (Piikki & Söderström, 2019), elevation and slope were derived (Lantmäteriet, 2020). For vegetation monitoring, we acqureid Sentinel-2 data-derived 10-day PPI composites and the annual total productivity (TPROD) product (Smets et al., 2024). TPROD is the sum of all PPI values during the growing season. The relationship between TPROD and yield data was examined using linear regression analysis. The annual statistics of total yields in Scania, by crop type, were used with the regional average TPROD. The average TPROD per field was used at the field level, along with harvester machine-derived yield estimates, for winter wheat and spring barley.

A statistical technique called propensity score matching was applied to make the field-level observations from the drought year 2018 and the reference year 2017 comparable (Stuart, 2010). This method paired observations from fields with as similar soil properties as possible and the same crop type, grown during different years. For paired fields, PPI was used to track intra-annual crop drought responses, and the impact of drought on yields was estimated by calculating the percentage difference between TPROD from paired fields (ΔTPROD).

To study local variation in drought impact severity, ΔTPROD was used as a response variable in an efficient gradient boosting decision tree model, Light Gradient-Boosting Machine (LigthGBM) (Ke et al., 2017). The data was split into 80% training and 20% testing sets. Model hyperparameters were tuned, and performance assessments were conducted using 10-fold cross-validation with a grid search that included 150 hyperparameter configurations to minimise the root mean square error (RMSE) (Kuhn & Wickham, 2020). Initial tuning results were used as input for iterative search of best parameters using Bayesian optimisation. The contribution of each variable to each field-level prediction was quantified, and their dynamics were investigated using SHAP values. Here, positive SHAP values indicate a percentage increase in ΔTPROD, which is interpretable as a lower yield loss due to the specific variable. Conversely, negative SHAP values were associated with higher yield losses during drought. This provided quantified information to assess the contribution of soil and topographical variables to variation in ΔTPROD and to investigate whether the contribution of these variables varies between crop types (Figure 5).

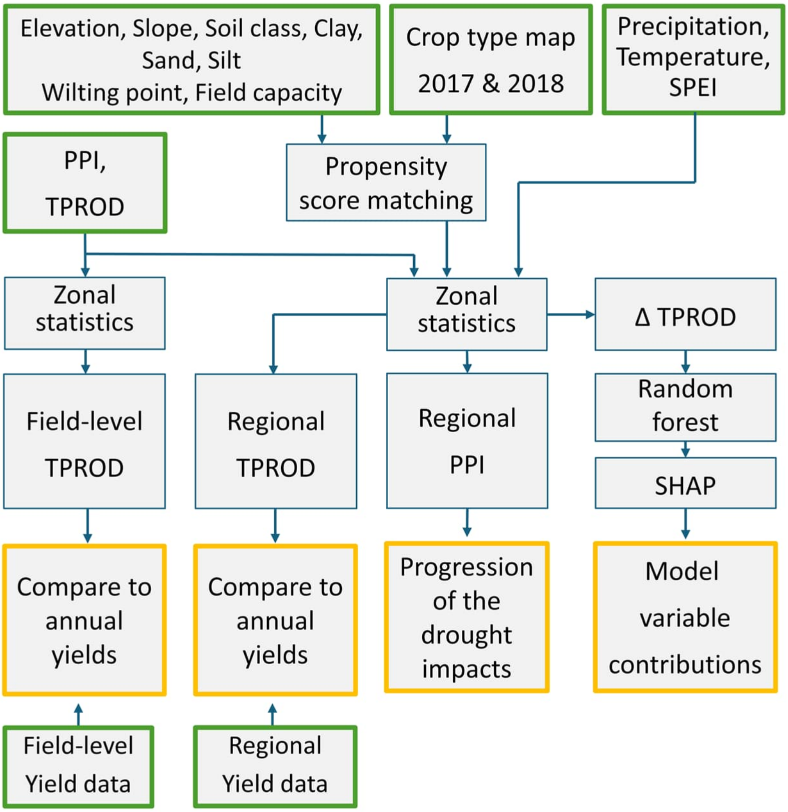


Figure 5. Summary of the causal inference framework from input data to results used in this study. The data inputs are marked with wide green borders. The processing steps and intermediate outputs are marked with thin blue borders. Results are marked with wide yellow borders.

Paper IV

It has been shown that trees that were less resilient to previous non-lethal droughts, in terms of radial growth, are at higher risk of drought-related mortality in the future (Desoto et al., 2020). Paper I proposed a methodology for detecting drought-related forest crown changes, but the short reference period length and mixed signals from multi-species stands were identified as areas for improvement. This study addresses these issues by focusing on longer VI series derived exclusively from Landsat data of Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* (L.)) monocultures. However, the presence of complex interactions between tree carbon allocation strategies and meteorological drivers (Trugman et al., 2018) makes it difficult to conclude the magnitude of drought impacts on tree growth from the VI data. Additionally, the relationships between radial growth estimates and VIs are likely influenced not only by climate but also by the spatial resolution of VI data, local environmental factors, and species-specific responses (Zhang et al., 2023).

We used Landsat Collection 2 data to calculate the near-infrared reflectance of vegetation (NIRv), which has a linear relationship with the fraction of absorbed photosynthetically active radiation (Badgley et al., 2017) and the Normalized difference water Index (NDWI) (Gao, 1996), which is sensitive to changes in VWC to monitor the foliar dynamics of the trees. Changes in leaves and needles are essential for photosynthesis. Thus, they may be correlated with changes in vegetation productivity. For validation, VI-detected changes were compared with in-situ LAI measurements from three Integrated Carbon Observation System (ICOS) (Aalto et al., 2024).

Ogana et al. (2024) collected tree-ring chronologies from 16 paired pine and spruce stands distributed across latitudinal gradients in Sweden. From this data, the tree ring width index (RWI) was calculated, which describes whether the increment of radial growth was above or below the average growth of the trees for each site to assess the responses to environmental changes (Xu et al., 2017). De-trending was performed to remove long-term term trends in the VI time series, which were considered to be related to canopy development, by calculating standardised residuals of VIs from linear regression. SPEI data on a 3-month timescale were used to represent the variation in drought conditions. VI residual and RWI data were used to investigate foliar and radial growth responses to the 2018 drought and recovery times derived from these two datasets.

Lastly, two RF modes were trained to predict annual RWI at pine and spruce stands, using information on average temperature, precipitation sum and VIs during months, recognized as important for the growth of pine and spruce, complemented with static SWC estimates from each site. The importance and dynamics of model variables were investigated by calculating SHAP values (Lundberg & Lee, 2017) and partial dependency plots (Greenwell, 2017), which were used to further examine the relationship between predictors and RWI (Figure 6). Combining predictive mapping of areas with high drought mortality risk with information on species-specific growth dynamics during extreme weather events could provide valuable information for planning forest management and climate adaptation strategies.

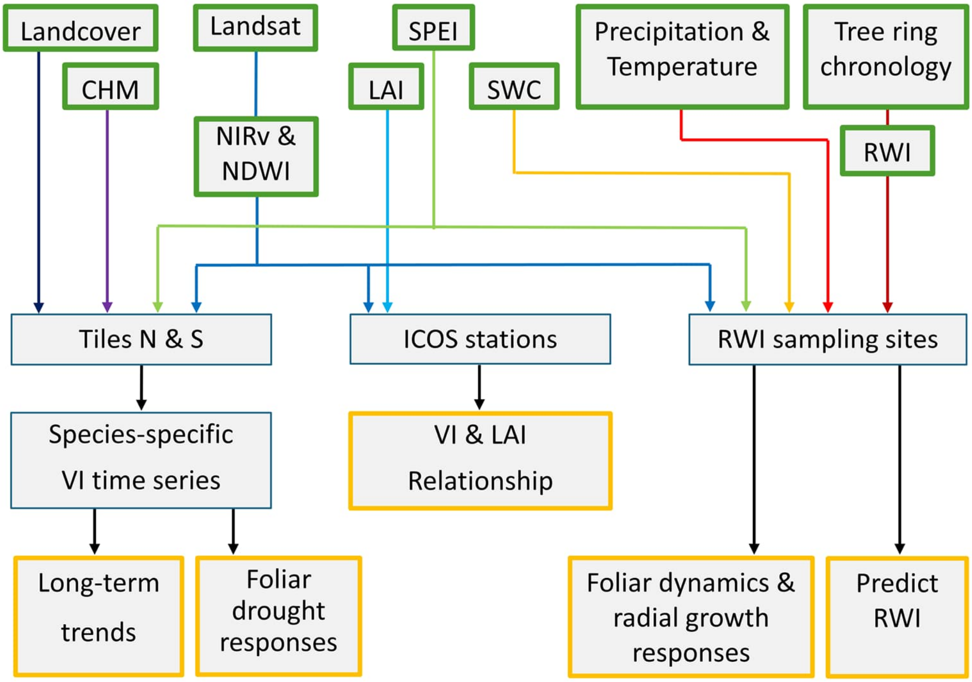


Figure 6. Summary of the workflow with steps from input data to results used in this study. The data inputs are marked with wide green borders. The three different types of study sites, with differing processing steps, are marked with thin blue borders. Results are marked with wide yellow borders

Results and discussion

Detecting response and resilience to drought in forests

In paper I, a satellite data-based framework was developed to investigate the capacity of Sentinel-2 data to identify response and resilience to drought across six forest types in Sweden (Figure 3). On average, the VIs detected successive stages of vegetation drought stress in an ecologically reasonable way. SWC measured at the study sites initially decreased, followed by the satellite-estimated VWC, then chlorophyll content, and finally LAIg. On average, changes in in VWC content of spruce, mixed coniferous, and mixed forests were detected within a week of the onset of the meteorological drought. At one of the sites, SWC changes were detected in all forest types except pine stands before the onset date of the meteorological drought, indicating that in certain areas, a decline in VWC can be detected before climatic conditions considered as drought are reached. Longer average latency in SWC changes detected in pine forests may be related to differences in rooting depths and the ability of pines to develop deep taproots (Martinez-Sancho et al., 2017). However, there was a large variation in latency of detecting a change in chlorophyll content between the forest types and sites, which suggested that it’s hard to separate the chlorophyll content and LAIg signals using VIs. High POS values were still detected in early summer, and larger decreases in forest productivity often occurred later in the growing season.

A longer reference period could have further lowered uncertainties related to the daily reference values, and data on stand species composition could have helped interpret the S2 signal when multiple species were present. Overall, the within-year vegetation drought response results show that VWC-related VI responded earlier to drought than greenness-related VIs. When possible, high temporal resolution observations should be prioritised over annual maximum vegetation index values (POS) to determine the intensity of disturbance.

Further analysis was conducted over a larger spatial extent, using a 40 × 240 km transect characterized by a strong gradient in annual precipitation. This analysis suggested that long-term precipitation patterns influence the depletion rate of root-zone available water on vast geographical extents. In a local context, drought resilience may be dependent on stand species composition; regardless, the most severe impacts of drought were consistently observed in areas with limited soil moisture availability. Forest recovery took up to four years (Figure 7).

Drought exposure over consecutive years can be especially harmful to species that require longer recovery times than a single growing season, as it has been demonstrated that frequent low-intensity dry conditions, not just high-intensity droughts, contribute to forest mortality (Sánchez-Pinillos et al., 2022). However, given the large geographic extent, we were unable to rule out the possibility that biotic agents influenced the signal following the drought or trees dying as a result of drought stress. Therefore, mapping of forest areas at high risk during potential future droughts could be further improved by integrating VI data with information on local water availability, forest composition and structure, and the presence of other potential stressors. Furthermore, the methodology described here cannot process Sentinel-2 images continuously as they become available. Therefore, further developments to monitor the forest state and drought responses in near-real time are encouraged.

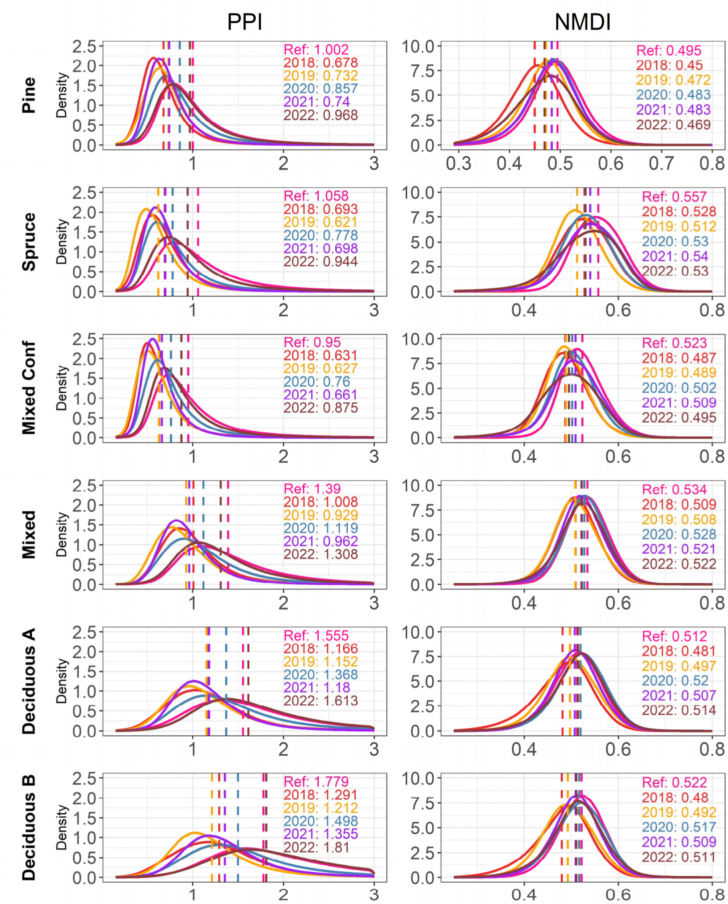


Figure 7. Kernel density estimates of PPI and NMDI POS at the transect. The area under the horizontal line at the y-axis value of one is equal to the total of the areas under each density line. Note the difference in the Y-axis scale between PPI and NMDI columns. Variance in density patterns and mean values illustrate shifts in ecosystem status between the years.

Secondary impacts of drought on forests and the role of local environmental factors

Paper I demonstrated that satellite data can be utilised to detect both direct and legacy impacts of drought on forests; however, indirect or secondary effects of drought and the role of local environmental factors were not considered. The 2018 drought weakened the defence capability of the forests and, as an indirect impact of drought, resulted in the largest documented outbreak of European bark beetles (*Ips Typographus*) in Sweden (Schroeder, 2023).

Paper II investigated how various environmental features influence the risk of bark beetle attacks during a drought year and the subsequent years with more normal weather conditions across a 48,600 km² study area in South-eastern Sweden. Geospatial data representing local forest stand attributes, topography, soil type and wetness, the proximity of clear-cuts, and previous bark beetle attacks, with a spatial resolution of 10 meters, were included in the analysis. The RF binary classification model achieved an accuracy of 85% for the drought period and 88.5% for the normal period, respectively (Figure 8A). Differences in accuracy can likely be attributed to the normal period model, which includes information about the distance to and intensity of previous attacks, as the beetles are likely to attack the closest suitable host trees. SHAP values were used to describe the contribution of each environmental feature to each prediction individually (Figure 8B).

The feature importance analysis suggested that the most important features controlling predisposition to bark beetle attacks are average canopy height (used as a proxy for tree age), spruce volume, soil type and average soil moisture, showing that that older forests with high spruce volume in drier sites had a high risk of bark beetle attacks during both study periods. Agreeing with the results of paper I, showing that the average soil wetness and coarse soil types with low water holding capacity lower the drought resilience of the trees. During the drought, the positive relationship between SHAP values and average canopy height was weaker during the normal period, suggesting that even the younger trees have a higher risk of bark beetle attacks during severe drought stress. Results show that mixing deciduous trees with Norway spruce lowered the attack risk. The proximity of a previous attack significantly increased the likelihood of a subsequent attack. The risk increases due to a short distance to a previously attacked tree declined rapidly with increasing distance. Risk decreased the fastest between 0 and 125 meters, after which it decreased slowly until no influence could be seen at a distance of 750 meters.

As climate change progresses, the ecological and economic impacts of bark beetle outbreaks are likely to increase. Methods that can support forest management decision-making and aid in the development of climate adaptation strategies will become increasingly valuable. Paper II combined "big data" from harvester machines with geospatial data describing local environmental factors to train RF machine learning models capable of accurately identifying the forest stands predisposed to bark beetle attacks. Importantly, the methodology provided quantifiable information on the importance and dynamics of predisposing features contributing to the risk at a pixel level, allowing for a more thorough consideration of where and how to take action. The models presented did not consider temporal aspects of climate, bark beetle phenology or detection of new bark beetle attacks. Promoting the development of methods capable of updating predicted predisposition risk predictions periodically is encouraged, as a next step towards operational use. Possible solutions could integrate risk maps with detecting new attacks with satellite remote sensing products (Abdullah et al., 2019; Huo et al., 2021) and modelling of bark beetle population dynamics (Bentz et al., 2019).

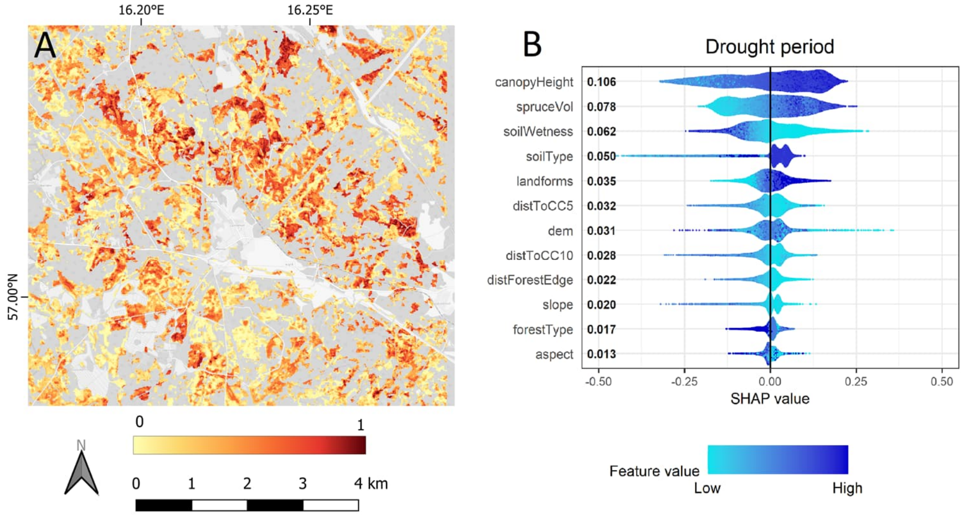


Figure 8A shows risk predictions on a subset of the study during the drought period. The colour scale represents the estimated probability (range 0 to 1) of a pixel being classified as ‘attacked by bark beetle’, which can be seen as quantified information of the risk of attack. Figure 8B summarizes the relative importance of features in the drought period model, ranked by averaging the absolute SHAP values (next to the feature abbreviation). Colouring of the points (individual estimates) follows a relative scale of the original feature values, ranging from minimum to maximum. The X-axis represents SHAP values, where negative values decrease, and positive values increase the risk of attack.

Drought impacts on agricultural crop yields

Paper III presented a causal inference framework that addressed the problem of crop rotation and variation in soil properties, which complicates VI time series analysis in agricultural fields. The propensity score matching, used to minimise the bias introduced by crop rotation and variation in soil properties, could pair 92% of the observations from the drought year with a control observation. Following the findings of paper I, PPI integrated over the growing season (TPROD) was used. The paired observations were filtered for any missing data and or noise in TPROD estimates, resulting in a final output set of 52,124 pairs. The regression analysis demonstrated that TPROD can accurately estimate regional-level yields when crop types are known ($R^2 = 0.93$) and field-level accuracy ranging from R^2 of 0.42 to 0.73, depending on the crop type. PPI could detect when drought began to slow down crop growth. The season length was reduced with crops sown the previous year when compared to spring-sown crops, but their yields were reduced less.

On the field extent, the impacts of agricultural drought were estimated as percentage differences in TPROD per field pair (ΔTPROD). This approach controlled for the influence of local topography and soil, as well as crop rotation, enabling the quantification of the relative severity of drought on specific crops in individual fields without requiring in situ training data (Figure 9).

Lastly, a LightGBM model using soil texture and topographical information was trained to predict ΔTPROD variation during drought at the field level. Results indicated that the contribution of soil and topography to the variation in yield losses caused by drought was small, as the model could explain 13% of the variation in the training data and 6% of the variation in the independent testing data. This finding aligns with previously suggested ranges, where Qiao et al. (2022) demonstrated that high-quality soils (medium-textured with high soil organic matter) reduced the sensitivity of yield to climate variability, increasing the mean crop yield by $10.3 \pm 6.7\%$ when analysing observations from sites representing 90% of total cereal production in China.

SHAP values were used to examine further the contributions of soil and topography variables to each field-level prediction of ΔTPROD. Permanent wilting point was the most important variable in explaining the variation in ΔTPROD. Clay content was the most important variable among the soil texture variables, indicating that increased clay content reduced yield losses. However, it had an upper limit, peaking at 20% clay, and a higher proportion of clay resulted in lower ΔTPROD (Figure 10A). Aschonitis et al. (2013) reported that clay content correlates with multiple soil properties related to cation exchange capacity and hydraulic properties and estimated the relationship between winter wheat yields and soil clay content, where the function curve similarly peaks around 20% clay. However, specifically for grasses, the clay-rich soils reduced yield losses (Figure 10B). Many forage grasses have most of their root biomass in the 0-10 cm soil depth (Skersiene et al., 2024). High-clay-content soils store proportionately more water near the surface than soils with a coarser texture, so they likely favour shallow-rooted vegetation (Jiang et al., 2020). However, grasses produced multiple harvests per year, and we could not ensure that the grass that was actually harvested (regional yield statistics) was not harvested during the drought. This produces uncertainty in model predictions at grass fields.

The causal inference framework addressed the problems introduced by crop rotation and variation in local environmental factors to time series analysis on croplands. PPI and TPROD demonstrate high potential for further developing methods for identifying crop response patterns to climatic stressors and yield prediction. The local soil and topography made a small contribution to yield loss variation among the fields but could still aid in directing adaptive measures on a local level. Thus, the methodology presented can help select suitable crops for a specific site and mitigate the impacts of climatic extremes; however, management and climate remain the primary drivers of crop yield variation.

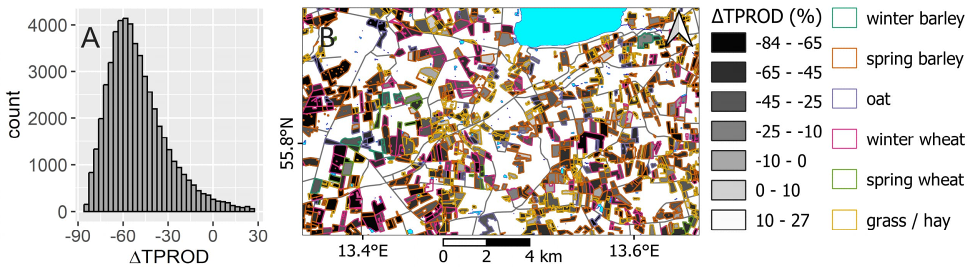


Figure 9A presents a histogram of all the ΔTPROD values. 9B presents an example of mapping ΔTPROD by crop type on a subset of the study area, where the fill colour indicates ΔTPROD and the border colour represents the crop type.

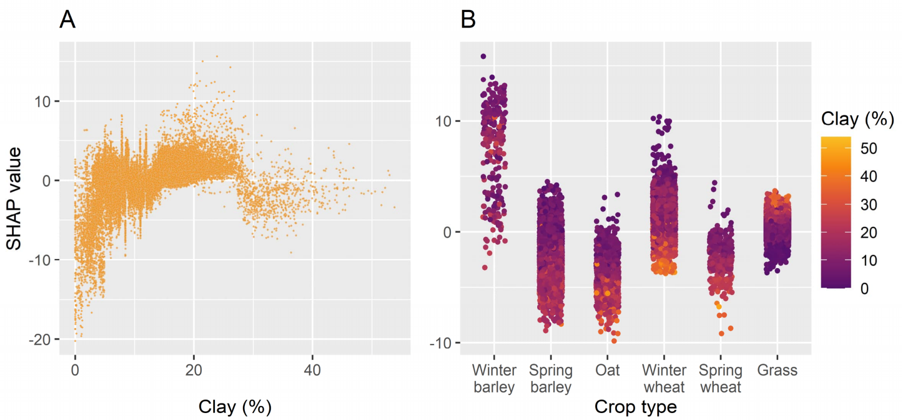


Figure 10A illustrates the dependence of ΔTPROD estimates on the average Clay percentage per field. Figure 10B represents how crop type influences yield loss estimates compared to the average ΔTPROD of all crops, and points are coloured by the clay content at each field.

Foliar dynamics and radial growth under drought

Paper IV examined the foliar dynamics and radial growth responses of spruce and pine stands to drought periods on a multidecadal scale and whether multi-source geospatial data can be utilised to predict annual variations in the radial growth of pine and spruce trees. A moderate positive Pearson's correlation between NIRv and LAI was observed (0.52, $p=0.003$), but the covariance of NIRv and RWI seemed to differ between the sites. NDWI appeared to be more generalisable across all sites (0.79, $p < 0.001$). Increasing trends in VI time series were observed between 1984 and 2021 in spruce and pine monocultures. Therefore, standardised residuals of VIs were calculated for RWI sampling sites, and they were able to detect drought impacts on foliar dynamics in both pine and spruce stands.

The RWI and standardised residuals of NIRv and NDWI were compared during the pre-drought period, the 2018 drought, and three years post-drought. Results show that the RWI of pine trees decreased more during the drought year 2018 than that of spruce trees. However, pine RWI showed growth rates above the long-term average as early as 2019, but VI detected foliar recovery took at least two years to reach pre-drought levels. Ovenden et al. (2021) showed that the legacy impacts of drought on pine growth rates can become positive, where trees reclaim growth lost due to drought. However, they suggested that this compensatory "excess growth" occurs mainly 4-5 years after the drought. Estimates from both RWI and VI-derived estimates from spruce stands indicate that neither radial growth nor foliar biomass reached pre-drought levels three years after the drought. Accordingly, spruce trees are considered more susceptible to summer droughts and take longer to recover from them than pines (Aldea et al., 2022).

Lastly, two RF models were used to predict RWI for each forest stand. On average, the RF models could explain 29% of the RWI variation at pine stands and 40% at spruce stands. Low performance at certain spatial folds can be attributed to the presence of data points outside of the training data range, where RF models are not capable of reliable extrapolation. Although the prediction performance of the models was not high, they surpassed recent efforts to predict tree-ring widths for multiple species, including pine and spruce (Jevsenak et al., 2024). These findings suggest the potential for further development of methods to map regions where extreme weather periods severely impact the radial growth of trees and to investigate how environmental factors influence this growth.

SHAP analysis revealed differences in both the importance and the influence of environmental factors on the radial growth of pine and spruce. Warm average temperatures in March contributed the most to the predictions for pine trees. RWI predictions for spruce were most dependent on precipitation in June, where high precipitation promoted growth. Overall, variable importance ranking indicates that pine is more dependent on temperature-related variables, whereas precipitation variables were generally higher ranked in the spruce model. Similarly, it has been demonstrated that pine growth depends on both temperature and drought, whereas spruce growth is primarily influenced by drought (Aldea et al., 2021).

Both models exhibited an upper limit to monthly mean temperatures during the summer months, after which an increase in temperature strongly reduces the RWI predictions (Figure 11). Drought years reduced RWI predictions in both models. In both models, negative NIRv residuals reduced the predicted RWI, and both VIs were also shown to respond to drought. However, positive residuals did not seem to promote higher growth for spruce, suggesting that foliar changes during years without extreme weather events may not be as strongly related to the trees' radial growth as drought-driven foliar changes. SWC had little influence on both models, but wetter areas experienced smaller reductions in RWI during droughts.

The drivers of the RWI could be identified using RF models; however, due to the limited number of RWI sampling sites, the movability of our models to new areas was low. We conclude that Landsat data shows potential to improve monitoring of both long-term growth trends and drought responses of forest stands. However, training data for even larger spatial and temporal coverage will be needed to increase the reliability and movability of the models. These developments could aid in mapping forest areas with increased drought mortality risk, providing valuable information for forest management and climate adaptation strategy planning.

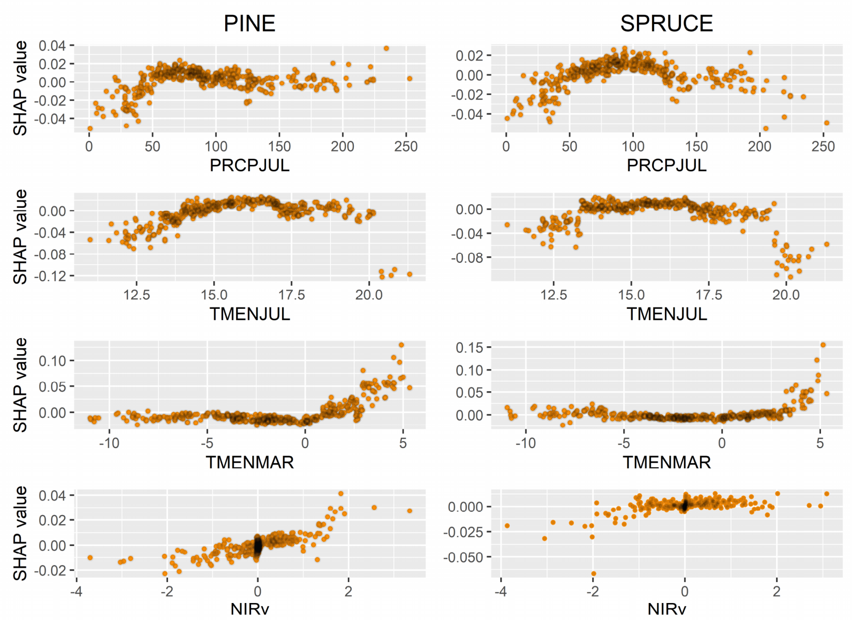


Figure 11. SHAP dependency plots show how the precipitation sum of July, mean temperature of July, mean temperature in March, and standardised residuals of NIRv influenced the predictions of the RWI variation in pine and spruce RF models.

Conclusions

This thesis presents an in-depth analysis of methodologies for detecting and quantifying the spatially explicit effects of drought on Swedish agricultural and forest ecosystems and their productivity. It has provided insights that improved our understanding of vegetation drought responses and resilience patterns.

Paper I developed a change-detection framework to quantify immediate and delayed drought-related vegetation changes in forest ecosystems and their recovery times. Results indicate that Sentinel-2 data can be used to monitor vegetation stress associated with drought progression and estimate the characteristics of forest resilience. When data is available, high-temporal-resolution observations should be prioritised over annual maximum VI values to assess the severity of drought impacts. Most severe impacts were consistently observed in areas with limited soil moisture availability. The recovery time for forests to pre-drought levels took up to four years. However, the short duration of the Sentinel-2 mission may have introduced uncertainties when compiling the reference data of an average period without extreme climate events. Additionally, developments regarding spectral unmixing of the VI signals when multiple species are present are proposed to enhance the estimation of species-specific responses to drought.

As droughts affect tree vigour in unison with local environmental factors, Paper II focused on identifying drivers and map forest areas with a high risk of European spruce bark beetle disturbances as a secondary effect of drought. Forest stands with increased risk of bark beetle attack were identified with high accuracy, and information on the importance and dynamics of environmental features controlling the risk in the local context was derived. However, the method developed did not consider temporal aspects of climate, bark beetle phenology and monitoring of new attacks. Thus, further advancements in integrating data sources that can provide information on the detection of new attacks and bark beetle phenology to periodically update the predicted bark beetle attack risk status across vast geographical areas would enhance operational usage.

Paper III developed a causal inference framework considering crop rotation and local environmental factors when quantifying climate-driven changes in agricultural crop yields between selected periods. Based on the information from Papers I and II, Paper III utilised an integrated VI approach to assess crop type-specific drought impacts throughout the entire growing season while considering the effects of crop rotation and local soil and topography. The regional yields were estimated with high accuracy, while greater variation was observed in the field-level prediction accuracies. The monitoring of common production crops in Sweden during drought revealed that all crops had a shortened growing season, with spring-sown crops experiencing greater yield loss. The effect of soil texture on the variation in drought-induced yield losses was quantified, and seasonal dynamics were analysed, thereby enhancing the understanding of interactions among the soil, plants, and the atmosphere at a local level.

Paper IV investigated the foliar and radial growth responses of Norway spruce and Scots pine trees to drought at national and multidecadal scales by combining satellite, meteorological, soil wetness, and dendrochronological data. The issues related to the length of the study period and mixed signals noted in the previous studies were addressed by focusing exclusively on spruce and pine monocultures, along with longer VI time series derived from Landsat data to investigate the foliar dynamics and radial growth of spruce and pine trees under drought conditions. Results indicate that long-term trends related to forest canopy development in the VI time series should be considered when assessing climate-driven foliar dynamics. Both RWI- and VI-derived drought response estimates for pine and spruce stands were analysed, showing that pines exhibit higher drought resilience and faster recovery than spruce trees. Also, the drivers of variance in annual radial growth were identified. However, the limited availability of images constrained the calculation of annually integrated VI values, potentially hindering the ability to characterise vegetation changes that occur during different periods of the growing season across various years. Also, the limited number of sampling sites restricted the ability to upscale the RWI predictions. Larger training datasets are required to enhance the reliability of detecting forest stands with low drought growth resilience.

Trade-offs between Sentinel-2 and Landsat missions, related to spectral, temporal and spatial resolution as well as the length of the observation period, are currently challenging to navigate and must be evaluated on a case-by-case basis according to the priorities of individual studies. All the studies in this thesis utilised static variables in varying combinations to characterise local topography, soil attributes, SWC, forest composition or structure. An important finding was that especially variables describing local water availability with high spatial resolution are important in mapping areas predisposed to direct, secondary, and legacy effects of drought on vegetation.

The effective use of multi-source geospatial data can identify and map the risks and impacts of drought on forests and agricultural ecosystems over time and across different regions, addressing the urgent need to improve drought preparedness in societies. The findings presented in this thesis can support a shift toward more sustainable management practices by providing the information essential for informed policy planning and decision-making, based on scientific knowledge.

Outlook

Historically, wood production and the economic dimension have been prioritised, but in recent decades, sustainability challenges have led to increased interest in the more efficient integration of policies across sectors, promoting deliberation and the introduction of new management approaches (Lindahl et al., 2017). Over time, warmer winters and drier summers in Sweden may introduce conflict in the natural distribution of species and regions where they are currently growing or cultivated. One of the key components of increasing a society's drought preparedness is to understand better the drought resilience dynamics of both natural and managed ecosystems and to pre-emptively identify vulnerable areas. Society does not just passively experience variations in the amount of available water; policies and land management regulations can also guide agricultural and forest management practices. This, however, requires clear communication of information regarding drought risks and effects. This thesis contributed to this information need, demonstrating that mapping can effectively present and communicate spatial information on drought risk variation and its drivers, providing site- and species-specific information — bridging the gap between scientists and stakeholders.

The results of this thesis suggest that forest stands with a mixture of species could increase the resilience of forests against both direct and secondary drought impacts. Out of the most common monocultures, pines showed faster recovery than spruce trees. Thus, forest management strategies should consider valuing mixed and pine stands over spruce in terms of drought-resilient forest management. Regarding agriculture, the methodology presented here could help estimate crop-specific impacts on yields at the field level, also allowing for the estimation of the latency in which irrigation is needed to avoid the most severe losses in crop production. However, this thesis did not consider the influence of varying land management practices on the detected drought impacts, which is an important factor that should be included in future studies. Especially in agriculture, where fertilisers play a role and management practices can affect the infiltration capabilities of soils from year to year. Further developments are still required for these methods to enable updating the vegetation status and risk predictions in near real-time as new data becomes available.

Initial advancements towards more dynamic monitoring of trees predisposed to and attacked by bark beetles have already been made outside this thesis. Olsson et al. (2024) combined risk maps developed in paper II with Sentinel-2 data to detect bark beetle attacks, showing that including the risk maps increases the detection accuracy, especially when accuracy is low from Sentinel-2 data alone. Recently, it was demonstrated that the breakpoint detection method employed in Paper I is also suitable for mapping vegetation disturbances and recovery patterns in large-scale applications (Xu et al., 2025). In the future, the capability of Sentinel-2 data, used in papers I and III, to support long-term monitoring will improve, as the mission coverage period is extended, uncertainties in composing reference time series of average periods without extreme climate events will decrease as longer reference periods can be included. Varghese et al. (2021) emphasised the importance of Sentinel-2's ability to track changes following the slow pace of drought, as well as the fact that with the addition of Sentinel-2C and Sentinel-2D satellites, the mission will eventually cover a 20-year period. This will further enhance the reliability and value of Sentinel-2 data-based analyses in the future.

Despite advancements in efficiently using multi-source geospatial data, the need for high-quality in-situ measurements persists. For instance, Haberstroh and Werner (2022) discovered that mixed-species forests can exhibit beneficial species interactions during mild droughts, such as enhanced water relations. However, trees with complementary resource-use strategies may compete for water resources during severe droughts. A forest stand consisting of a variety of drought-resistant species is likely to recover more quickly; however, if soil moisture availability is not fully replenished, the recovery of less drought-resistant species may take longer. These types of interactions among individual trees or plants will be challenging to detect, relying solely on similar geospatial datasets as used in this thesis.

While challenges persist in reliably separating species-specific signals and accounting for the complex interplay of biotic and abiotic stressors and vegetation carbon allocation strategies, ongoing methodological advancements and innovative applications show great promise. With continued method development and advanced applications, the ability to harness the full potential of multi-source geospatial data and data-driven models is being progressively enhanced, This will enable actionable insights informing decision-making and promoting sustainable solutions in a changing climate through mapping vegetation dynamics under drought stress.

References

Aalto, J., Aaltonen, H., Aiguier, T., Akubia, J., Aluome, C., Andersson, T., Aurela, M., Back, J., Bagheri, S., Barten, S., Bastos Campos, F., Baur, T., Bazot, S., Beauclair, P., Becker, N., Belelli Marchesini, L., Bergström, G., Bernhofer, C., Berveiller, D., . . . Šlížek, J. (2024). Ecosystem final quality (L2) product in ETC-Archive format - INTERIM release 2024-2. In: ICOS ERIC -- Carbon Portal.

Abdullah, H., Darvishzadeh, R., Skidmore, A., & Heurich, M. (2019). Sensitivity of Landsat-8 OLI and TIRS Data to Foliar Properties of Early Stage Bark Beetle (Ips typographus, L.) Infestation. *Remote Sensing*, *11*(4), 398. https://doi.org/10.3390/rs11040398

Adamczyk, B. (2021). How do boreal forest soils store carbon? *BioEssays*, *43*(7), 2100010. https://doi.org/10.1002/bies.202100010

Adeniyi, O. D., Bature, H., & Mearker, M. (2024). A Systematic Review on Digital Soil Mapping Approaches in Lowland Areas. *Land*, *13*(3), 379. https://doi.org/10.3390/land13030379

Aghakouchak, A., Farahmand, A., Melton, F. S., Teixeira, J., Anderson, M. C., Wardlow, B. D., & Hain, C. R. (2015). Remote sensing of drought: Progress, challenges and opportunities. *Reviews of Geophysics*, *53*(2), 452-480. https://doi.org/10.1002/2014rg000456

Aldea, J., Ruiz-Peinado, R., del Río, M., Pretzsch, H., Heym, M., Brazaitis, G., Jansons, A., Metslaid, M., Barbeito, I., Bielak, K., Granhus, A., Holm, S.-O., Nothdurft, A., Sitko, R., & Löf, M. (2021). Species stratification and weather conditions drive tree growth in Scots pine and Norway spruce mixed stands along Europe. *Forest Ecology and Management*, *481*. https://doi.org/10.1016/j.foreco.2020.118697

Aldea, J., Ruiz-Peinado, R., Del Río, M., Pretzsch, H., Heym, M., Brazaitis, G., Jansons, A., Metslaid, M., Barbeito, I., Bielak, K., Hylen, G., Holm, S. O., Nothdurft, A., Sitko, R., & Löf, M. (2022). Timing and duration of drought modulate tree growth response in pure and mixed stands of Scots pine and Norway spruce. *Journal of Ecology*, *110*(11), 2673-2683. https://doi.org/10.1111/1365-2745.13978

Andersson, S., Bärring, L., Landelius, T., Samuelsson, P., & Schimanke, S. (2021). *SMHI Gridded Climatology* Swedish Meteorological and Hydrological Institute. https://www.smhi.se/publikationer/publikationer/smhi-gridded-climatology-1.177514

Aschonitis, V. G., Lithourgidis, A. S., Damalas, C. A., & Antonopoulos, V. Z. (2013). Modelling Yields of Non-Irrigated Winter Wheat In A Semi-Arid Mediterranean Environment Based On Drought Variability. *Experimental Agriculture*, *49*(3), 448-460. https://doi.org/10.1017/s001447971300015x

Badgley, G., Field, C. B., & Berry, J. A. (2017). Canopy near-infrared reflectance and terrestrial photosynthesis. *Science Advances*, *3*(3), e1602244. https://doi.org/10.1126/sciadv.1602244

Bakke, S. J., Ionita, M., & Tallaksen, L. M. (2020). The 2018 northern European hydrological drought and its drivers in a historical perspective. *Hydrology and Earth System Sciences*, *24*(11), 5621-5653. https://doi.org/10.5194/hess-24-5621-2020

Bastviken, S., Bratt, A., Ek Henning, H., & Lindmark, P. (2015). *Jordbruk och vattenmiljöer i ett förändrat klimat*. Länsstyrelsen Östergötland. https://www.lansstyrelsen.se/ostergotland/om-oss/vara-tjanster/publikationer/2015/jordbruk-och-vattenmiljoer-i-ett-forandrat-klimat-jovak.html. Accessed 27.05.2022.

Beguería, S., Serrano, S. M. V., Reig-Gracia, F., & Garcés, B. L. (2024). SPEIbase v.2.10 [Dataset]: A Comprehensive Tool for Global Drought Analysis. https://doi.org/10.20350/digitalCSIC/16497

Bentz, B. J., Jönsson, A. M., Schroeder, M., Weed, A., Wilcke, R. A. I., & Larsson, K. (2019). Ips typographus and Dendroctonus ponderosae Models Project Thermal Suitability for Intra- and Inter-Continental Establishment in a Changing Climate [Original Research]. *Frontiers in Forests and Global Change*, *2*(1). https://doi.org/10.3389/ffgc.2019.00001

Bergqvist, J., Eriksson, A., Eggers, J., Nilsson, C., Paulsson, J., Pettersson, J., Roberge, J.-M., & Wikberg, P.-E. (2022). *Skogliga konsekvensanalyser 2022 - syntesrapport*. https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-20222021202020192018/rapport-2022-11-skogliga-konsekvensanalyser-2022---syntesrapport.pdf

Bista, D., Heckathorn, S., Jayawardena, D., Mishra, S., & Boldt, J. (2018). Effects of Drought on Nutrient Uptake and the Levels of Nutrient-Uptake Proteins in Roots of Drought-Sensitive and -Tolerant Grasses. *Plants*, *7*(2), 28. https://doi.org/10.3390/plants7020028

Breiman, L. (2001). Random Forests. *Machine Learning*, *45*(1), 5-32. https://doi.org/10.1023/a:1010933404324

Chaplin, M. F. (2001). Water: its importance to life. *Biochemistry and Molecular Biology Education*, *29*(2), 54-59. https://doi.org/https://doi.org/10.1016/S1470-8175(01)00017-0

Chen, J., Saunders, S. C., Crow, T. R., Naiman, R. J., Brosofske, K. D., Mroz, G. D., Brookshire, B. L., & Franklin, J. F. (1999). Microclimate in Forest Ecosystem and Landscape Ecology: Variations in local climate can be used to monitor and compare the effects of different management regimes. *BioScience*, *49*(4), 288-297. https://doi.org/10.2307/1313612

Cheng, L., Abraham, J., Trenberth, K. E., Boyer, T., Mann, M. E., Zhu, J., Wang, F., Yu, F., Locarnini, R., Fasullo, J., Zheng, F., Li, Y., Zhang, B., Wan, L., Chen, X., Wang, D., Feng, L., Song, X., Liu, Y., . . . Lu, Y. (2024). New Record Ocean Temperatures and Related Climate Indicators in 2023. *Advances in Atmospheric Sciences*, *41*(6), 1068-1082. https://doi.org/10.1007/s00376-024-3378-5

Condon, L. E., & Maxwell, R. M. (2015). Evaluating the relationship between topography and groundwater using outputs from a continental-scale integrated hydrology model. *Water Resources Research*, *51*(8), 6602-6621. https://doi.org/10.1002/2014wr016774

Copernicus. (2024). *Climate indicators: Temperature*. https://climate.copernicus.eu/climate-indicators/temperature. Accessed 25.02.2025.

Copernicus European Drought Observatory. (2018). *Drought in Central-Northern Europe – July 2018* (EDO Analytical Report, Issue. https://edo.jrc.ec.europa.eu/documents/news/EDODroughtNews201807_Central_North_Europe.pdf

Crawford, C. J., Roy, D. P., Arab, S., Barnes, C., Vermote, E., Hulley, G., Gerace, A., Choate, M., Engebretson, C., Micijevic, E., Schmidt, G., Anderson, C., Anderson, M., Bouchard, M., Cook, B., Dittmeier, R., Howard, D., Jenkerson, C., Kim, M., . . . Zahn, S. (2023). The 50-year Landsat collection 2 archive. *Science of Remote Sensing*, *8*. https://doi.org/10.1016/j.srs.2023.100103

de Brito, M. M. (2021). Compound and cascading drought impacts do not happen by chance: A proposal to quantify their relationships. *Science of The Total Environment*, *778*, 146236. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.146236

Debeer, D., Hothorn, T., & Strobl, C. (2021). *permimp: Conditional Permutation Importance.* In (Version 1.0-2) [R package]. https://CRAN.R-project.org/package=permimp

Debeer, D., & Strobl, C. (2020). Conditional permutation importance revisited. *BMC Bioinformatics*, *21*(1). https://doi.org/10.1186/s12859-020-03622-2

Desoto, L., Cailleret, M., Sterck, F., Jansen, S., Kramer, K., Robert, E. M. R., Aakala, T., Amoroso, M. M., Bigler, C., Camarero, J. J., Čufar, K., Gea-Izquierdo, G., Gillner, S., Haavik, L. J., Hereş, A.-M., Kane, J. M., Kharuk, V. I., Kitzberger, T., Klein, T., . . . Martínez-Vilalta, J. (2020). Low growth resilience to drought is related to future mortality risk in trees. *Nature Communications, 11*(1). https://doi.org/10.1038/s41467-020-14300-5

Dronova, I., & Taddeo, S. (2022). Remote sensing of phenology: Towards the comprehensive indicators of plant community dynamics from species to regional scales. *Journal of Ecology*, *110*(7), 1460-1484. https://doi.org/10.1111/1365-2745.13897

European Space Agency. (2015). *Sentinel-2 User Handbook*. European Space Agency. https://sentinel.esa.int/documents/247904/685211/Sentinel-2_User_Handbook. Accessed 04.04.2025.

Gao, B.-C. (1996). NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, *58*(3), 257-266. https://doi.org/10.1016/s0034-4257(96)00067-3

Garonna, I., De Jong, R., De Wit, A. J. W., Mücher, C. A., Schmid, B., & Schaepman, M. E. (2014). Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982-2011). *Global Change Biology*, *20*(11), 3457-3470. https://doi.org/10.1111/gcb.12625

Gebrechorkos, S. H., Peng, J., Dyer, E., Miralles, D. G., Vicente-Serrano, S. M., Funk, C., Beck, H. E., Asfaw, D. T., Singer, M. B., & Dadson, S. J. (2023). Global high-resolution drought indices for 1981–2022. *Earth System Science Data*, *15*(12), 5449-5466. https://doi.org/10.5194/essd-15-5449-2023

Gitelson, A. A. (2003). Novel technique for remote estimation of CO_2 flux in maize. *Geophysical Research Letters*, *30*(9). https://doi.org/10.1029/2002gl016543

Gourlez de la Motte, L., Beauclaire, Q., Heinesch, B., Cuntz, M., Foltynova, L., Sigut, L., Kowalska, N., Manca, G., Ballarin, I. G., Vincke, C., Roland, M., Ibrom, A., Lousteau, D., Siebicke, L., Neiryink, J., & Longdoz, B. (2020). Non-stomatal processes reduce gross primary productivity in temperate forest ecosystems during severe edaphic drought. *Philos Trans R Soc Lond B Biol Sci*, *375*(1810), 20190527. https://doi.org/10.1098/rstb.2019.0527

Greenwell, B. M. (2017). pdp: An R Package for Constructing Partial Dependence Plots. *The R Journal*, *9*, 421-436. https://doi.org/10.32614/RJ-2017-016

Greiser, C., Meineri, E., Luoto, M., Ehrlén, J., & Hylander, K. (2018). Monthly microclimate models in a managed boreal forest landscape. *Agricultural and Forest Meteorology*, *250-251*, 147-158. https://doi.org/10.1016/j.agrformet.2017.12.252

Grusson, Y., Wesström, I., & Joel, A. (2021). Impact of climate change on Swedish agriculture: Growing season rain deficit and irrigation need. *Agricultural Water Management*, *251*, 106858. https://doi.org/https://doi.org/10.1016/j.agwat.2021.106858

Haberstroh, S., & Werner, C. (2022). The role of species interactions for forest resilience to drought. *Plant Biology*, *24*(7), 1098-1107. https://doi.org/10.1111/plb.13415

Hamanishi, E. T., Thomas, B. R., & Campbell, M. M. (2012). Drought induces alterations in the stomatal development program in Populus. *Journal of Experimental Botany*, *63*(13), 4959-4971. https://doi.org/10.1093/jxb/ers177

Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., Lopez, R., Saenz-Romero, C., Hartmann, H., Breshears, D. D., & Allen, C. D. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nat Commun*, *13*(1), 1761. https://doi.org/10.1038/s41467-022-29289-2

Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., Qin, H., Raffa, K. F., Schelhaas, M.-J., Svoboda, M., Viiri, H., & Seidl, R. (2021). Bark Beetle Outbreaks in Europe: State of Knowledge and Ways Forward for Management. *Current Forestry Reports*, *7*(3), 138-165. https://doi.org/10.1007/s40725-021-00142-x

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1-23. https://doi.org/10.1146/annurev.es.04.110173.000245

Huo, L., Persson, H. J., & Lindberg, E. (2021). Early detection of forest stress from European spruce bark beetle attack, and a new vegetation index: Normalized distance red & SWIR (NDRS). *Remote Sensing of Environment*, *255*, 112240. https://doi.org/10.1016/j.rse.2020.112240

Hurteau, M. D. (2021). The role of forests in the carbon cycle and in climate change. In *Climate Change* (pp. 561-579). https://doi.org/10.1016/b978-0-12-821575-3.00027-x

Jactel, H., Petit, J., Desprez-Loustau, M.-L., Delzon, S., Piou, D., Battisti, A., & Koricheva, J. (2012). Drought effects on damage by forest insects and pathogens: a meta-analysis. *Global Change Biology*, *18*(1), 267-276. https://doi.org/10.1111/j.1365-2486.2011.02512.x

Jamali, S., Jönsson, P., Eklundh, L., Ardö, J., & Seaquist, J. (2015). Detecting changes in vegetation trends using time series segmentation. *Remote Sensing of Environment*, *156*, 182-195. https://doi.org/10.1016/j.rse.2014.09.010

Jevsenak, J., Klisz, M., Masek, J., Cada, V., Janda, P., Svoboda, M., Vostarek, O., Treml, V., van der Maaten, E., Popa, A., Popa, I., van der Maaten-Theunissen, M., Zlatanov, T., Scharnweber, T., Ahlgrimm, S., Stolz, J., Sochova, I., Roibu, C. C., Pretzsch, H., . . . Buras, A. (2024). Incorporating high-resolution climate, remote sensing and topographic data to map annual forest growth in central and eastern Europe. *Sci Total Environ*, *913*, 169692. https://doi.org/10.1016/j.scitotenv.2023.169692

Jiang, P., Ding, W., Yuan, Y., & Ye, W. (2020). Diverse response of vegetation growth to multi-time-scale drought under different soil textures in China's pastoral areas. *J Environ Manage*, *274*, 110992. https://doi.org/10.1016/j.jenvman.2020.110992

Jin, H., & Eklundh, L. (2014). A physically based vegetation index for improved monitoring of plant phenology. *Remote Sensing of Environment*, *152*, 512-525. https://doi.org/10.1016/j.rse.2014.07.010

Jordbruksverket. (2015). *Årslager skiftesdata*. https://doi.org/https://jordbruksverket.se/e-tjanster-databaser-och-appar/e-tjanster-och-databaser-stod/kartor-och-gis. Accessed 27.02.2025.

Joshi, J., Stocker, B. D., Hofhansl, F., Zhou, S., Dieckmann, U., & Prentice, I. C. (2022). Towards a unified theory of plant photosynthesis and hydraulics. *Nature Plants*. https://doi.org/10.1038/s41477-022-01244-5

Jönsson, A. M., Eklundh, L., Hellström, M., Bärring, L., & Jönsson, P. (2010). Annual changes in MODIS vegetation indices of Swedish coniferous forests in relation to snow dynamics and tree phenology. *Remote Sensing of Environment*, *114*(11), 2719-2730. https://doi.org/10.1016/j.rse.2010.06.005

Karlsson, S., Andersson, E., Roberge, J.-M., & Österdahl, S. (2022). *Sustainable Forests In-depth evaluation 2023*. https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-20222021202020192018/rapport-2022-12-sustainable-forests-in-depth-evaluation-2023-english-summary.pdf

Ke, G., Meng, Q., Finley, T., Wang, T., Chen, W., Ma, W., Ye, Q., & Liu, T.-Y. (2017). *LightGBM: A Highly Efficient Gradient Boosting Decision Tree*. 3149–3157. Proceedings of the 31st International Conference on Neural Information Processing Systems. Curran Associates, Inc. Long Beach, California. USA. https://dl.acm.org/doi/10.5555/3294996.3295074

Knutzen, F., Averbeck, P., Barrasso, C., Bouwer, L. M., Gardiner, B., Grünzweig, J. M., Hänel, S., Haustein, K., Johannessen, M. R., Kollet, S., Pietikaeinen, J.-P., Pietras-Couffignal, K., Pinto, J. G., Rechid, D., Rousi, E., Russo, A., Suarez-Gutierrez, L., Wendler, J., Xoplaki, E., & Gliksman, D. (2023). *Impacts and damages of the European multi-year drought and heat event 2018–2022 on forests, a review*. Copernicus GmbH.

Kopp Hollunder, R., Garbin, M. L., Rubio Scarano, F., & Mariotte, P. (2022). Regional and local determinants of drought resilience in tropical forests. *Ecol Evol*, *12*(5), e8943. https://doi.org/10.1002/ece3.8943

Kuhn, M. (2008). Building Predictive Models in R Using the caret Package. *Journal of Statistical Software*, *28*(5), 1 - 26. https://doi.org/10.18637/jss.v028.i05

Kuhn, M., & Wickham, H. (2020). *Tidymodels: a collection of packages for modeling and machine learning using tidyverse principles*. In (Version 1.2.0) https://www.tidymodels.org

Lantmäteriet. (2020). *GSD-Höjddata, grid 2+*. https://www.lantmateriet.se/sv/geodata/vara-produkter/produktlista/. Accessed 20.05.2021

Liang, S., Wang, J., & editors. (2020). Estimate of vegetation production of terrestrial ecosystem. In S. Liang & J. Wang (Eds.), *Advanced Remote Sensing* (pp. 581-620). Elsevier. https://doi.org/10.1016/b978-0-12-815826-5.00015-5

Lindahl, K. B., Sténs, A., Sandström, C., Johansson, J., Lidskog, R., Ranius, T., & Roberge, J.-M. (2017). The Swedish forestry model: More of everything? *Forest Policy and Economics*, *77*, 44-55. https://doi.org/10.1016/j.forpol.2015.10.012

Lindroth, A., Holst, J., Linderson, M. L., Aurela, M., Biermann, T., Heliasz, M., Chi, J., Ibrom, A., Kolari, P., Klemedtsson, L., Krasnova, A., Laurila, T., Lehner, I., Lohila, A., Mammarella, I., Molder, M., Lofvenius, M. O., Peichl, M., Pilegaard, K., . . . Nilsson, M. (2020). Effects of drought and meteorological forcing on carbon and water fluxes in Nordic forests during the dry summer of 2018. *Philos Trans R Soc Lond B Biol Sci*, *375*(1810), 20190516. https://doi.org/10.1098/rstb.2019.0516

Lindstad, B. H. (2002). *A comparative study of forestry in Finland, Norway, Sweden, and the United States, with special emphasis on policy measures for nonindustrial private forests in Norway and the United States* (Vol. 538). US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Lundberg, S. M., Erion, G., Chen, H., Degrave, A., Prutkin, J. M., Nair, B., Katz, R., Himmelfarb, J., Bansal, N., & Lee, S.-I. (2020). From local explanations to global understanding with explainable AI for trees. *Nature Machine Intelligence*, *2*(1), 56-67. https://doi.org/10.1038/s42256-019-0138-9

Lundberg, S. M., & Lee, S.-I. (2017). *A unified approach to interpreting model predictions* Proceedings of the 31st International Conference on Neural Information Processing Systems, Long Beach, California, USA.

Martinez-Sancho, E., Dorado-Linan, I., Hacke, U. G., Seidel, H., & Menzel, A. (2017). Contrasting Hydraulic Architectures of Scots Pine and Sessile Oak at Their Southernmost Distribution Limits. *Front Plant Sci*, *8*, 598. https://doi.org/10.3389/fpls.2017.00598

Martinez-Vilalta, J., Anderegg, W. R. L., Sapes, G., & Sala, A. (2019). Greater focus on water pools may improve our ability to understand and anticipate drought-induced mortality in plants. *New Phytologist*, *223*(1), 22-32. https://doi.org/10.1111/nph.15644

Marzano, F. S. (2014). Radiative Transfer, Theory. In *Encyclopedia of Remote Sensing* (pp. 624-634). Springer New York. https://doi.org/10.1007/978-0-387-36699-9_152

Mas, J.-F., & Soares De Araújo, F. (2021). Assessing Landsat Images Availability and Its Effects on Phenological Metrics. *Forests*, *12*(5), 574. https://doi.org/10.3390/f12050574

Mckee, T., Doesken, N., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. Eighth Conference on Applied Climatology, Anaheim, California.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1-2), 202-216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Misra, G., Cawkwell, F., & Wingler, A. (2020). Status of Phenological Research Using Sentinel-2 Data: A Review. *Remote Sensing*, *12*(17), 2760. https://doi.org/10.3390/rs12172760

Mohammadi, S., Rydgren, K., Bakkestuen, V., & Gillespie, M. A. K. (2023). Impacts of recent climate change on crop yield can depend on local conditions in climatically diverse regions of Norway. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-30813-7

Morin-Bernard, A., Coops, N. C., White, J. C., & Achim, A. (2023). Predicting net growth rates in boreal forests using Landsat time series and permanent sample plot data. *Forestry: An International Journal of Forest Research*. https://doi.org/10.1093/forestry/cpad055

Nasiri, V., Beloiu, M., Asghar Darvishsefat, A., Griess, V. C., Maftei, C., & Waser, L. T. (2023). Mapping tree species composition in a Caspian temperate mixed forest based on spectral-temporal metrics and machine learning. *International Journal of Applied Earth Observation and Geoinformation, 116*. https://doi.org/10.1016/j.jag.2022.103154

Nationella expertrådet för klimatanpassning. (2022). *Första rapporten från Nationella expertrådet för klimatanpassning 2022*. Stockholm, Sweden. https://klimatanpassningsradet.se/publikationer/forsta-rapporten-fran-nationella-expertradet-for-klimatanpassning. Accessed 10.10.2023

Netherer, S., Matthews, B., Katzensteiner, K., Blackwell, E., Henschke, P., Hietz, P., Pennerstorfer, J., Rosner, S., Kikuta, S., Schume, H., & Schopf, A. (2015). Do water-limiting conditions predispose Norway spruce to bark beetle attack? *New Phytologist*, *205*(3), 1128-1141. https://doi.org/10.1111/nph.13166

Netherer, S., Panassiti, B., Pennerstorfer, J., & Matthews, B. (2019). Acute Drought Is an Important Driver of Bark Beetle Infestation in Austrian Norway Spruce Stands. *Frontiers in Forests and Global Change, 2*. https://doi.org/10.3389/ffgc.2019.00039

Official Statistics of Sweden. (2023). *Yield by region, crop, observations and year*. Version 2024-04-24. https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__JO__JO0601/SkordarL2/. Accessed 12.02.2025

Ogana, F. N., Holmström, E., Aldea, J., & Liziniewicz, M. (2024). Growth response of Pinus sylvestris L. and Picea abies [L.] H. Karst to climate conditions across a latitudinal gradient in Sweden. *Agricultural and Forest Meteorology*, *353*. https://doi.org/10.1016/j.agrformet.2024.110062

Olsson, P.-O., Zhao, P., Müller, M., Mansourian, A., & Ardö, J. (2024). Combining Sentinel-2 Data and Risk Maps to Detect Trees Predisposed to and Attacked by European Spruce Bark Beetle. *Remote Sensing*, *16*(22), 4166. https://www.mdpi.com/2072-4292/16/22/4166

Orimoloye, I. R. (2022). Agricultural Drought and Its Potential Impacts: Enabling Decision-Support for Food Security in Vulnerable Regions. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.838824

Ou, T. (2017). *Droughts and wildfires in Sweden - past variation and future projection*. https://www.msb.se/siteassets/dokument/publikationer/english-publications/droughts-and-wildfires-in-sweden-past-variation-and-future-projection.pdf

Ovenden, T. S., Perks, M. P., Clarke, T. K., Mencuccini, M., & Jump, A. S. (2021). Life after recovery: Increased resolution of forest resilience assessment sheds new light on post-drought compensatory growth and recovery dynamics. *Journal of Ecology*, *109*(9), 3157-3170. https://doi.org/10.1111/1365-2745.13576

Palmer, W. C. (1965). *Meteorological drought* (Vol. 45). US Department of Commerce, Weather Bureau. Washington DC, USA. https://www.droughtmanagement.info/literature/USWB_Meteorological_Drought_1965.pdf. Accessed 13.12.2024

Park, H., Kim, K., & Lee, D. K. (2019). Prediction of Severe Drought Area Based on Random Forest: Using Satellite Image and Topography Data. *Water*, *11*(4), 705. https://doi.org/10.3390/w11040705

Pekala, K., Woznica, K., & Biecek, P. (2021). *Triplot: model agnostic measures and visualisations for variable importance in predictive models that take into account the hierarchical correlation structure*. https://doi.org/https://doi.org/10.48550/arXiv.2104.03403

Piikki, K., & Söderström, M. (2019). Digital soil mapping of arable land in Sweden – Validation of performance at multiple scales. *Geoderma*, *352*, 342-350. https://doi.org/https://doi.org/10.1016/j.geoderma.2017.10.049

Price, K. (2011). Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. *Progress in Physical Geography: Earth and Environment*, *35*(4), 465-492. https://doi.org/10.1177/0309133311402714

Prodhan, F. A., Zhang, J., Hasan, S. S., Pangali Sharma, T. P., & Mohana, H. P. (2022). A review of machine learning methods for drought hazard monitoring and forecasting: Current research trends, challenges, and future research directions. *Environmental Modelling & Software*, *149*. https://doi.org/10.1016/j.envsoft.2022.105327

Qiao, L., Wang, X., Smith, P., Fan, J., Lu, Y., Emmett, B., Li, R., Dorling, S., Chen, H., Liu, S., Benton, T. G., Wang, Y., Ma, Y., Jiang, R., Zhang, F., Piao, S., Müller, C., Yang, H., Hao, Y., . . . Fan, M. (2022). Soil quality both increases crop production and improves resilience to climate change. *Nature Climate Change, 12*(6), 574-580. https://doi.org/10.1038/s41558-022-01376-8

Robakowski, P., Wyka, T. P., Kowalkowski, W., Barzdajn, W., Pers-Kamczyc, E., Jankowski, A., & Politycka, B. (2020). Practical Implications of Different Phenotypic and Molecular Responses of Evergreen Conifer and Broadleaf Deciduous Forest Tree Species to Regulated Water Deficit in a Container Nursery. *Forests*, *11*(9), 1011. https://doi.org/10.3390/f11091011

Roussel, C. (2024). Visualization of explainable artificial intelligence for GeoAI. *Frontiers in Computer Science*, *6*. https://doi.org/10.3389/fcomp.2024.1414923

Salim, B., & Zanchi, G. (2019). Water limitation can negate the effect of higher temperatures on forest carbon sequestration. *European Journal of Forest Research*, *138*(2), 287-297. https://doi.org/10.1007/s10342-019-01168-4

Sánchez-Pinillos, M., D'Orangeville, L., Boulanger, Y., Comeau, P., Wang, J., Taylor, A. R., & Kneeshaw, D. (2022). Sequential droughts: A silent trigger of boreal forest mortality. *Global Change Biology*, *28*(2), 542-556. https://doi.org/10.1111/gcb.15913

Schauberger, B., Jägermeyr, J., & Gornott, C. (2020). A systematic review of local to regional yield forecasting approaches and frequently used data resources. *European Journal of Agronomy*, *120*. https://doi.org/10.1016/j.eja.2020.126153

Schimanke, S., Joelsson, M., Andersson, S., Carlund, T., Wern, L., Hellström, S., & Kjellström, E. (2022). *Observerad klimatförändring i Sverige 1860–2021* (Klimatologi, Issue. https://www.smhi.se/publikationer/publikationer/observerad-klimatforandring-i-sverige-1860-2021-1.189738

Schroeder, M. (2023). *Granbarkborrens förökningsframgång i dödade träd under sommaren 2022 i sydöstra Småland, Värmland och Uppland/Västmanland*. https://www.slu.se/globalassets/ew/org/inst/ekol/rapporter/granbarkborrens-forokningsframgang-2022.pdf

Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T. E. E., Hauck, M., Hajek, P., Hartmann, H., Hiltbrunner, E., Hoch, G., Holloway-Phillips, M., Körner, C., Larysch, E., Lübbe, T., Nelson, D. B., Rammig, A., . . . Kahmen, A. (2020). A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic and Applied Ecology*, *45*, 86-103. https://doi.org/https://doi.org/10.1016/j.baae.2020.04.003

See, L., Lesiv, M., & Schepaschenko, D. (2024). Integrating Remote Sensing and Geospatial Big Data for Land Cover and Land Use Mapping and Monitoring. *Land*, *13*(6), 769. https://doi.org/10.3390/land13060769

Sjulgård, H., Keller, T., Garland, G., & Colombi, T. (2023). Relationships between weather and yield anomalies vary with crop type and latitude in Sweden. *Agricultural Systems*, *211*. https://doi.org/10.1016/j.agsy.2023.103757

Skersiene, A., Slepetiene, A., Stukonis, V., & Norkeviciene, E. (2024). Contributions of Different Perennial Grass Species and Their Roots' Characteristics to Soil Organic Carbon Accumulation. *Sustainability*, *16*(14). https://doi.org/10.3390/su16146037

Skogsstyrelsen. (2018). *Skog för över 900 miljoner kronor har brunnit* https://www.skogsstyrelsen.se/pressmeddelanden/ReadArticle?id=3003678. Accessed 10.03.2025

Smets, B., Cai, Z., Eklundh, L., Tian, F., Bonte, K., Van Hoost, R., De Roo, B., Jacobs, T., Camacho, F., Sánchez-Zapero, J., Martinez-Sánchez, E., Swinnen, E., Scheifinger, H., Hufkens, K., & Jönsson, P. (2024). Product User Manual - High Resolution Vegetation Phenology and Productivity - ST and VPP. E. E. A. (EEA). *Copernicus Land Monitoring Service Product user manual*(2.4), 36. https://land.copernicus.eu/en/technical-library/product-user-manual-of-seasonal-trajectories

SMHI. (2017, 25.03.2018). *Sommaren 2017 - Typisk svensk sommar.* Swedish Meteorological and Hydrological Institute. Retrieved 20.06.2023 from https://www.smhi.se/klimat/klimatet-da-och-nu/arets-vader/sommaren-2017-meteorologi-1.123378

Sommerfeld, A., Rammer, W., Heurich, M., Hilmers, T., Müller, J., & Seidl, R. (2021). Do bark beetle outbreaks amplify or dampen future bark beetle disturbances in Central Europe? *Journal of Ecology*, *109*(2), 737-749. https://doi.org/10.1111/1365-2745.13502

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., & Dosio, A. (2017). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, *38*(4), 1718-1736. https://doi.org/10.1002/joc.5291

Stein, B., Glick, P., Edelson, N., Green, N., Lawler, J., Girvetz, E., Enquist, C., Hayhoe, K., Jones, K., Gross, J., Joyce, L., Cross, M., Inkley, D., & O'Leary, J. (2011). *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment.*

Stuart, E. A. (2010). Matching Methods for Causal Inference: A Review and a Look Forward. *Statistical Science*, *25*(1), 1-21. https://doi.org/10.1214/09-sts313

Suarez-Gutierrez, L., Müller, W. A., & Marotzke, J. (2023). Extreme heat and drought typical of an end-of-century climate could occur over Europe soon and repeatedly. *Communications Earth & Environment*, *4*(1). https://doi.org/10.1038/s43247-023-01075-y

Tanner, B. D. (1990). Automated weather stations. *Remote Sensing Reviews*, *5*(1), 73-98.

Tolan, J., Yang, H.-I., Nosarzewski, B., Couairon, G., Vo, H. V., Brandt, J., Spore, J., Majumdar, S., Haziza, D., Vamaraju, J., Moutakanni, T., Bojanowski, P., Johns, T., White, B., Tiecke, T., & Couprie, C. (2024). Very high resolution canopy height maps from RGB imagery using self-supervised vision transformer and convolutional decoder trained on aerial lidar. *Remote Sensing of Environment*, *300*. https://doi.org/10.1016/j.rse.2023.113888

Tolk, J. (2003). Soils, Permanent Wilting Points. *In B. A. Stewart & T. A. Howell (Eds.), Encyclopedia of Water Science (pp. 893–896). Dekker.*

Trugman, A. T., Detto, M., Bartlett, M. K., Medvigy, D., Anderegg, W. R. L., Schwalm, C., Schaffer, B., & Pacala, S. W. (2018). Tree carbon allocation explains forest drought-kill and recovery patterns. *Ecology Letters*, *21*(10), 1552-1560. https://doi.org/10.1111/ele.13136

van Wesemael, B., Cammeraat, E., Mulligan, M., & Burke, S. (2003). The impact of soil properties and topography on drought vulnerability of rainfed cropping systems in southern Spain. *Agriculture, Ecosystems & Environment*, *94*(1), 1-15. https://doi.org/https://doi.org/10.1016/S0167-8809(02)00019-1

Varghese, D., Radulović, M., Stojković, S., & Crnojević, V. (2021). Reviewing the Potential of Sentinel-2 in Assessing the Drought. *Remote Sensing*, *13*(17), 3355. https://doi.org/10.3390/rs13173355

Vicca, S., Balzarolo, M., Filella, I., Granier, A., Herbst, M., Knohl, A., Longdoz, B., Mund, M., Nagy, Z., Pintér, K., Rambal, S., Verbesselt, J., Verger, A., Zeileis, A., Zhang, C., & Peñuelas, J. (2016). Remotely-sensed detection of effects of extreme droughts on gross primary production. *Scientific Reports*, *6*(1), 28269. https://doi.org/10.1038/srep28269

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, *23*(7), 1696-1718. https://doi.org/10.1175/2009jcli2909.1

Vila-Viçosa, C., Arenas-Castro, S., Marcos, B., Honrado, J., García, C., Vázquez, F. M., Almeida, R., & Gonçalves, J. (2020). Combining Satellite Remote Sensing and Climate Data in Species Distribution Models to Improve the Conservation of Iberian White Oaks (Quercus L.). *ISPRS International Journal of Geo-Information*, *9*(12). https://doi.org/10.3390/ijgi9120735

Vulova, S., Horn, K., Rocha, A. D., Brill, F., Somogyvári, M., Okujeni, A., Förster, M., & Kleinschmit, B. (2025). Unraveling the response of forests to drought with explainable artificial intelligence (XAI). *Ecological Indicators*, *172*. https://doi.org/10.1016/j.ecolind.2025.113308

Wang, L., & Qu, J. J. (2007). NMDI: A normalized multi-band drought index for monitoring soil and vegetation moisture with satellite remote sensing. *Geophysical Research Letters*, *34*(20). https://doi.org/10.1029/2007gl031021

Wei, P., Lu, Z., & Song, J. (2015). Variable importance analysis: A comprehensive review. *Reliability Engineering & System Safety*, *142*, 399-432. https://doi.org/https://doi.org/10.1016/j.ress.2015.05.018

Westman, W. E. (1978). Measuring the Inertia and Resilience of Ecosystems. *BioScience*, *28*(11), 705-710. https://doi.org/10.2307/1307321

Wilcke, R. A. I., Kjellström, E., Lin, C., Matei, D., Moberg, A., & Tyrlis, E. (2020). The extremely warm summer of 2018 in Sweden – set in a historical context. *Earth System Dynamics*, *11*(4), 1107-1121. https://doi.org/10.5194/esd-11-1107-2020

Wilhite, D. A., & Glantz, M. H. (1985). Understanding: the Drought Phenomenon: The Role of Definitions. *Water International*, *10*(3), 111-120. https://doi.org/10.1080/02508068508686328

Wiréhn, L. (2018). Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. *Land Use Policy*, *77*, 63-74. https://doi.org/10.1016/j.landusepol.2018.04.059

Wright, A. J., & Francia, R. M. (2024). Plant traits, microclimate temperature and humidity: A research agenda for advancing nature-based solutions to a warming and drying climate. *Journal of Ecology*, *112*(11), 2462-2470. https://doi.org/10.1111/1365-2745.14313

Xu, K., Wang, X., Liang, P., An, H., Sun, H., Han, W., & Li, Q. (2017). Tree-ring widths are good proxies of annual variation in forest productivity in temperate forests. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-02022-6

Xu, Y., Yang, G., Zhang, Y., Guo, J., & Zhang, C. (2025). Mapping and interpreting spatio-temporal trends in vegetation restoration following mining disturbances in large-scale surface coal mining areas. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1531424

Yeakley, J. A., Swank, W. T., Swift, L. W., Hornberger, G. M., & Shugart, H. H. (1998). Soil moisture gradients and controls on a southern Appalachian hillslope from drought through recharge. *Hydrology and Earth System Sciences*, *2*(1), 41-49. https://doi.org/10.5194/hess-2-41-1998

Younes, N., Joyce, K. E., & Maier, S. W. (2021). All models of satellite-derived phenology are wrong, but some are useful: A case study from northern Australia. *International Journal of Applied Earth Observation and Geoinformation*, *97*, 102285. https://doi.org/10.1016/j.jag.2020.102285

Yu, Z., Wang, J., Liu, S., Rentch, J. S., Sun, P., & Lu, C. (2017). Global gross primary productivity and water use efficiency changes under drought stress. *Environmental Research Letters*, *12*(1), 014016. https://doi.org/10.1088/1748-9326/aa5258

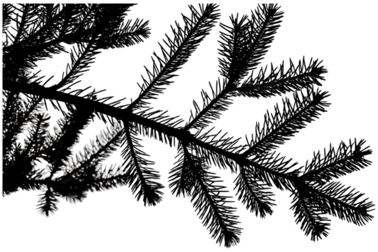
Zargar, S. M., Gupta, N., Nazir, M., Mahajan, R., Malik, F. A., Sofi, N. R., Shikari, A. B., & Salgotra, R. K. (2017). Impact of drought on photosynthesis: Molecular perspective. *Plant Gene*, *11*, 154-159. https://doi.org/10.1016/j.plgene.2017.04.003

Zhang, C., & Li, X. (2022). Land Use and Land Cover Mapping in the Era of Big Data. *Land*, *11*(10), 1692. https://doi.org/10.3390/land11101692

Zhang, T., Song, J., Fan, Y., Liu, Y., Yu, S., Guo, D., Hou, T., & Guo, K. (2023). Vegetation Index Research on the Basis of Tree-Ring Data: Current Status and Prospects. *Forests*, *14*(10), 2016. https://doi.org/10.3390/f14102016

Zhou, S., Williams, A. P., Berg, A. M., Cook, B. I., Zhang, Y., Hagemann, S., Lorenz, R., Seneviratne, S. I., & Gentine, P. (2019). Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proceedings of the National Academy of Sciences*, *116*(38), 18848-18853. https://doi.org/10.1073/pnas.1904955116

Ågren, A. M., Larson, J., Paul, S. S., Laudon, H., & Lidberg, W. (2021). Use of multiple LIDAR-derived digital terrain indices and machine learning for high-resolution national-scale soil moisture mapping of the Swedish forest landscape. *Geoderma*, *404*, 115280. https://doi.org/https://doi.org/10.1016/j.geoderma.2021.115280



NORDIC SWAN ECOLABEL 3041 0903
Printed by Media-Tryck, Lund 2025

Mapping Vegetation Dynamics Under Drought Stress

The productivity and ability of forests and agricultural ecosystems to provide ecosystem services are threatened by the increasing frequency and severity of droughts in a warming climate. Understanding the dynamics of drought resilience in natural and managed ecosystems and identifying areas at risk in advance are key components of increasing society's preparedness for drought. In this thesis, methods for detecting and quantifying the spatially explicit effects of drought on Swedish agricultural and forest ecosystems are developed, tested, and applied. Overall, this thesis demonstrates that the effective use of multi-source geospatial data has the potential to map the effects of drought on terrestrial vegetation over time and space. These results can provide the information needed for policy planning and decision-making, supporting a shift toward more sustainable management practices.

The author of this thesis, **Mitro Müller**, is a remote sensing and GIS enthusiast with a background in physical geography. His primary research interests include satellite-based environmental monitoring and the development of methods to support decision-making in a changing climate.

LUND UNIVERSITY

Department of Physical Geography
and Ecosystem Science
Faculty of Science

ISBN 978-91-89187-53-5