

The Potential Role of Mapping Ectomycorrhizal Fungi in Scandinavia's Boreal Forests for Climate Change Mitigation: An Integrated Geospatial Approach.

Abstract

Forest ecosystems play a crucial role in climate change mitigation by sequestering carbon dioxide and supporting biodiversity. Ectomycorrhizal fungi (EMF) are essential to these ecosystems, forming symbiotic relationships with trees and promoting nutrient cycling, growth, and resilience. This study investigates the potential of remote sensing for mapping EMF in forests and their implications for climate change mitigation and focuses on three different research areas: (1) analysing tree species distribution and their associated EMF in Trysil, Norway and protected areas, using Landsat satellite imagery and LiDAR data over 26 years; (2) examining soil moisture content and EMF resilience in Trysil forest areas during extreme weather years; and (3) monitoring and understanding the effects of forest fires on ecosystems and recovery in forests in Enskogen, Sweden. The results not only presented valuable insights into forest ecosystems, but also highlighted the capability of remote sensing in aiding them. The presence of EMF networks in boreal forests such as in Trysil, could potentially cause soil moisture increase during extreme weather years by 15.6% and possibly enhance forest fire recovery in Enskogen by 33.4% over a four-year period following a fire event.

The study also contributes to the understanding of forest dynamics, resilience, and the critical role of effective climate change mitigation plans for these vital ecosystems. Although low resolution data and lack of ground truthing options to validate the results limited the scope and timeframe of this study, future research could be carried out using a similar approach over a larger area and longer period using more accurate sensor data like LiDAR and ground truth data from national sources to increase accuracy.

1.0 Introduction

Climate change is one of the most pressing global challenges of our time. It comes with consequences that demands urgent action from our governments on a global scale. Boreal forests play a significant role in mitigating climate change by sequestering large amounts of carbon (Tognetti, 2022). These forests cover approximately 33% of the Earth's forested area, with the boreal region residing in Scandinavia, which includes Norway, Sweden, Finland, and northern Russia, being the largest home to some of the oldest and biodiverse forests on the planet (Ruckstuhl, 2008).

The boreal forest is the world's second-largest biome, 25% of which is natural and untouched (Ruckstuhl, 2008). As a major carbon reserve and source, the boreal forest plays a crucial role in global carbon cycles (Pan, 2011; Sabatini, 2018). Scandinavian forests cover approximately 2,156,900 km² and include some of Europe's oldest and largest ancient forests (Sabatini, 2018). These forests predominantly consist of Spruce and Pine, along with deciduous species such as birch (*Betula* spp.), Aspen (*Populus tremula*), Rowan (*Sorbus aucuparia*), and Willows (*Salix* spp.) (Nature and biodiversity, 2023).

Despite their importance, forest ecosystems globally are experiencing anthropogenic degradation (DeFries, 2010). The industrial revolution in the 19th century led to extensive logging in Nordic countries (Castagneri, 2012), reducing natural biodiversity and impacting the benefits and services provided by forests (Chazdon, 2008). However, forest legislation was established around 100 years ago in Finland, Norway, Sweden and Denmark which has helped double the size of Scandinavian forests (Stjern, 2021).

Forests contribute to ecosystem services and play a vital role in regulating the climate. Resilience, carbon sequestration, recovery, restoration and biodiversity are key aspects in forest management systems (Smith, 2008). Forest ecosystems show amazing resilience and an ability to recover from disturbances and adapt to changing environments, which is essential for maintaining their health (Allen, 2010).

Forests act as carbon sinks, removing and storing large amounts of CO₂ from the atmosphere, which mitigates climate change (Pan, 2011). Through the process of photosynthesis, trees absorb CO₂ and release oxygen reducing greenhouse gas concentrations. The stored carbon in trees, vegetation, and soil helps to stabilise the global carbon cycle and reduce the impacts of global warming (Lundmark, 2014).

Forests are essential for maintaining biodiversity, which is crucial for the functioning of ecosystems. The diverse array of plant and animal species in forests contributes to various ecosystem services. Forests aid in temperature regulation by providing shade, lowering heat island effects, and affecting the local micro-climate (Sabatini, 2018). They also play a role in water purification, acting as filters which enhances water quality. In addition, forests serve as habitats for numerous species, promoting ecological balance (Sabatini, 2018).

EMF play a crucial role in boreal forest ecosystems due to their symbiotic relationships with the roots of woody plants. These associations enable host plants to acquire nutrients, water, and minerals from the soil, while the fungi receive photosynthetically derived carbon in return (Policelli, 2020). EMF networks store around 22% of net carbon production in forests (Hobbie, 2006) and recent studies suggest that elevated CO₂ levels lead to increased root colonisation and biomass of EMF (Kasurinen, 2005). Research has shown that these symbiotic relationships have a positive effect on the growth and health of host plants and can enhance their ability to withstand harsh environmental conditions and stress (Kasurinen, 2005). Furthermore, older forests tend to have more robust EMF networks, which play a critical role in maintaining the stability and resilience of these ecosystems (Cline, 2005).

In recent years, an increase of forest fires has been seen in Scandinavia due to climate change and human activities (Smith, 2008). These fires have caused significant disruptions to forest ecosystems, including the loss of habitats, reduced biodiversity and the release of stored carbon into the atmosphere (Bond, 2010). Understanding the impact of forest fires on EMF networks and their role in post-fire recovery is crucial for developing effective forest management strategies that promote ecosystem resilience and contribute to climate change mitigation efforts.

In addition, extreme weather events such as droughts and heavy precipitation can significantly impact EMF networks and the associated soil moisture content in forests (IPCC, 2014). This may influence the ability of boreal forests to store carbon and adapt to global warming. Therefore, studying the interactions between EMF, soil moisture and extreme weather events can provide valuable insights for forest management and climate change mitigation plans (Branco, 2022).

In Scandinavia, climate change mitigation efforts in forestry have primarily focused on sustainable forest management practices, such as continuous cover forestry, selective logging, and increased tree species diversity (Lundmark, 2014). Additionally, these efforts emphasise carbon sequestration through enhanced tree growth and the utilisation of wood products as a substitute for fossil fuel-intensive materials (Nabuurs, 2013). These strategies contribute significantly to reducing greenhouse gas emissions and promoting climate change adaptation (Lundmark, 2014). However, current mitigation efforts in Scandinavian forestry have largely overlooked the health or inclusion of EMF in their methods.

In Scandinavia, a large percentage of forest is privately owned. For example, in Norway, about 80% of the productive forest area is privately owned (Bjørnstad, 2017). Although there are some regulations on management and felling practices, a percentage of private forests remain unregulated and don't fully comply with the government requirements. This lack of regulation could make it harder to implement climate change mitigation strategies.

Evaluating the ability of EMF networks to support mitigation plans is essential to improve our understanding of their distribution, their dynamics and responses to various environmental factors. Remote sensing and geographic information systems (GIS) can be useful tools for mapping EMF networks, allowing researchers to monitor changes in these networks (Leitão, 2019). Combining such data with information from forest fires, extreme weather events, and other environmental events can help develop these plans.

Various studies have used remote sensing and GIS methods for similar projects, which demonstrates the potential of these techniques in understanding forest ecosystems and their responses to environmental factors. For instance, Zhao (2008) utilised remote sensing and GIS to analyse the distribution of EMF networks and their response to climate change, highlighting the advantages of these methods in providing large-scale, high-resolution data. Likewise, Doughty (2018) used remote sensing to monitor the effects of drought on forest ecosystems, showing the importance of incorporating geospatial data when developing such strategies.

The use of remote sensing and GIS technologies has the potential to provide accurate spatial and temporal data on EMF networks in boreal forests, contributing to more understanding of their distribution, function, and role (Fisher, 2016). Mapping EMF networks in Scandinavian forests could guide conservation, restoration and forest management practices by identifying areas with strong EMF networks that can enhance carbon sequestration and promote forest resilience within a changing environment (Dahlberg, 2002).

However, some challenges in using remote sensing and GIS methods have been identified, such as the need for ground truthing data to validate results and the limitations of certain sensors in detecting specific ecosystem components (Foody, 2002). Despite these challenges, the literature supports that remote sensing and GIS techniques can offer valuable insights into forest environments which could offer more accurate representation of EMF distribution and density across Scandinavia (Bolduc, 2011).

The aim of this study is to investigate the potential role of mapping EMF in Scandinavian forests for climate change mitigation, following the concept of "myco-carbon" sequestration (Phillips, 2013), the distribution, abundance, and associations of EMF with various tree species in selected forest areas (Smith, 2008) and analysing the changes over a 26-year period using satellite imagery. The CO₂ generated underground by plants and microbes and released into the atmosphere — termed soil respiration — comprises the second largest terrestrial carbon flux. It has been suggested that the flow of CO₂ from this source must change with climate, but this has been difficult to confirm through observation. Bond-Lamberty and used a two-decade database of soil respiration measurements to show that not only is soil respiration increasing over time, but also that this increase is strongly associated with temperature changes. They estimate that total global soil respiration is increasing by about 0.1% per year, implying a sensitivity to air temperature. This is consistent with an acceleration of the carbon cycle in recent decades (Lamberty, 2010). By using advanced mapping techniques and satellite imagery, this study aims to provide valuable insights into the ecological dynamics involving EMF and forest ecosystems and evaluate their implications for climate change mitigation plans.

2.0 Methodology

This section outlines the various approaches and techniques used to address the aims of this study, which are focused on understanding the distribution, abundance, and associations of EMF networks in Scandinavian forests by analysing their changes over a 26-year period and assessing their resilience to extreme weather events and forest fires by employing advanced mapping techniques and satellite imagery.

The methodology is divided into three separate studies. The first focuses on mapping EMF networks in Trysil, Norway and their associated tree species over a 26-year period using satellite imagery; the second analyses the resilience of EMF networks during extreme weather events with a focus on changes in soil moisture; and the third one explores the effects of forest fires in Enskogen, Sweden which experienced a forest fire in July 2018, and evaluates EMFs role in post-fire recovery and ecosystem resilience.

2.1 Study 1: Mapping EMF networks in Scandinavian Forests

2.1.1 Study Area

Map of the study area: Trysil,

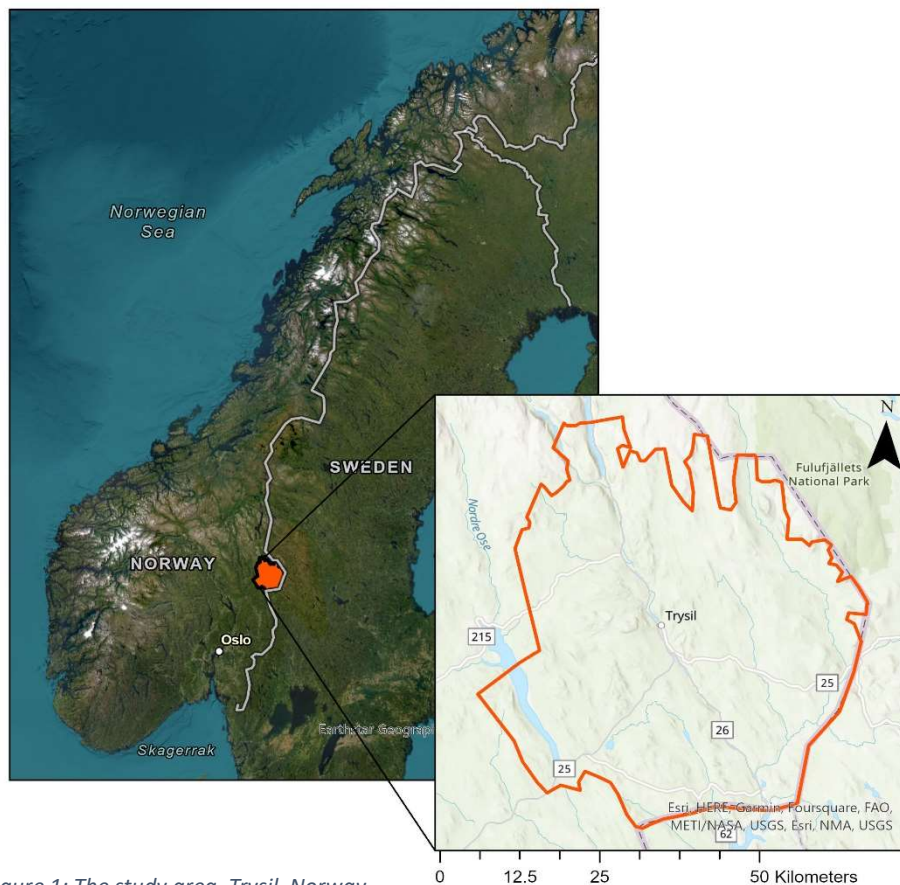


Figure 1: The study area, Trysil, Norway

The study area is located in Trysil, Norway (Figure 1), a region covered in extensive forest, diverse tree species, and unique environmental features, such as mountains, lakes and rivers.

Trysil is situated in south-eastern Norway next to the border of Sweden and spans an area of approximately 3,000 square kilometres (Trysil Municipality, 2023).

The region is also home to several nature reserves, including those containing old-growth forests with trees exceeding 160 years in age (SatSkog). These ancient forests provide an opportunity to study the intricate relationships between EMF, tree species, and their response to environmental factors (Linder, 1998).

The choice of Trysil as the study area is also due to its accessibility to national datasets, such as the Norwegian Forest and Landscape Institute's National Forest Inventory, which provides information on forest resources, including tree species, age, volume, and growth (Næsset, 2013).

2.1.2 Data Sources

This study aims to analyse forest composition and tree species distribution in Trysil Kommune and within a protected area using Landsat satellite imagery from June 1992, 2007, and 2016, and 2018. The 2018 data was taken from SatSkog, which uses LiDAR and ground truth data to provide accurate data and used to determine the accuracy.

Data Acquisition: Landsat data was obtained for the study area from the United States Geological Survey (USGS) EarthExplorer platform. The dataset included near-infrared (NIR) and red bands (Band 4 and Band 3 for Landsat 5/7; Band 5 and Band 4 for Landsat 8) for the Near Difference Vegetation Index (NDVI) calculation.

Table 1: Summary of Landsat 5 (TM), Landsat 8 (OLI & TIRS), and LiDAR data used in the study, including acquisition dates, data sources, bands/parameters, and spatial resolutions.

Data Type	Date	Source	Bands/Parameters	Spatial Resolution
Landsat 5,8	June 1992, 2007, 2016	USGS, EarthExplorer	NIR, Red	30
LiDAR Data, Ground Truth data.	2018	SATSKOG, NIBIO	Tree type, age.	n/a

2.1.3 Processing and Analysis

An overview of the processes and analysis used in the study can be seen in the workflow in Figure 2 below.

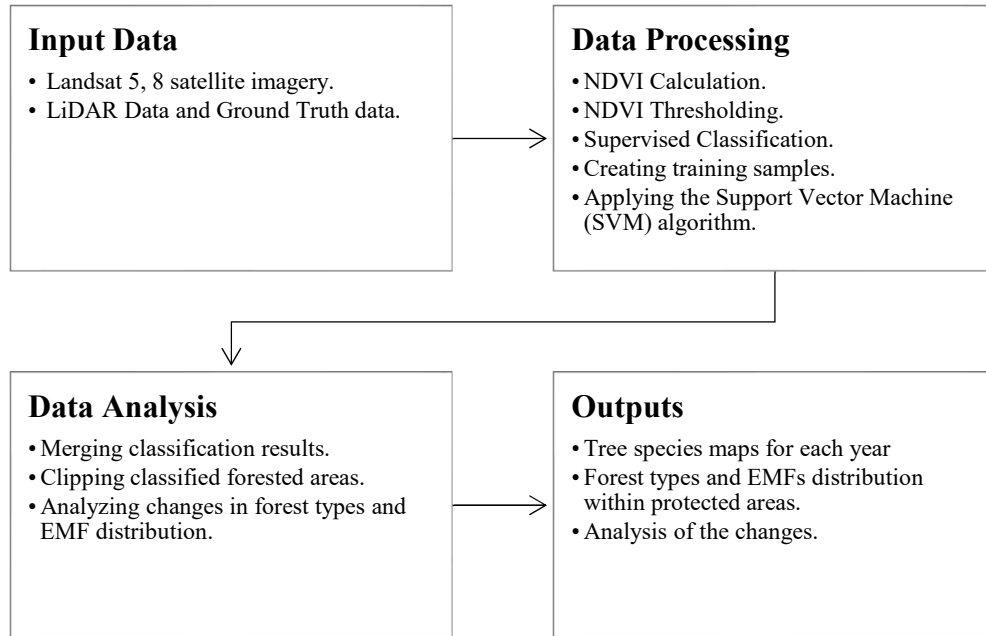


Figure 2: A methodology flowchart for Study 1.

An NDVI was calculated for each Landsat image using the NIR and red bands to identify vegetation cover and differentiate between forested and non-forested areas. The output of the NDVI process was a series of images representing vegetation cover, which was used as a basis for the supervised classification. The NDVI was calculated using the following formula in Equation 1:

$$\text{Equation 1: } NDVI = (NIR - Red) / (NIR + Red).$$

An NDVI threshold was applied to each image to extract forested areas for the years 1992, 2007, and 2016. The study used a supervised classification approach. A total of 128 training samples were created by visually interpreting the high-resolution LiDAR data and Landsat images. The generated land cover classes included: Mixed Forest, Coniferous Forest, Pine-dominated, Spruce-dominated, Deciduous-dominated.

The thresholded NDVI images were classified using a Support Vector Machine (SVM) algorithm based on the prepared training samples. This classification generated tree species maps for each year. The output of the supervised classification was a series of maps showing the distribution of different tree species and land cover/use classes in the study area.

Classification results were merged with the EMF associations table, assigning classification names and fungi associations to the forested areas. The classified forested areas were then clipped to the protected area in ArcGIS Pro software, resulting in maps depicting forest types and EMF distributions within the protected areas. Changes in forest types and tree species distribution were compared, then analysed across the years 1992, 2007, and 2016, highlighting changes in forest composition and potential impacts on EMF associations.

2.2 Study 2: Analysis and Method for mapping mycelium networks

2.2.1 Study Area

This study aimed to analyse soil moisture content and EMF resilience in Trysil forest areas (Figure 1) during extreme weather years. The Trysil area was chosen due to its dense and productive boreal forest, as mentioned in Study 1. The Normalized Difference Moisture Index (NDMI) was used as a method for this analysis because it is a well-established remote sensing technique for monitoring and estimating soil moisture content in forested areas , which could provide insights into the resilience of EMF networks and their potential role in promoting forest health and adaptation to climate change (Tedersoo, 2020).

2.2.3 Data Sources

Table 2 provides an overview of the data sources used in the study, as well as the time periods and spatial resolutions for each dataset. The Landsat images were obtained from the United States Geological Survey (USGS), from the month of October and covering the years 2006, 2010, and 2018, with a spatial resolution of 30 meters. The forest data was obtained from the National Forest Inventory for the year 2018. The data was imported into ArcGIS Pro for processing.

Table 2: Data sources used to explore soil moisture.

Data Type	Date	Source	Band Parameters	Spatial Resolution
Landsat 5 & 8	October 2006, 2010, 2018	USGS Earth Explorer	Landsat 5: 1-7, Landsat 8: 1-11	30 m
Forest data	Release 2018	National Forest Inventory, SATSKOG, NIMBU	N/A	N/A

2.2.4 Processing and Analysis

An overview of the workflow can be seen in Figure 3 below showing the stages in the processing of data.

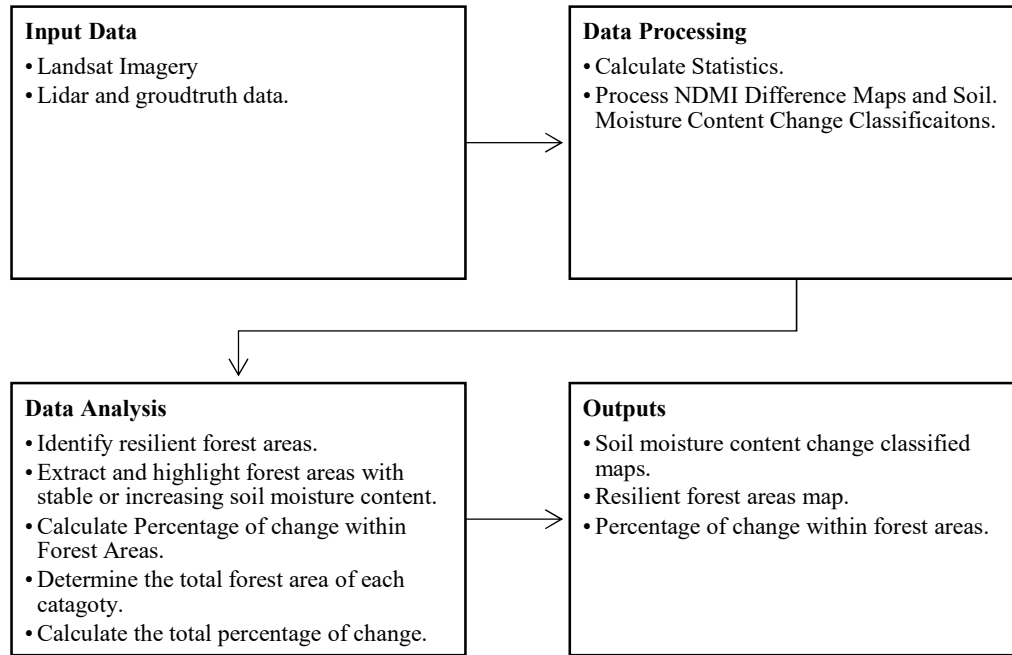


Figure 3: Methodology flowchart for Study 2.

NDMI maps for 2006, 2010, and 2018 were created to visualise soil moisture content during the extreme weather years. To calculate statistics, Minimum, maximum, and mean values for the NDMI maps were calculated using table statistics. A bar graph displaying the maximum and minimum values for the NDMI maps was created. The difference between NDMI images for the years 2006-2010 and 2010-2018 was calculated using Equation 2:

$$\text{Equation 2: Difference Raster} = \text{Raster year2} - \text{Raster year 1}$$

The difference maps were then reclassified to categorise the soil moisture content changes into significant decrease, little to no change, and significant increase. Then NDMI difference maps and soil moisture content change classified maps were created to visualise the type of change that occurred.

To identify resilient forest areas forest areas with little to no change or an increase in soil moisture content between 2006 and 2018 were extracted using the 'Extract by Mask' tool in ArcGIS Pro. The extracted raster was reclassified to highlight the forest areas with little to no change, or an increase in soil moisture content. A map showing the resilient forest areas, highlighting areas with soil moisture stability and increase during drought years, was then created.

To calculate percentage of change within forest areas, the 'Zonal Statistics as Table' tool was used to calculate statistics for the raster values within each forest area. The total area of the forest and the total area of forest with an increase in moisture and little to no change was calculated. Finally, the percentage of change within forest areas between 2006 and 2018 was calculated by dividing the total area of forest with an increase in moisture and little to no change by the total forest area and multiplying by 100. See equation 3:

Equation 3:

A is the total area of forest with an increase in moisture and little to no change.

B is the total forest area.

Then, the percentage of change (P)

$$P = (A / B) * 100$$

2.3 Study 3: Assessment of forest fire impacts on EMF networks.

2.3.1 Study Area

The Enskogen forest fire of 2018 was a significant wildfire event that occurred in Sweden, causing extensive damage to the forest ecosystem, highlighting the vulnerability of boreal forests to climate change. The fire started on July 15, 2018, and rapidly spread due to the unusually hot and dry weather conditions, which were exacerbated by climate change (Wessel, 2018). The fire affected an area of approximately 25,000 hectares, making it one of the largest forest fires in modern Swedish history (Andersson, 2018).

The Enskogen fire had a profound impact on the local ecosystem, including the EMF networks that play a crucial role in forest health and carbon sequestration (Clemmensen, 2013). Understanding the impact of the fire on EMF networks and their role in post-fire recovery is essential for developing effective forest management strategies that promote ecosystem resilience (Holden, 2013).

This case study aimed to assess the impact of the Enskogen forest fire on EMF networks using a combination of synthetic aperture radar (SAR) imagery and optical analysis with Sentinel-2 satellite data. The choice of Sentinel-2 imagery was due to its high spatial resolution, frequent revisit times, and availability of multispectral bands that are suitable for vegetation analysis (Drusch, 2012). SAR data was analysed using change detection techniques, which allowed for the identification of areas where EMF networks were disrupted or altered due to the fire event (Yin, 2012). The optical data analysis involved calculating the modified soil-adjusted vegetation index (MSAVI) and the near differential vegetation index (NDVI), which are remote sensing techniques used to assess vegetation health. MSAVI was specifically chosen for its sensitivity to vegetation cover and its ability to minimise soil background effects (Ma, 2021). By comparing pre- and post-fire MSAVI and NDVI values, the study intended to evaluate the recovery of the burn areas four years after the event.

2.3.2 Data Sources

The methodology employed several steps to process, analyse, and visualise the data acquired from various sources.

Data Acquisition: The Sentinel-1 SAR and Sentinel-2 optical data used in this study were downloaded from the Copernicus Open Access Hub (Copernicus, 2021) see Table 3. The timescale considered for the study included data from before the fire event in 2017, shortly after the fire event in 2018, and four years after the fire event in 2022. The acquired data was analysed to explore the impact of fire on forest ecosystems and the subsequent effects on the EMF networks.

Table 3: Data sources used in Study 3.

Data type	Date	Data Source	Bands/ Parameters	Resolution
Sentinel-1 SAR	July 27, 2017 August 27, 2018 July 10, 2022	Copernicus Open Access Hub	Interferometric Wide swath (IW), Vertical receive (VV)	5mx5m (range x azimuth)
Sentinel-2 (MSI) Multispectral Instrument.	July10, 2017 August 27, 2018 August 11, 2021	Copernicus Open Access Hub	Band 2 -Blue Band 3- Green Band 4- Red Band 8 - NIR	10m x 10m

2.3.3 Processing and Analysis

An overview of the workflow can be seen in Figure 4 below showing the stages of the methodology.

Optical data was pre-processed using ArcGIS Pro, and SAR data was pre-processed using the Sentinel Application Platform (SNAP) (ESA, 2021).

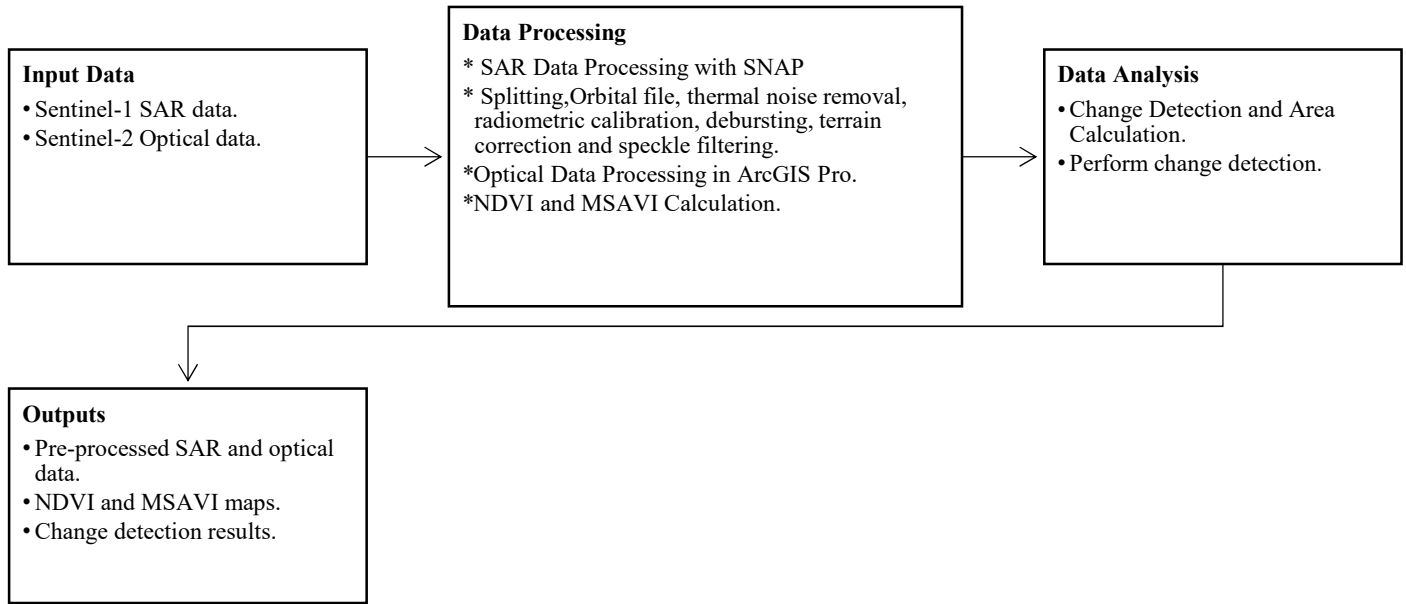


Figure 4: Methodology flowchart for Study 3.

The acquired Sentinel-1 SAR data underwent several pre-processing steps in SNAP, including splitting, application of the orbital file, thermal noise reduction, calibration, debursting, terrain correction, and speckle filtering (Sentinel-1 Toolbox, 2017)

Optical data was imported into ArcGIS Pro and the NDVI and MSAVI maps were calculated using the respective spectral bands using raster calculator (Drusch, 2012). The NDVI Calculation was made using the equation used in Study 1, Equation 1 and the MSAVI was calculated using the following formula in Equation 4:

$$\text{Equation 4: } \text{MSAVI} = (2 * \text{NIR} + 1 - \sqrt{(2 * \text{NIR} + 1)^2 - 8 * (\text{NIR} - \text{Red})}) / 2.$$

The change detection analysis was performed in ArcGIS Pro to determine the differences between the NDVI and MSAVI values in the study area over the selected time periods.

3.0 Theory

The theoretical background for this study draws on several interconnected ecological principles. The first is symbiosis, which describes the mutual relationship between trees and ectomycorrhizal fungi (EMF). EMFs role in conjunction with trees improves nutrient cycling, which promotes growth and reinforces resilience in forest ecosystems (Policelli, 2020). This symbiotic relationship between EMF and host trees underpins the study's primary focus.

The second principle comes from biogeography which relates to the distribution and diversity of species over space and time (MacArthur, 2001). The boreal forests biome can be studied in the framework of island biogeography in terms of the distribution of tree species in the study area and their associated EMF. The species-distribution patterns over time explored in biogeography assist in the understanding of the role of EMF in these dynamics.

The third principle in the study is regarding disturbance theory. This theory aids in understanding how disturbances influence the forest's structure, function and its resilience in the face of adversities (Rogers, 1996). In this context, following extreme weather events or

forest fires, the resilience of EMF play a substantial role in forest recovery after disturbances, influencing carbon sequestration and overall forest health (Smith, 2008).

This study's central concern is the principle of climate change mitigation, which is a growing focus in governments and international bodies. This is due to the role of boreal forests in carbon sequestration (Tognetti, 2022). This study extends this to investigate the role of EMF in this function and whether understanding the dynamics of EMF could potentially contribute to more effective mitigation strategies.

In summary, the theories underpinning this study stem from the interconnected roles of various parts of the ecosystem, how they respond to environmental disturbances and their potential contributions to climate change research.

4.0 Results and Discussion

4.1 Study 1: Mapping EMF networks in Scandinavian Forests

The study shows significant shifts in tree species distribution and EMF associations over a span of 26 years. Table 4 is a combined data table showing the EMF associations with Norwegian forest tree classifications which indicates the fungi species that are exclusive to tree species in a symbiotic relationship, this table forms the foundation for the data associations within this study. Figure 5 illustrates the tree species classification for the years 1992, 2007, 2016, and 2018 of the Trysil area.

Table4: A summary of EMF associations with Norwegian forest tree classifications, indicating the fungi species that are exclusive to trees species in a symbiotic relationship (Schirkonyer, 2013).

Ectomycorrhizal Fungi Associations with Norwegian Forest Tree Classifications

Norwegian Tree Classification	English Translation	Tree Species	Associated Ectomycorrhizal Fungi	Fungi Association
Blanding	Mixed Forest	Fagus sylvatica	Laccaria, Russula, Cortinarius, Inocybe	Ubiquitous
		Quercus petraea	Lactarius tabidus, Russula ochroleuca, Thelephora terrestris, Tomentella spp.	
Barblanding	Coniferous Mixed Forest	Picea abies	Suillus, Amanita, Lactarius, Hebeloma	Conifer Exclusive
		Abies alba	Laccaria amethystine, Lactarius hepaticus, Cortinarius subserotipes, Scleroderma citrinum	
Furudominert	Pine-dominated	Larix decidua	Paxillus, Rhizopogon, Boletus, Tomentella	Pine Exclusive
Grandominert	Spruce-dominated	Picea abies	Tylospora, Thelephora, Cenococcum, Tricholoma	Spruce Exclusive

Lauvdominert	Deciduous-dominated.	Fagus sylvatica	Amanita, Lactarius, Russula, Tuber	Deciduous Exclusive
		Quercus petraea	Lactarius quietus, Cortinarius casimiri, Paxillus involutus, Boletus edulis	

Tree Species classification for years 1992,2007,2016 and 2018

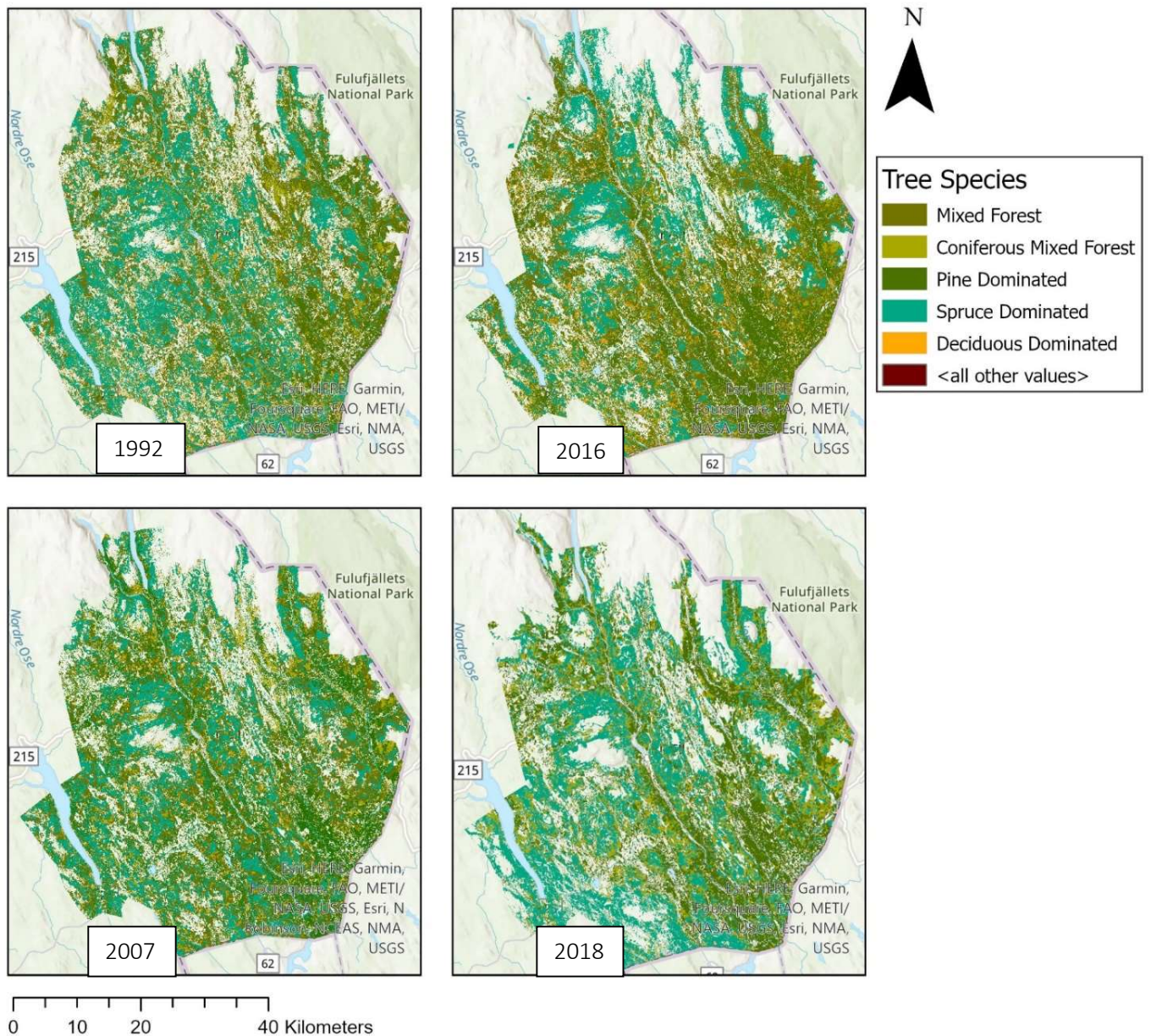


Figure 5: Tree species classification maps for 1992,2007,2016 and 2018 visualising the distribution of tree species.

Although the classification maps display similarities, it is evident that the distribution of tree species has undergone significant changes over the years. Despite the variation in forest density in the maps, there appears to be a correlation between the location of tree species across the different time periods. The distribution of the tree species variation can be seen more clearly in Figure 6, which shows a time series of pie charts displaying how the distribution of species has changed in percentage over km² over time.

Percentage of Area change between 1992 and 2016

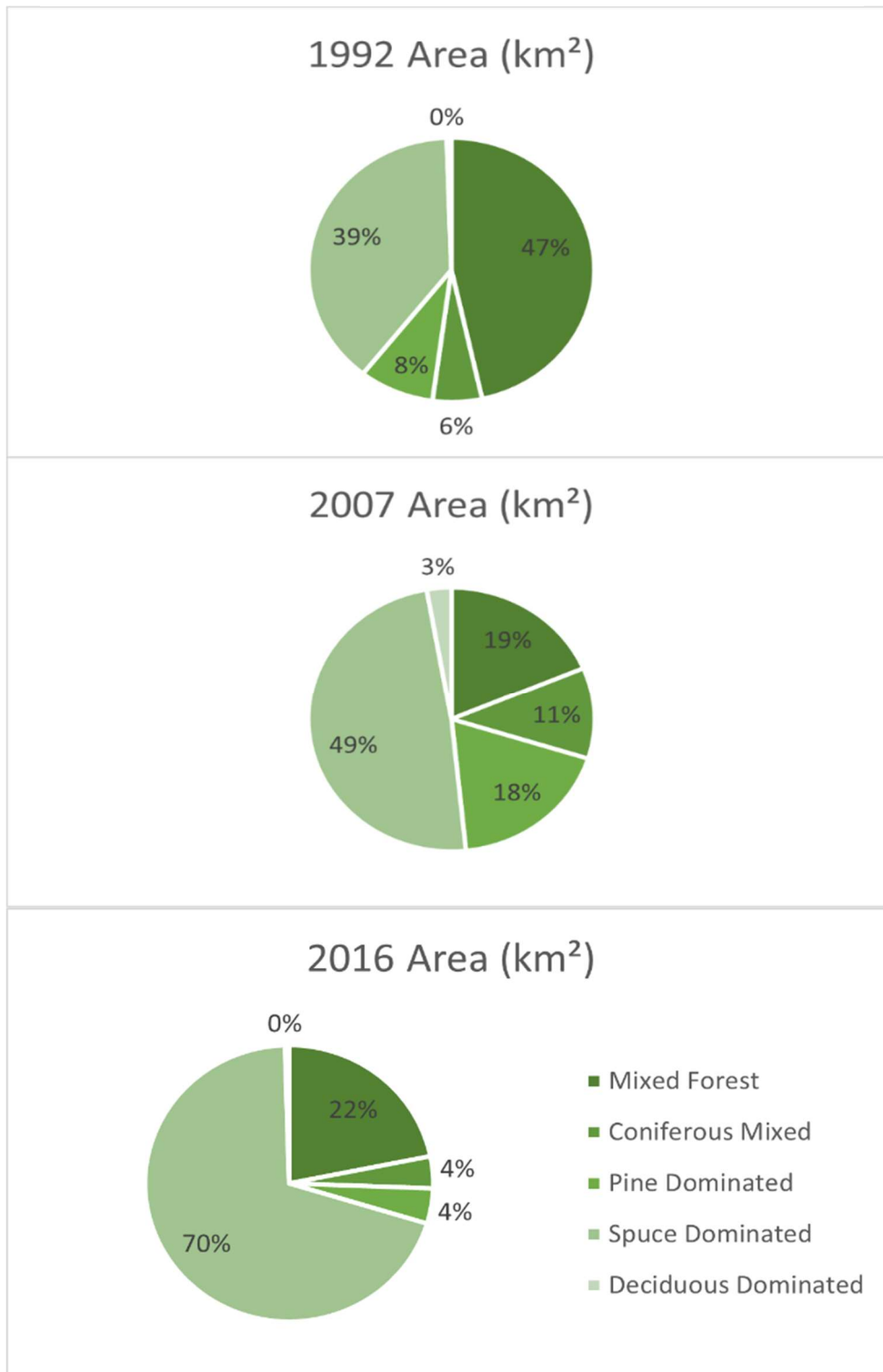


Figure 6: Pie charts for the years 1992, 2007 and 2016 showing the percentage of change for area km² change of tree species distribution in Trysil, Norway.

The changes in the distribution of EMF can be seen in Figure 7, which corresponds with the shifts observed in tree species distribution shown in Figure 5. This is because the tree species maps and EMF associations rely on the same attribute values.

Fungi association classification for years 1992,2007,2016 and 2018

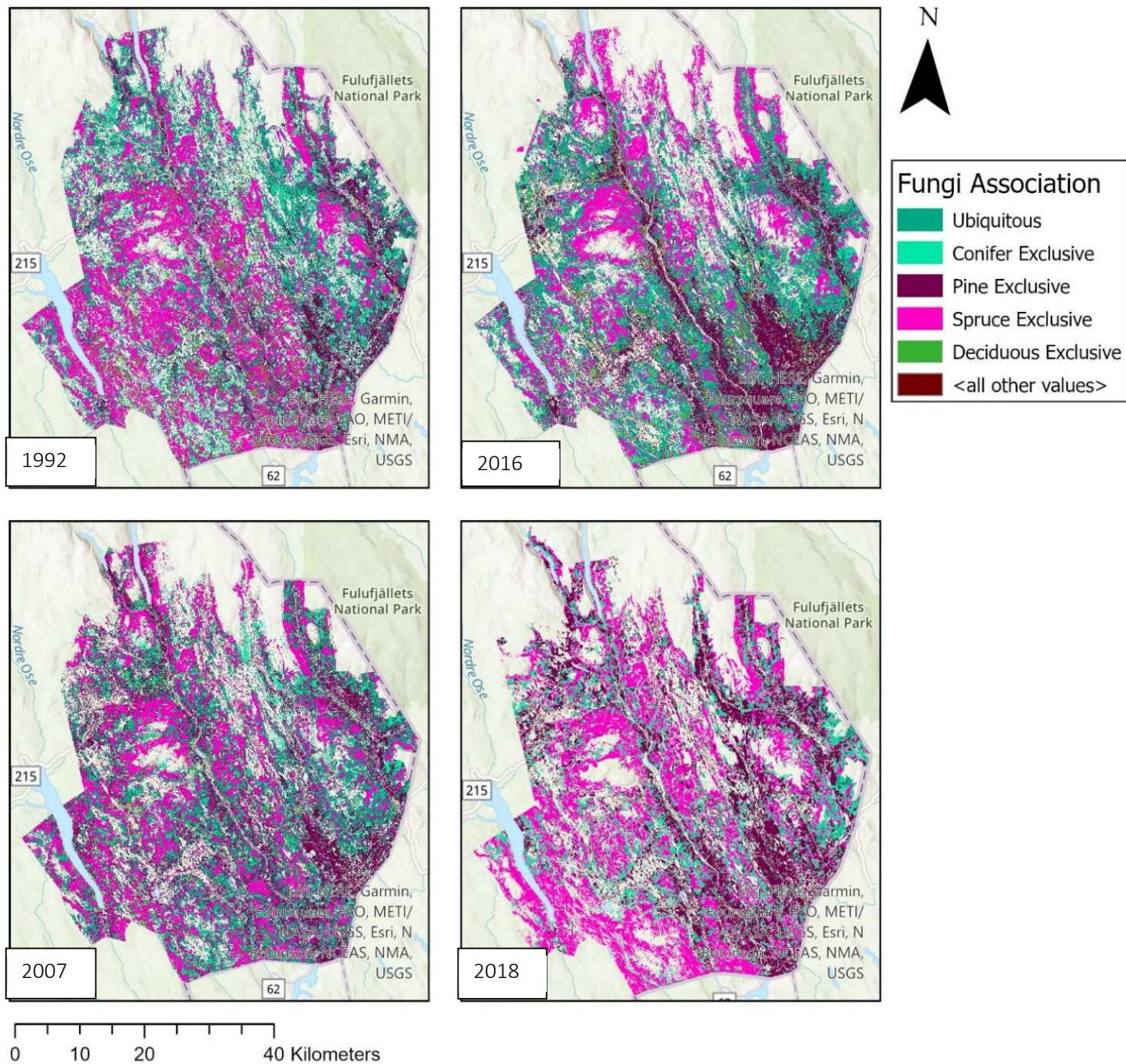


Figure 7: Fungi association classification maps for the years 1992,2007,2016 and 2018 highlighting the distribution of ectomycorrhizal fungi in Trysil.

The maps in Figure 8 and chart and table in Figure 9 show the change and percentage of changes for the protected areas in Trysil below.

Protected Areas in Trysil and Fungi Association for 1992,2007,2016.

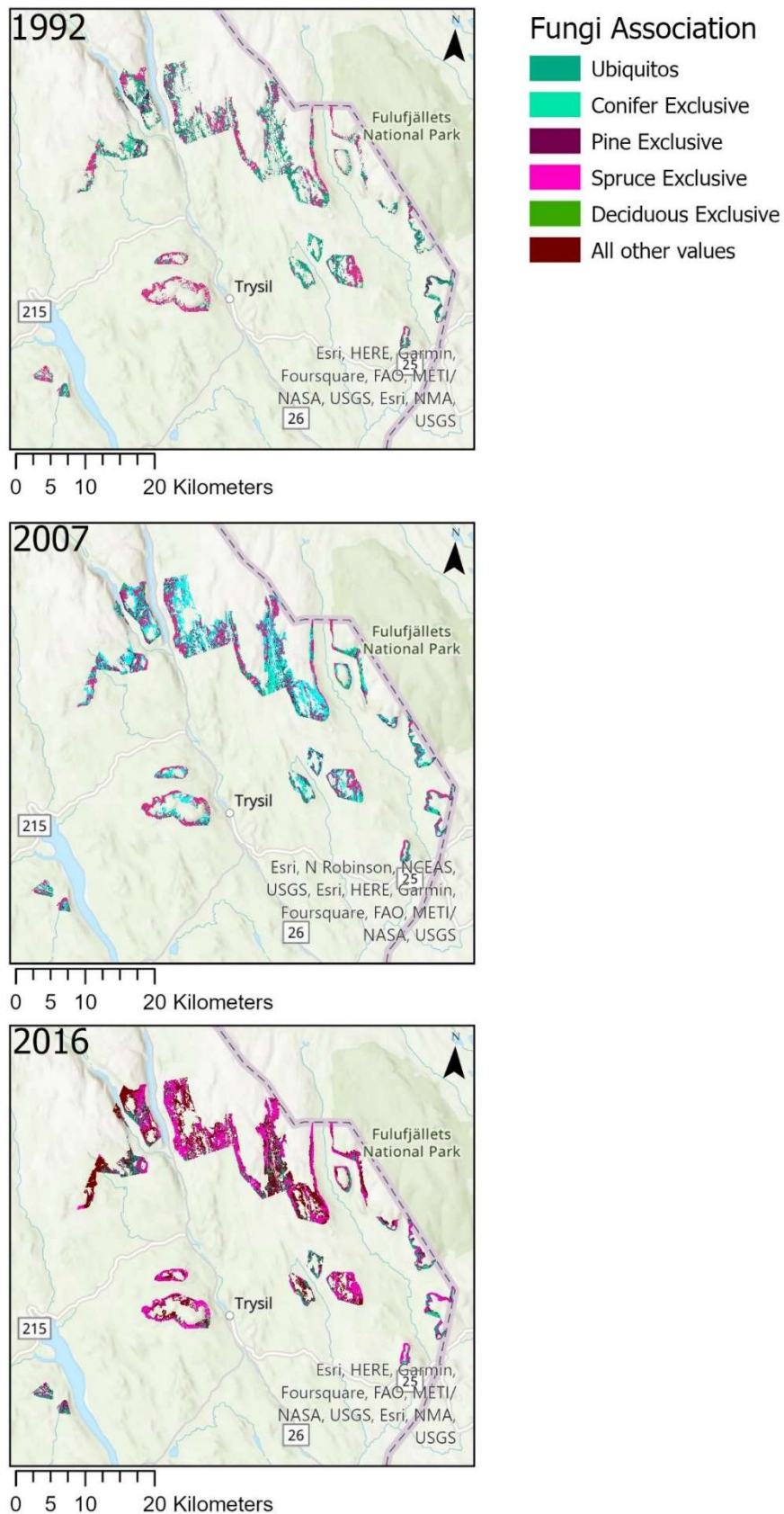


Figure 8: Protected Areas classified map of Fungi Association from 1992, 2007 and 2016.

Changes in Tree Species Distribution in Protected Areas from 1992 to 2016.

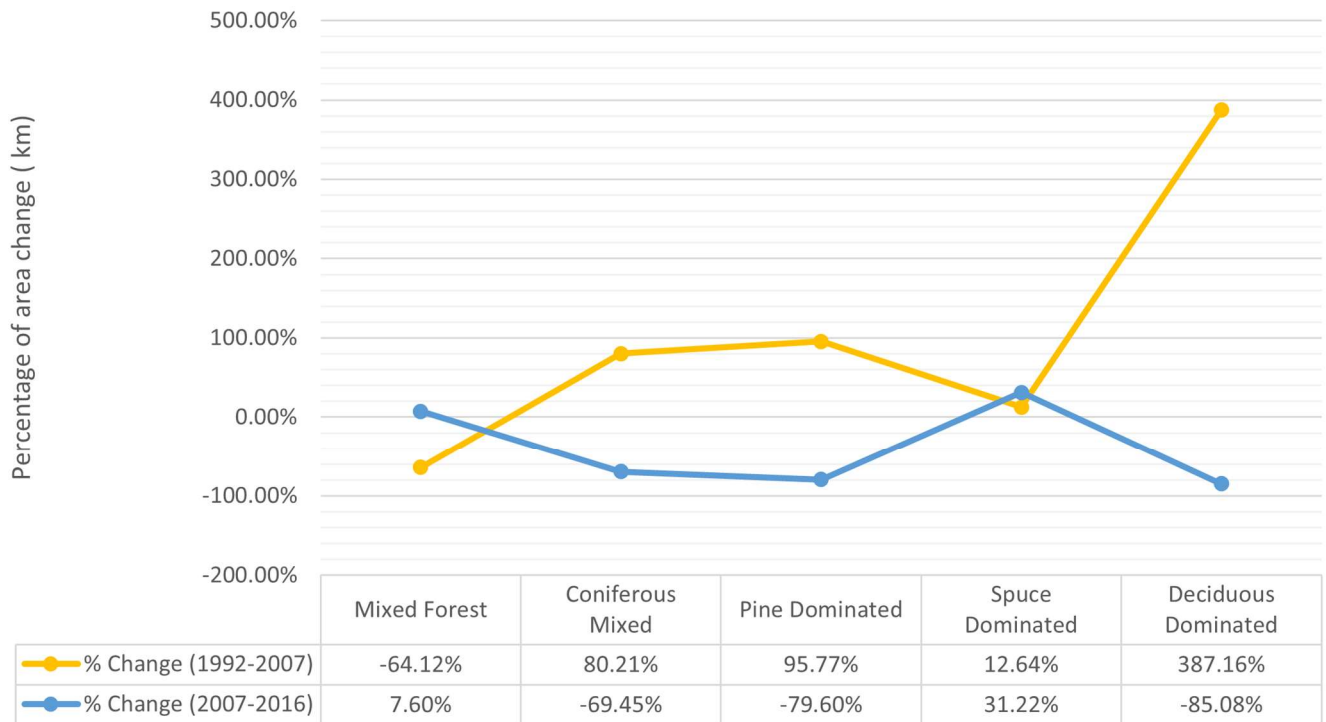


Figure 9(a): A graph showing the changes in tree species distribution in Protected Areas in Trysil for 1992, 2007, 2016 and (b) combined results table.

Based on the classification of fungi associations seen in Figure 8 and 9, the following interpretations can be made about the changes in the protected areas between the years 1992, 2007, and 2016:

- Ubiquitous species: The area of this class decreased significantly by 64.12% between 1992 and 2007. There was a small increase of 7.60% between 2007 and 2016.
- Exclusive to conifer trees: There was a substantial increase of 80.21% in the area of this class between 1992 and 2007. This trend reduced between 2007 and 2016, with a decrease of 69.45%.
- Exclusive to fir trees: The area of this class increased significantly by 95.77% between 1992 and 2007. But, between 2007 and 2016, there was a drastic decline of 79.60%.
- Exclusive to spruce trees: The area of this class experienced a steady increase, with a 12.64% rise between 1992 and 2007 and a further 31.22% increase between 2007 and 2016.
- Exclusive to all deciduous trees: There was a dramatic increase of 387.16% in the area of this class between 1992 and 2007. This is a very dramatic increase, but it did not continue as it decreased by 85.08% between 2007 and 2016.

The protected areas show different patterns of change for different tree species classes over the years. Some classes (Figure 8) like spruce trees, showed a consistent increase in area, while others, like fir trees and conifer trees, experienced an initial increase followed by a decrease. Ubiquitous species experienced a significant decrease at first, followed by a slight increase and deciduous trees had a dramatic increase followed by a considerable decrease. These changes indicate that the composition of tree species in the nature reserve has evolved over time.

This study highlights the shifts in tree species distribution and EMF associations over time. As illustrated in Figure 5 and 6, these changes are vital for understanding how diverse tree species respond to external factors and natural processes (Lambin, 2003).

Understanding the dynamics of tree species distribution and EMF associations is instrumental in making effective forest management strategies and mitigation plans. The results from the EMF distribution patterns (Figure 7) can show the overall health and resilience of these ecosystems (Bonan, 2008). By tracking these changes, we could improve current conservation efforts and more accurately predict the impacts of global warming on boreal forests (Linder, 1998).

The study shows the potential of using geospatial techniques to monitor tree species distribution and EMF associations in forest landscapes. The data derived from these methods can aid in identifying conservation priority areas and potentially forecast how forest landscapes might respond to certain types of environmental changes. This relates to a study by Potter (2003) who uses similar techniques in conservation biology. These findings could also support the growing research exploring the interactions between tree species, EMF, and the environment (Smith, 2008).

However, limitations in the study are evident. The Landsat imagery used to capture shifts in tree species distribution and EMF associations (Figures 5-8) may lack the resolution necessary for accurate fine-scale representation (Foody, 2002). Future research could address this by using higher-resolution remote sensing data, like those offered by Sentinel-2, and supplementing it with extensive ground truth information and small-scale radars like LiDAR, which was utilised in the 2018 data for Figures 5, 7 and 8.

4.2 Study 2: Soil moisture content resilience in extreme weather years

The results of this study provide insights into the soil moisture content and EMF resilience in the forest areas during extreme weather years. Three figures were created to visualize and identify the changes in soil moisture during the drought years 2006, 2010, and 2018.

The NDMI maps in Figure 10a (Page 19) show the study area for the extreme weather years 2006, 2010, and 2018 and provide a visual representation of the spatial distribution of soil moisture content during these years. Accompanying the maps is a graph (Figure 10b) displaying the maximum and minimum values for the NDMI maps. The graph indicates that soil moisture content varied across the study area, with the highest values observed in 2010 and the lowest in 2018.

NDMI difference maps in Figure 11a (Page 20) show the soil moisture values between different weather years and Figure 11b shows Soil Moisture Content change classified maps illustrate the type of change that occurred. The NDMI difference maps reveal variations in soil moisture content between the years, with changes occurring between 2006 and 2018. The classified maps further highlight the areas where soil moisture content experienced increases, decreases, or little to no change.

Normalized Difference Moisture Index (NDMI) values for each of the years 2006, 2010, and 2018.

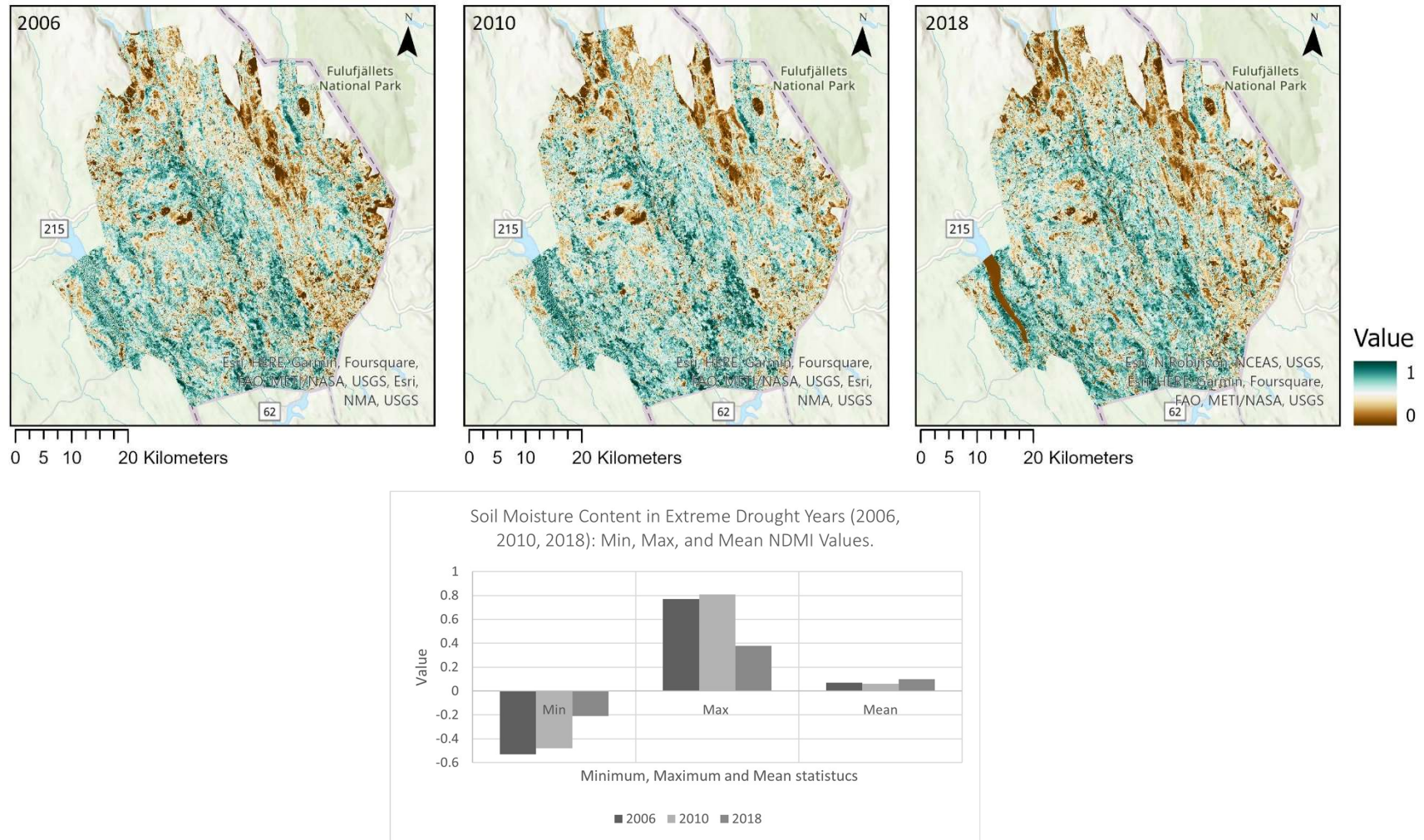


Figure 10: (a) NDMI Maps for 2006, 2010 and 2018 showing maps showing high values up to 1 and the lowest values down to and (b) Graph depicting min, max and mean values for the maps.

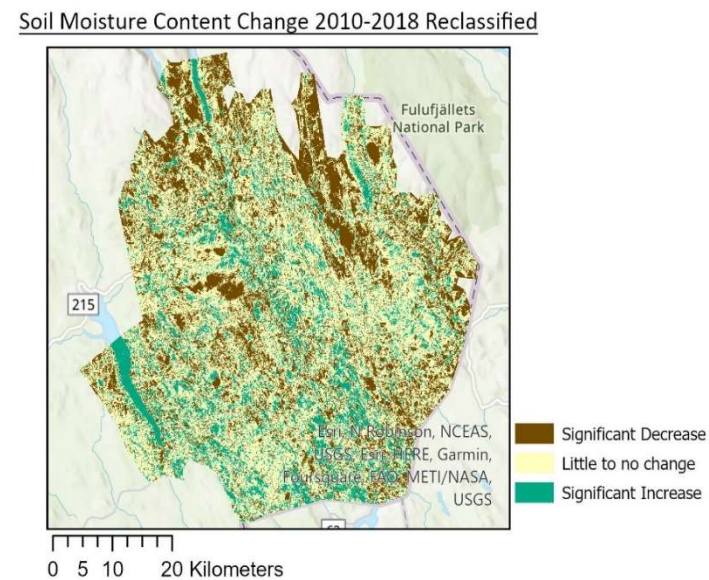
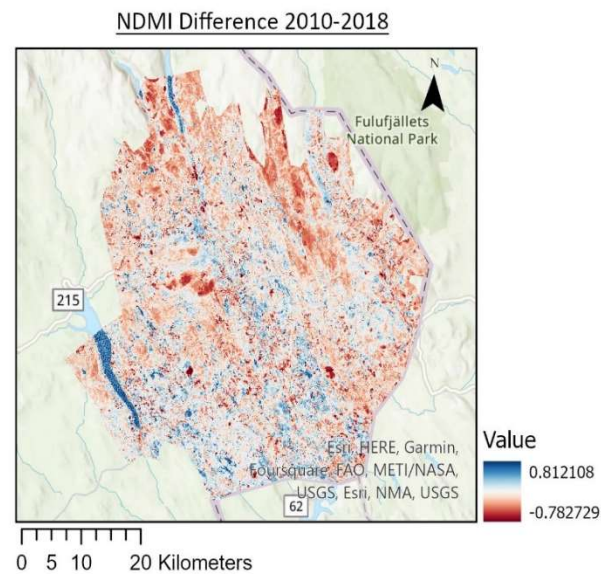
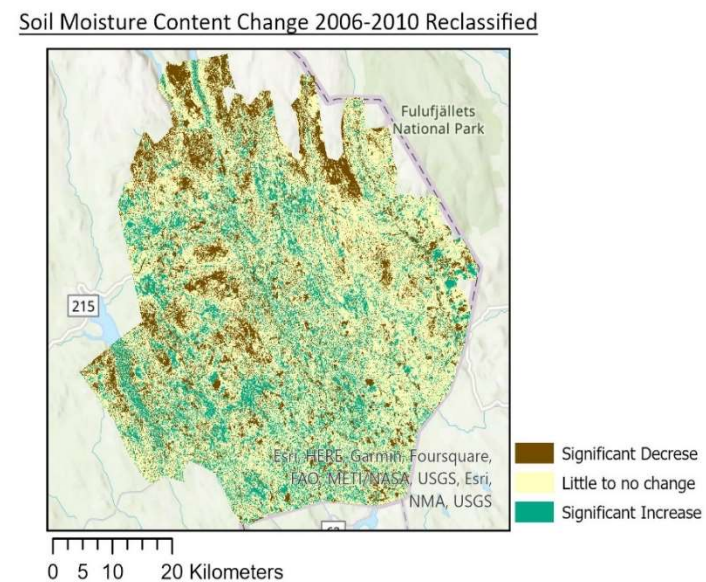
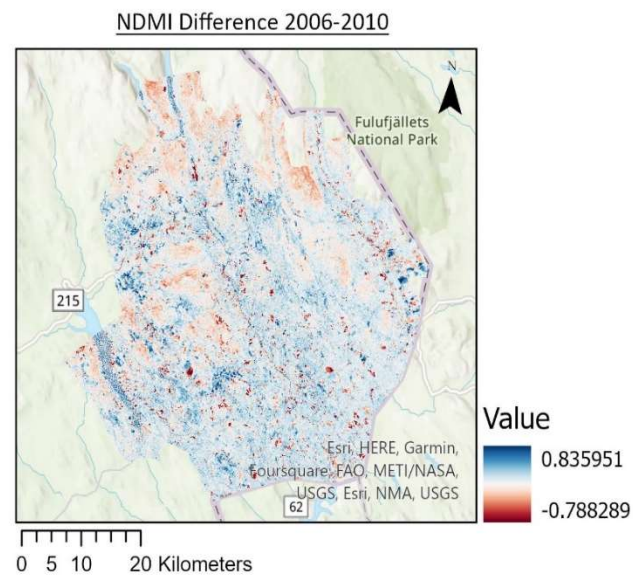


Figure 11a: NDMI difference maps show the soil moisture values between different weather years, -ve values show decrease in moisture over time, whereas +ve values indicate an increase in moisture and b, Soil Moisture Content change classification maps showing the type of changes that has occurred.

Resilient forest areas shown in Figure 12a highlight areas with soil moisture stability and increase during drought years. This map identifies specific regions where forest ecosystems have maintained or improved soil moisture conditions despite the extreme weather events. The pie chart in Figure 12b displays the percentage of change within forest areas between 2006 and 2018. The pie chart shows that 54.0% of the forest area experienced little to no change, 30.4% experienced a significant decrease, and 15.6% saw a significant increase in soil moisture content.

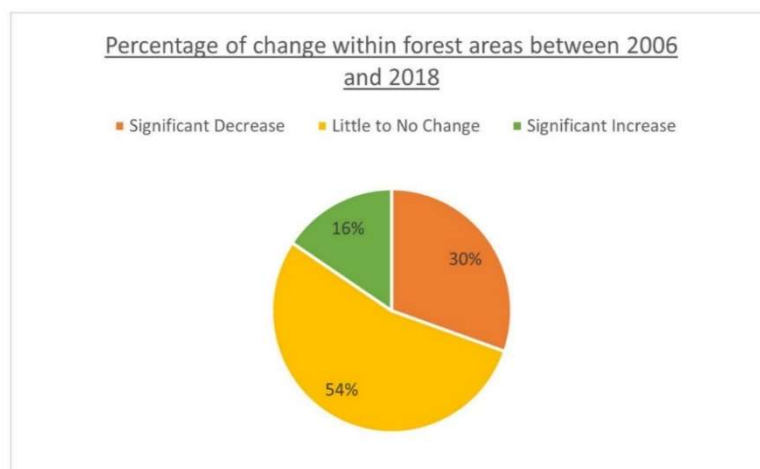
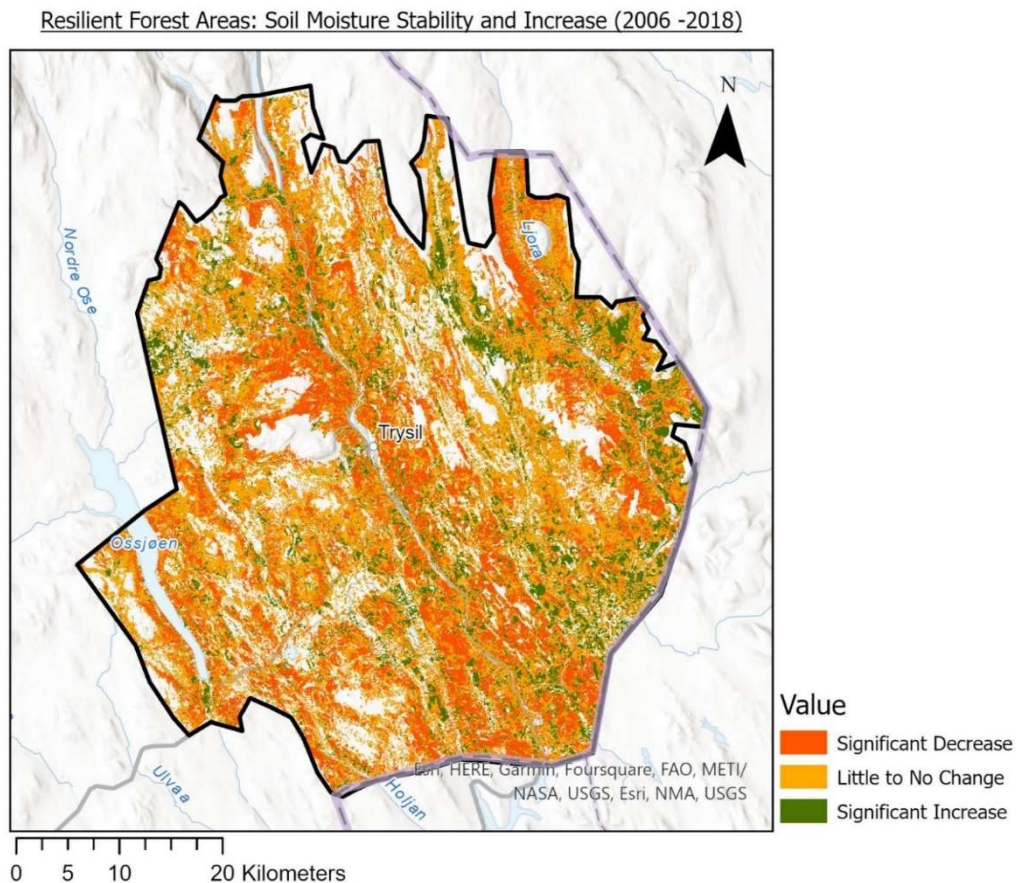


Figure 12 a) Soil moisture stability between 2006 and 2008 showing areas of significant decrease, little to no change and significant increase; b) Pie chart showing the percentage of change between the years.

The fluctuations in soil moisture content, with the highest values in 2010 (Figure 10b) and the lowest in 2018, correspond with earlier research on the impacts of climate change on boreal forests (Hember, 2017). The study highlights some of the dynamics occurring in the forest's landscape in response to extreme weather events. In Figure 11a the difference maps illustrate the spatial variation of the forests response to these events with some areas showing more pronounced changes in vegetation health and soil moisture (Dai, 2011). The resilience observed in specific areas of the forest, as seen in Figure 12, validates the idea that EMF networks can strengthen forest landscapes (Tedersoo, 2020).

The variation of soil moisture content and EMF resilience can support the development of management plans to enhance the forests health (Bastin, 2019). The preservation and restoration of forest areas identified in this study, shown in Figure 12, demonstrated an ability to maintain or improve soil moisture conditions during the drought years. Understanding the role of EMF networks in promoting forest resilience, possibly seen in Figure 10 and correlated with Figure 12, could assist in the development of management plans that support the establishment and maintenance of these networks in forests.

The applications of the soil moisture research create opportunities for further study. Firstly, the results in Figures 10a and 10b shows how the distribution of the soil moisture content could contribute to identifying and protecting resilient forest areas. Secondly, the study could support research on the role of EMF networks in promoting forest health and resistance to climate change, as supported by the results seen in Figure 12.

In this study the use of NDMI calculations for soil moisture content may not capture the full complexity of soil moisture dynamics (Gao, 1996). The study period is also short and therefore it is difficult to assess long-term changes. The study also does not directly measure EMF resilience and relies on the assumption that soil moisture content is a key factor influencing EMF network dynamics which was suggested by Tedersoo, (2020).

4.3 Study 3: Effects of forest fires on mycelium networks

The True Colour Image obtained from Sentinel-2 optical imagery (Figure 13) in October 2022 provides a detailed overview of the study area and its surroundings, serving as a reference point for understanding the landscape and context of the study area at the time of data collection. Enskogen is characterised by a lake, surrounded by a mixture of small urban settlements, forested areas and agricultural land, with the Ljusnan River flowing below the lake. The image reveals that the northwest region, extending to the south, has been cleared and is now characterized by low-level vegetation, indicated by the lighter green shades. The remaining areas exhibit patches of dark green forests, creating a stark contrast within the landscape.

Map of Study Area: Enskogen

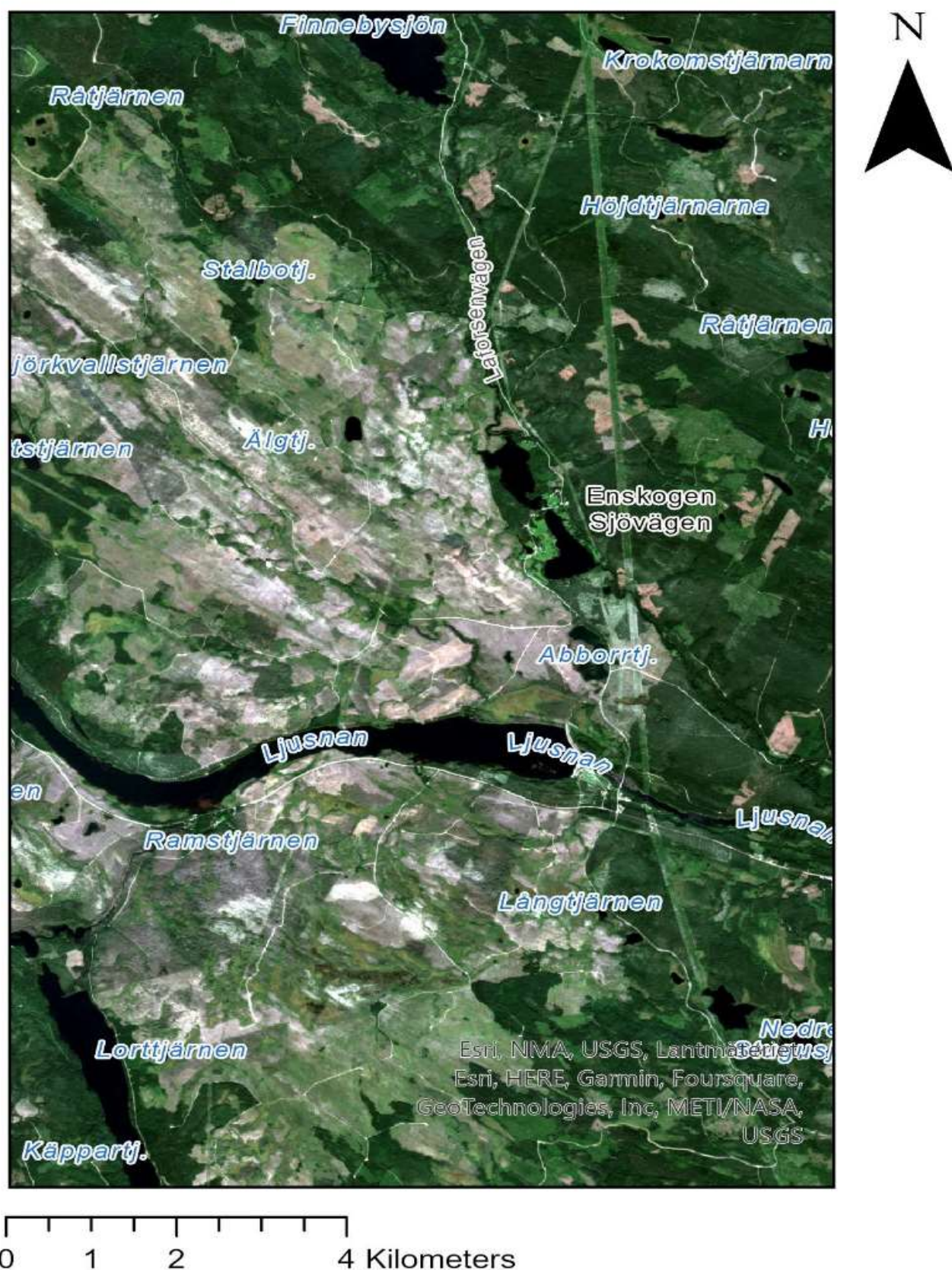


Figure 13: Map of the study area, Enskogen, Sweden.

The analysis of backscatter difference imagery between July 2018 and August 2018, as well as between August 2018 and August 2021 in Figure 14, shows the immediate impact of the fire and its long-term effects on the landscape. These differences emphasise areas of significant change. The first image displays texture and dense pixels, indicating that the change between the two dates has been widespread. Although some of the values are low, higher values seem to cluster around the area below Enskogen and along the river. The second image reveals a noticeable increase in backscatter to the south and northwest, suggesting that these areas have undergone the most substantial changes over time.

Backscatter difference for Enskogen, Sweden from July 2018 to

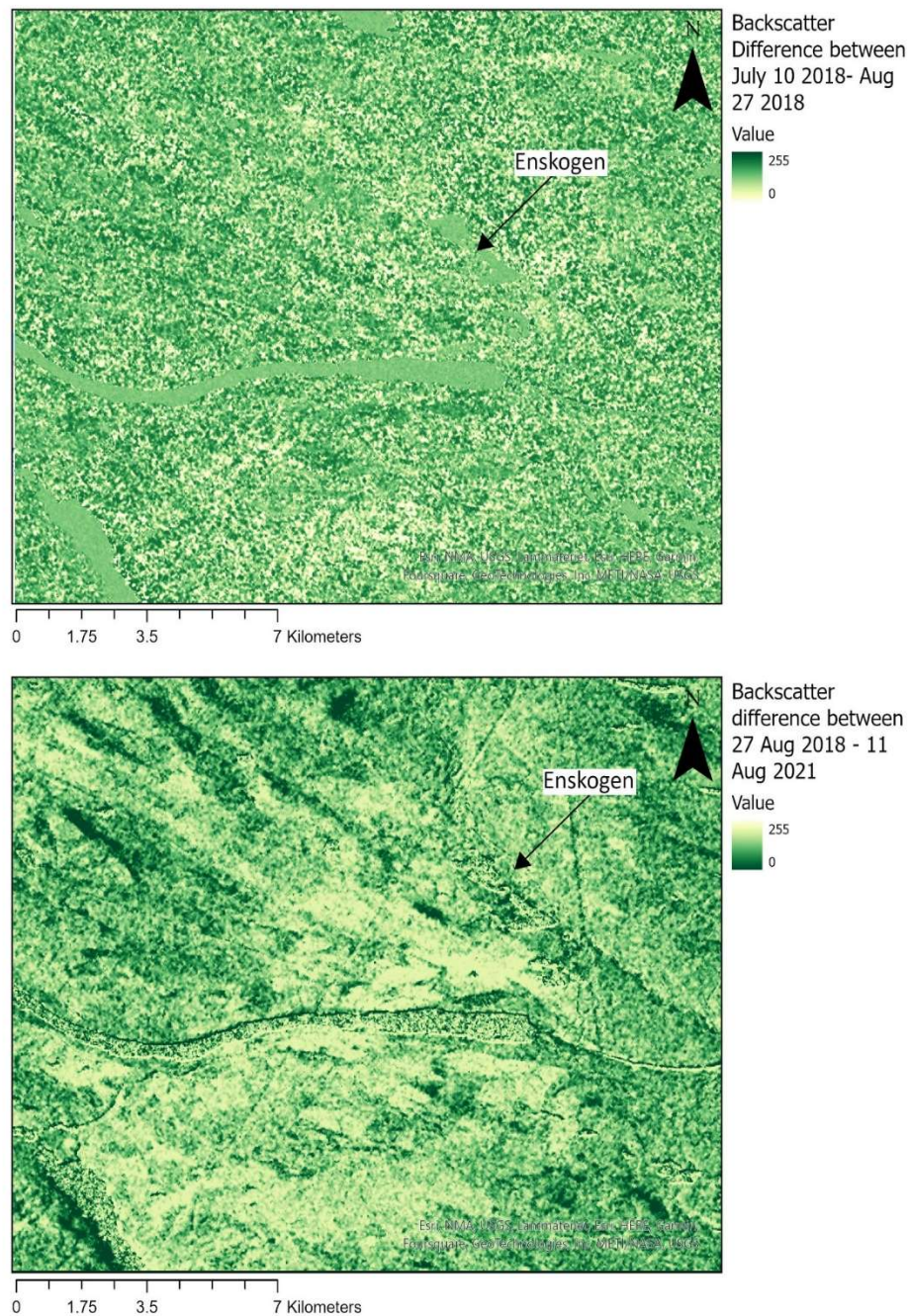


Figure 14: Backscatter difference images before and after the fire and three years later. Low values indicate areas that experienced low change and higher values indicating areas that had a high change between the two image dates.

The NDVI images for Enskogen, Sweden in Figure 15a show the years 2017, 2018, and 2022, along with the accompanying bar chart (15b), shows the changes in vegetation health and density before, during, and after the fire event. In 2017, the NDVI values range from -0.9 to 0.99, showing no burn area and suggesting healthy vegetation across the landscape. In 2018, the values range from -1 to 0.99, with the burn area appearing in the mid-range colours, indicating a decrease in vegetation health because of the fire. By 2022, the values range from -0.07 to 0.66, and the burn area shows mid to very low values, suggesting that the vegetation has not yet fully recovered but shows some progress.

NDVI images for 2017, 2018 and 2022 and statistics graph for Enskogen, Sweden

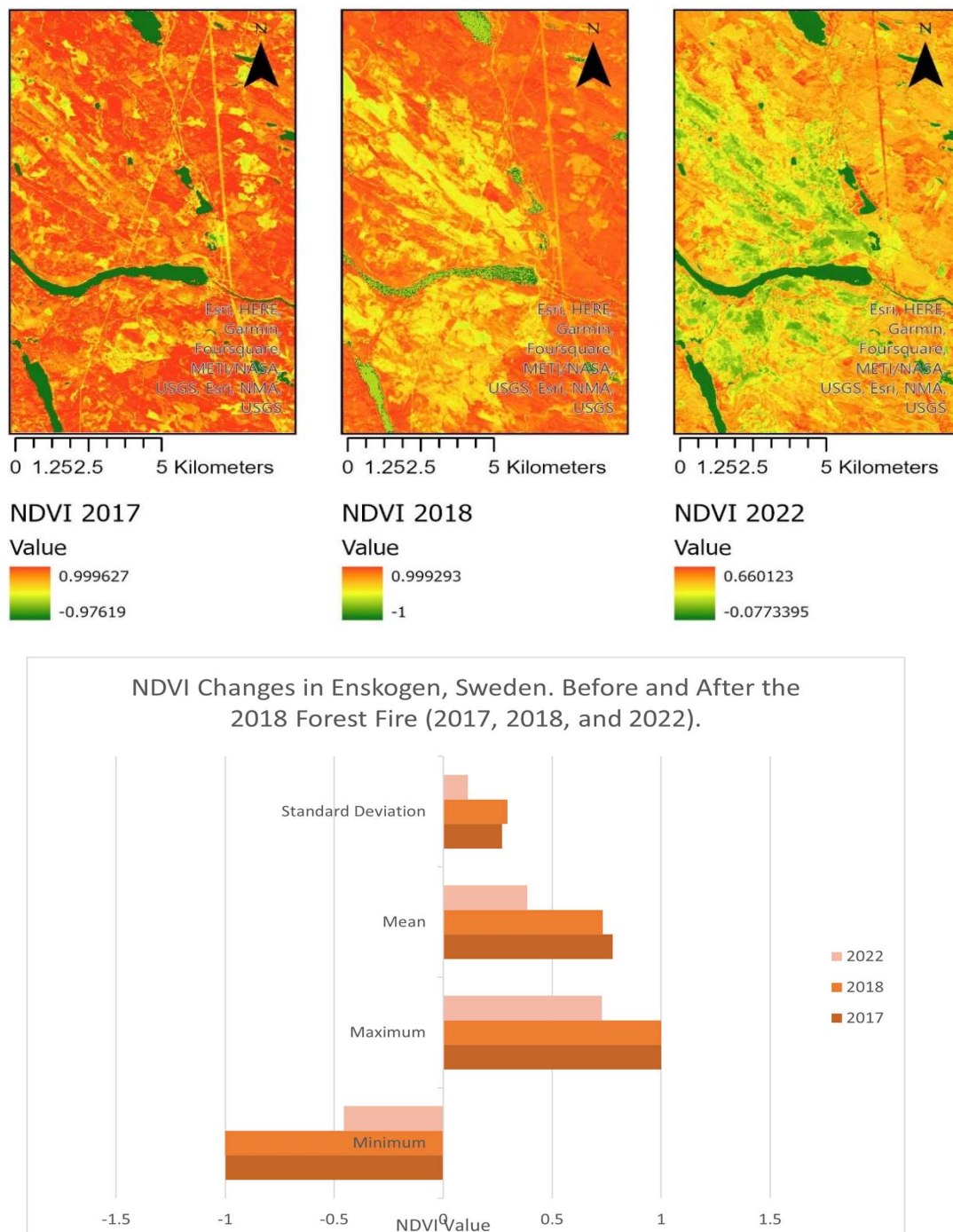


Figure 15a) NDVI images for Enskogen, Sweden for 2017, 2018 and 2022; b) A table showing the maximum, minimum and standard deviation of values for each image.

The MSAVI images for Enskogen, Sweden, for the years 2017, 2018, and 2021 (Figure 16; page 28) offers an alternative view of vegetation health and density by minimising the influence of soil and atmospheric conditions. In 2017, the MSAVI values range from -11 to 0.9, with very high values in most of the image, indicating healthy vegetation. In 2018, the values range from -14 to 0.9, with slightly lower values in the burn area (light green instead of dark green), suggesting a decline in vegetation health due to the fire. The MSAVI image from 2022 shows a range of -0.16 to 0.79, with the burn area displaying significantly lower to mid-range values compared to the other two images, indicating that the vegetation has not yet fully recovered.

The change detection between October 2018 and October 2022 in Figure 17 (page 28) highlights the burn area and shows the extent of landscape alteration caused by the fire. The results show that the burn area has a very high value of change detection, indicating significant landscape changes. Some parts of the forest exhibit lower values of change detection, which could be attributed to rapid regrowth, while other areas show less change due to slow or lack of regrowth. The percentage of change can be seen in Table 5 (page 29) showing the total burn area had reduced 18.33% from 2018 to 2022 and the non-burn area had increased by 34.27%. This highlights the recovery process and helps identify areas that may need more attention for restoration and observation.

MSAVI images for 2017, 2018 and 2022 Enskogen, Sweden.

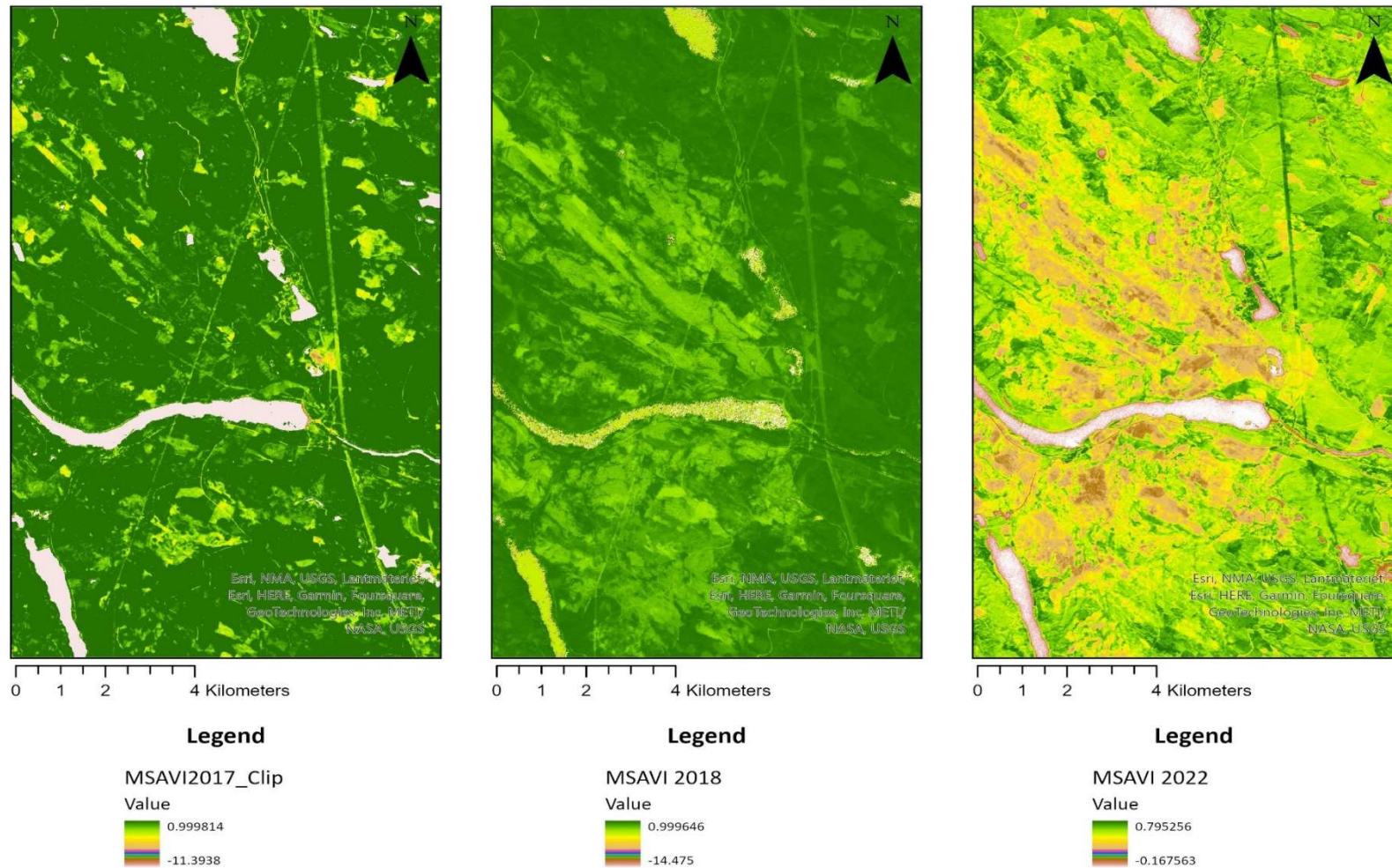


Figure 16: MSAVI images of Enskogen, Sweden for 2017, 2018, and 2021. High MSAVI values represent areas with more vegetation, while low values indicate less vegetation.

Change detection in Enskogen, Sweden in October 2018 and 2022 following a large forest fire in July 2018.

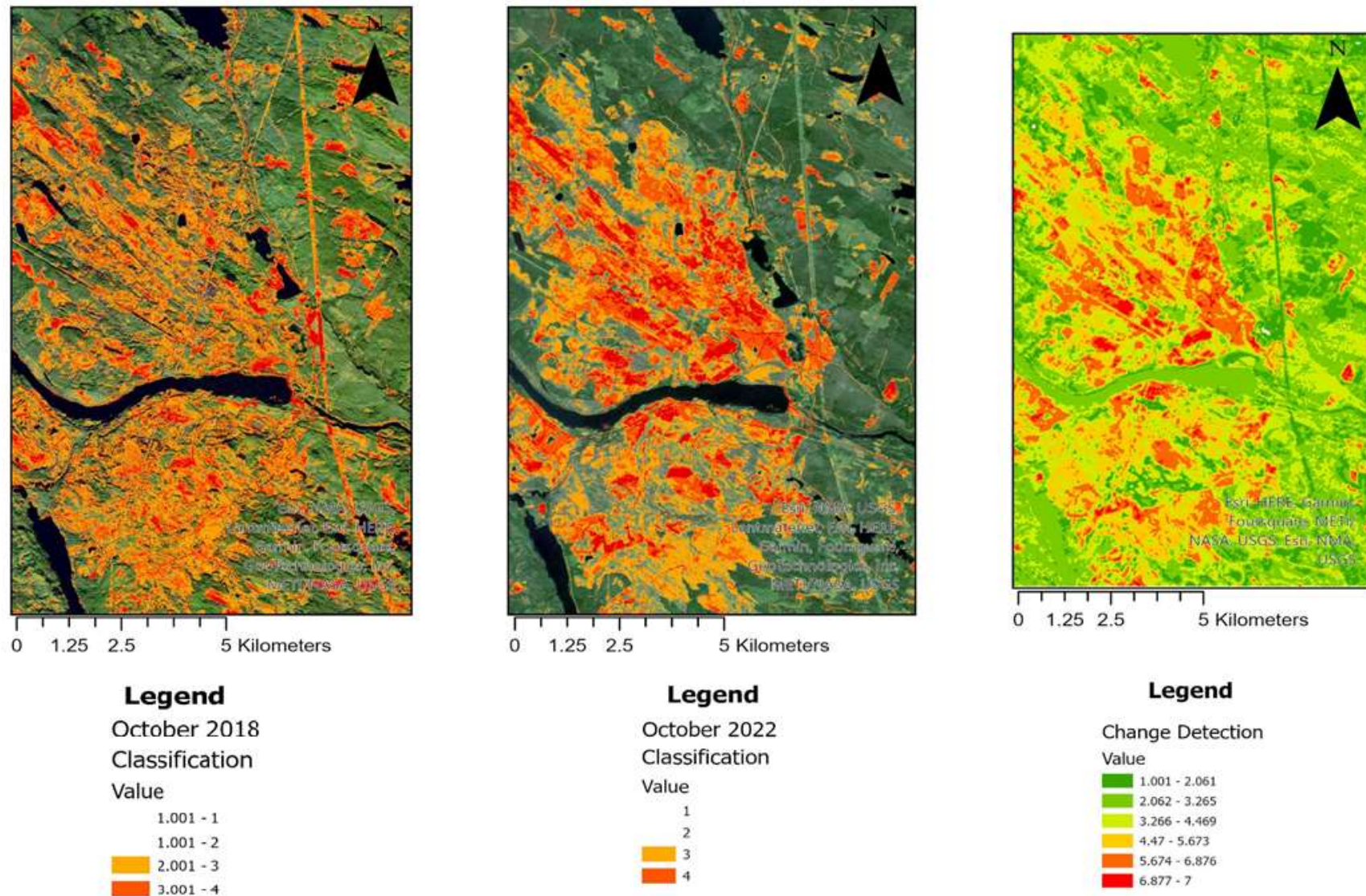


Figure 17a) Maps showing the areas with low vegetation values highlighted in orange and red; b) Change detection map showing values with the highest and lowest percent of change between October 2018 and 2022.

Table 5: Comparison of Burn and Non-Burn Areas in Enskogen, Sweden between 2018 and 2022, showing the percentage of change.

	2018	2022	Percentage of area change
Burn Area km ²	43.403	35.4479	-18.33
Non-Burn Area km ²	93.2096	125.1647	34.27

The results show the effects of the fire event on the landscape and the rate of recovery over time. The NDVI maps in Figure 15 and MSAVI maps in Figure 16 highlight the changes in vegetation health and density which shows the ecological resilience of the area (explored in Study 2) and changes in the landscape. This emphasises the impact of the fire event and recovery process which is supported in the research by Bonan (2008) who “stressed the crucial role of ecological resilience is vital in ensuring the long-term stability and functioning of ecosystems following disturbances”.

The trends shown in these results combined could support monitoring tools for post-fire recovery, which can help governments investigate EMFs role in resistance and make new conservation plans. This idea aligns with the findings of Kennedy (2010) who used remote sensing data to detect trends in forest disturbance and recovery.

The Enskogen fire event was limited as a study due to the relatively short time frame of the study (Figures 13-16 and Table 5) and the analysis was based on remote sensing data (Synthetic Aperture Radar (SAR)), which can be limited in terms of spatial and temporal resolution and atmospheric conditions (Merzouki, 2019). Another aspect which relates to the previous studies in 4.1 and 4.2 is that the areas of forest which were not in conservation areas will have been subjected to external factors such as potential clearing, urbanisation and agricultural practices which would have influenced the data (Aguilar, 2019). Thus, promoting conservation zones and protected areas as more vital than ever in potential future research.

5.0 Conclusion

This study investigated different aspects of boreal forest ecosystems, including tree species distribution and their associated EMF, soil moisture content and EMF resilience in extreme weather years and the effects of fire events on forest landscapes and recovery processes. The key findings across these studies add to our understanding of forest dynamics and resilience in the face of climate change.

The first study highlights the potential of remote sensing in monitoring tree species distribution and their associated EMF in the wider and protected areas of Trysil (Fisher, 2016) despite the limitations and challenges associated with these methods such as accuracy (Foody, 2002) they remain important tools in forest management (Næsset, 2013).

The second study provided valuable insights into soil moisture content and EMF resilience in Trysil forest areas during extreme weather years. This research could be used to compliment conservation plans in the future considering that the distribution of tree species and the water content in forests are significant factors in the sequestration of carbon (Phillips, 2013) and resilience as the planet warms (Policelli, 2020).

The third study shows the importance of understanding the effects of fire events on forest areas and the recovery process in the Enskogen area. This highlighted the need for further research as forest disturbances have been shown to have a considerable impact on global carbon cycles (Potter, 2003) and forest fire frequency is increasing (Dahlberg, 2002).

This study makes an important contribution to Scandinavian forest management projects, which highlights the importance of understanding the resilience of boreal forests (Bonan, 2008; Chazdon, 2008). These results have potential implications for developing strategies that can help maintain and enhance the health of boreal forests (Pan, 2011).

In the future, exploring the limitations of this study could help improve results when incorporating higher-resolution data and more extensive ground truth information and data on forest changes from human activity (Kennedy, 2010). Also, investigating changes over a longer period will help understand the changes occurring and possibly help predict them too (Lambin, 2003).

In conclusion, the study shows the significance of studying various aspects of the Scandinavian boreal forests and its relationship with EMF networks which could help design effective mitigation plans and play a role in reducing the impact of global warming on this vital environment (Bolduc, 2011).

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