GIS as risk assessment tools within decision support systems:

A systematic literature review based on the potential risks of climate change on Finnish forests

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Abstract

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Abstract:

The impact of climate change has been rapidly increasing over the last few decades which introduces new challenges for the Finnish forest sector. The mean annual temperature is expected to rise by about 2-6 degrees before the next century, potentially introducing new risks, such as invasive pest species, as well as amplifying risks already threatening the forests, such as wind damage and forest fires. Forest managers are in need of adaptive management tools capable of keeping the forests profitable. Forestry in Finland also plays an important socio-economic role in the Finnish society, since the Finnish forest industry which accounts for a large share of the Finnish GDP is heavily reliant on domestic forestry. A potential solution is utilizing GIS-based technology, which is increasing in effectiveness due to technological advancements, such as new and faster data gathering methods. By utilizing GIS-based risk assessment in DSS, the systems may assist forest managers with both identifying and mitigating the potential risks, as well as functioning as tools assisting decision-making based on the risks. A systematic literature review was conducted to analyze the overall usefulness of these systems based on the risks caused by climate change in Finnish forests, as well as to identify potential flaws in current practices. The results of the review are based on 28 primary studies that formed the foundation of the analysis as well as a consensus on the topic based on academic sources, addressing questions regarding evidence of existing systems, which risks they may assess, and how they may help planning efforts in the long or short-term. The results suggest that GIS-based risk assessment DSS generally prove useful for assessing most of the identified risks caused by climate change. The systems may assist planning efforts in mitigating these risks and the methods used by systems are expected to improve with increased access to higher quality and quantity of data. The adoption process of the systems may, however, possess some obstacles, and the practice of assessing isolated risks may introduce potential flaws and lower the overall reliability of the systems.

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List of Acronyms

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AISA	Airborne Imaging Spectrometer for Applications
ANN	Artificial Neural Networks
DMBS	Database Management Systems
DSS	Decision Support Systems
ES	Expert Systems
GIS	Geographic Information Systems
GPS	Global Positioning System
GUI	Graphical User Interface
ICT	Information and Communications Technology
iDSS	Intelligent Decision Support Systems
IS	Information Systems
IT	Information Technology
LiDAR	Light Detection and Ranging
MAUT	Multi-Attribute Utility Theory
MCDM	Multiple-Criteria Decision-Making
ML	Machine Learning
NN	Neural Networks

NFI	National Forest Inventory
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SDSS	Spatial Decision Support Systems
UAS	Unmanned Aerial Systems

1 Introduction

Climate change has been increasing rapidly during the last few decades and the direct effects of global warming are becoming steadily more visible globally (Houghton et al., 2001). While efforts are being made to decelerate the warming climate, no short-term solution that would halt its progress exists, which poses an extraordinary challenge for the near future. Within the earth's forests, multiple risks have emerged because of climate change. In large parts of Europe, forests are likely to be more exposed to drought which may lead to forest fires soon being more common. Other underlying threats such as the introduction of non-native species of pests to local ecosystems have also been identified, which can have a devastating impact on the contemporary structure and distribution of tree species (Lindner et al., 2014).

Significant changes in which tree species emerge as dominant in forests susceptible to the warming climate also have direct impact on the forest sector and, in turn, the economy. Since trees take years to grow, knowing which tree species will be more durable in the future is important for the forest sector. Hence, robust planning is required, both for economic and ecological reasons, in order to prepare for the potential changes. The potential risks that Finnish forests are likely to face include wind damage due to changes in the soil, wind speeds and storm patterns, the introduction of pests that have migrated north due to the longer summers, increased risks of forest fires, as well as increased winter precipitation (Vapaavuori et al., 2010). While risks such as these are known, few significant changes have occurred to date, but this is likely to change in the coming years.

An effective way to minimize both economic and ecological devastation is adaptive forest management that can both support and assist ecosystems exposed to rapid changes (Finnish Meteorological Institute, 2017). The rapid advancement of technology has brought forward new tools that can be applied for this purpose. Heavy machinery and computers have already been implemented in the field, but within forest management, data are also a valuable resource and are constantly gathered by the forest sector during everyday tasks (Ala-Kurikka, 2017). This spatial data and their attributes are key components of geographic information systems (GIS) and are crucial for accurate analyses. Decision-making for correct preparations and preventive measures against the risks contributed by environmental changes, can directly be enhanced with enough quality data.

Climate change, however, is unfortunately seldom factored into forest management and may therefore complicate decision-making that take possible future events into account (Nitschke & Innes, 2008). This thesis will study GIS implemented as risk assessment tools within decision support systems (DSS) and their usage for risks brought on by the effect of climate change in Finnish forests, and the possibility of integrating these risk assessment methods and decision-making tools for forest management.

1.1 Structure of the thesis

Chapter 2 introduces the risks posed to Finnish forests by climate change, and the general concepts of GIS-based DSS, as well as GIS-based risk assessment according to previous research. This is followed by chapter 3, discussing the methodology of the thesis and introducing the chosen method of conducting a systematic literature review and how the method is adapted for the research topic. Using this method, previous studies on the topic may be identified and analyzed in order to receive a broad overview on how these topics are dealt with in academic research.

The results of the review also assess what evidence exists of the usefulness of GIS-based risk assessment in forestry, and if these methods are capable of being incorporated into DSS. Another aspect of the results of the review is the search for contradicting statements and the absence of critical research that may influence the general consensus. The systematic literature review allows for the study of a broad research topic, as the one introduced in this thesis, and a chapter discussing the results, therefore, follows the results, with the objective to synthesize the results and construct a conclusion based on the identified research.

Not all effects of climate change may be considered negative for the forest sector. This thesis will not, however, cover any positive effects but will instead focus on the broader topic of assessing and mitigating risks using GIS, and how the methods may be incorporated into decision-making.

1.2 Research questions

The topic of the thesis is split into four different research questions covering the entire topic. The research questions are the following:

- RQ1: What evidence exists of GIS functioning as risk assessment tools within DSS for forest management?
- RQ2: Which consequences of climate change in Finnish forests can be assessed by GIS-based risk assessment?
- RQ3: Can GIS-based risk assessment help forest managers plan for the future?
- RQ4: Does GIS-based risk assessment offer long- or short-term solutions for forest managers?

The results of the systematic literature review are categorized under these questions, and further split under sub-categories describing the themes discussed in the identified studies.

1.2 Purpose and motivation for the thesis

Recent events, such as the 2018 wildfires that raged in Sweden due to an abnormally hot and dry summer, which researchers partially contributed to global warming, are motivation for further research on the topic, since the risk of these events occurring is expected to increase in the future (Krikken et al., 2019). The impact of the warming climate on forestry is largely based on its impact on the forests themselves, meaning that research on how to mitigate the potential damage is not only of interest for the industry, but also for forest management in general. Research into reducing the effects caused by climate change, whether directly or indirectly, therefore, benefits multiple parties and is becoming increasingly more essential.

The forest sector is, nevertheless, in economic terms most susceptible to these disturbances. The forest sector, referring to both forestry and the forest industry, constitutes a large proportion of the Finnish economy. The sector is estimated to account for about 20% of the export revenue (Ministry of Agriculture and Forestry, 2021a). While most of the value is created within the forest industry, the timber used is almost exclusively domestic (Mäntyranta, 2019).

Most risks brought on by the changing climate are not necessarily new, but their severity is increased, and changes may occur in their overall frequency (Kirilenko & Sedjo, 2007). The study of environmental risks affecting forestry is not restricted to one academic discipline, but quite the contrary, to a multitude of disciplines, which may cause difficulties due to the differences in purposes. Finding a clear consensus based on studies from different academic areas, whether it be, statistical, information or agricultural studies, is, however, essentially part of the motivation for the thesis itself.

2. Theoretical background

This chapter will introduce concepts that creates the foundation of the study, as well as identifying the current research on the subject. The foundation consists of information from several different disciplines, including studies on climatic changes and their effects, the obtaining of data and their use, as well as the technical solutions available.

2.1 Effects of climate change on Finnish forests and the forest sector

According to Vapaavuori et al. (2010), the potential effects of climate change on Finnish forests are mainly expected to be noticed in Finland's boreal vegetation zone. The mean annual temperature is predicted to rise by 2-6 degrees before the next century, more specifically 1-5 degrees during to summer months and up to 3-9 degrees during the winter months (Vapaavuori et al., 2010).

As mentioned by Vapaavuori et al. (2010), the rise in the yearly mean temperature will lead to longer growth periods that will increase up to 20–50 % depending on species. While this may have some positive effects related to vegetation growth, climate change also brings new challenges to the Finnish forest sector. Kellomäki et al. (2005) state that the tree dominance and distribution of species may change due to the change in temperature. For example, Norway spruce and partially Scots pine may decrease in southern Finland (Heinonen et al., 2018), and other tree species such as birch that can adapt to the climate more efficiently may takes their place.

While the length of growing seasons increases, so does the need for management of forests (Venäläinen et al., 2020). Due to the climate shifts in northern forests, they are expected to increase their volume of harvestable timber, but further south, the forests will require intensified management to keep their volumes. While these general assumptions can be made about the future of Finnish forests and the forest sector, other consequences of the changing climate do exist and may prove harder to assess.

2.1.1 Abiotic and biotic risks

Kellomäki et.al. (2005) mention that both abiotic and biotic risks are being introduced with the changing climate. Some risks are not necessarily new to Finnish forests, but they are expected to increase in either overall frequency or intensity in the future. These risks are mainly abiotic risks. Biotic risks on the other hand, may present a completely new risk factor to the forest environment as a result of the warming climate.

The main abiotic risks identified by Kellomäki et.al. (2005) are wind damage, snow damage, frost damage and forest fires due to abiotic factors such as wind, precipitation or snow and drought. Pests in the form of insects and fungi are identified as the main risk caused by biotic factors to Finnish forests. The relationship described by Kellomäki et.al. (2005) between abiotic factors and abiotic and biotic damages can be seen in Figure 1. This thesis will focus on the direct abiotic and biotic damage risks on Finnish forests, and not as heavily on the abiotic factors.

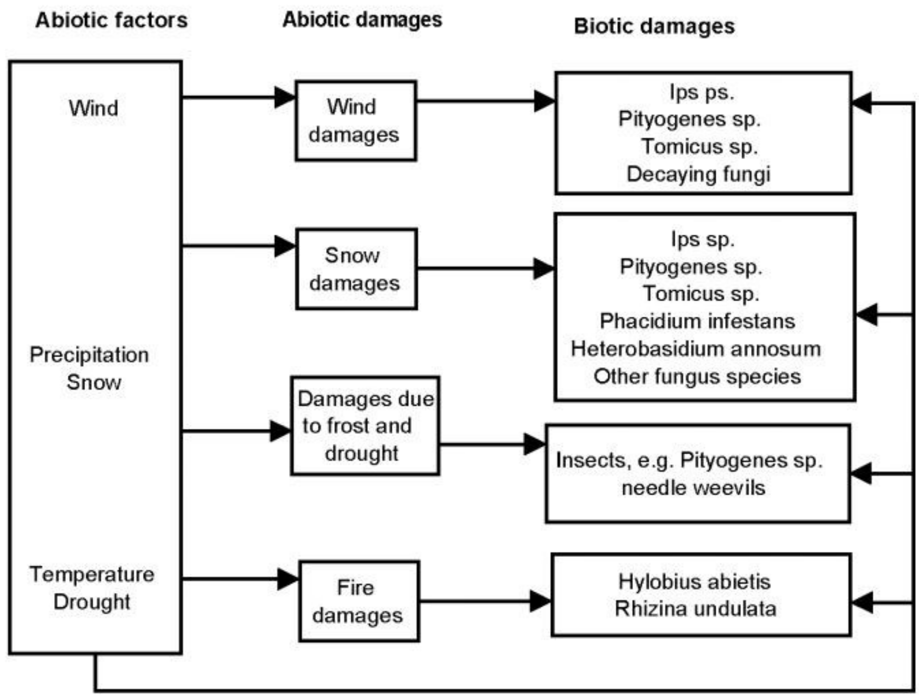

Figure 1 Outlining risks and factors (Kellomäki et.al., 2005)

Kellomäki et.al. (2005) note that damage caused by wind is often linked to the occurrence of high wind speeds and tends to more commonly affect older, taller trees in contrast to younger, smaller ones. The density of the stands is also a factor, meaning newly thinned forests or low-density stands are more susceptible to wind damage. Kellomäki et.al. (2005) do, however, mention that in the case of thinning, the damage decreases over time when roots gain mass and strength, meaning the management of a forest may have direct impact on its susceptibility to wind damage as well. Some uncertainties exist over how wind damage risks are expected to change in the future. Kellomäki et.al. (2005) mention that wind damage may increase due to more extreme wind speeds, but also highlight the unclarity whether climate change will affect the wind patterns at all. Nevertheless, Kellomäki et.al. (2005) also argue that while wind frequencies may not necessarily increase, other factors such as snow cover, and changes in the soil structure may indirectly cause increased risk of damages due to wind. Similar statements are also made by Venäläinen et al. (2020), also mentioning that while few indications suggest that strong winds may increase during certain times of the year, wind damage is still likely to increase overall and possess a big risk of timber volume losses for the forest sector.

Venäläinen et al. (2020) place heavy snow as one of the most important causes of abiotic damage on Finnish forests, just after wind damage. The main consequences are stem breakage or bending of the trees in case of heavy snow loads. Kellomäki et.al. (2005), however, note the uncertainties of identifying snow damage as a future risk. While the risks of excessive snow accumulations may be of some concern in northern regions, the general risks of winter precipitation outside of northern regions may decrease. The uncertainty with snow precipitation also affects the potential of freeze injury or frost damage. Kellomäki et.al. (2005) argue that essentially no empirical evidence exist that would claim that the risk of frost damage for spring budburst is expected to increase. In case of a decrease in snow cover, seedlings may, however, be more susceptible to the cold air causing frost damage (Yle, 2018). Nevertheless, frost damage due to lack of snow cover is not expected to be as damaging to mature trees (Repo et.al., 2014).

According to Ruosteenoja et al. (2018, as cited in Venäläinen et al., 2020), a decrease in average moisture and precipitation during the spring and summer months is expected. The combination of low air humidity, high temperature and strong winds may lead to an increased occurrence of wildfires. Venäläinen et al., (2020) note that the season during which risks of forest fires occurs has been quite short, but this its length is expected to increase in the future. Kellomäki et.al. (2005) also mention that one of the main factors is the seasonal distribution of precipitation, and that the risk is going to be especially visible in the southern parts of Finland. This statement is echoed by Vapaavuori et al. (2010), also stating that the annual frequency of forest fires is expected to increase by about 20% in the entire country by the end of the century.

Vapaavuori et al. (2010) claim that no current indications of forest pest in Finland that can be attributed to climate change exists, but they do mention that this is likely to change, and the risks of insect pest or pathogen outbreaks are expected to increase in the future. While these risks are mainly the result of the warming climate, making Finnish forests hospitable to new species of pests, the threat is also caused by the global market which may accidentally introduce new species of pests. This may still be partially tied to the warming climate since some species have an easier time settling down when the mean temperature rises. Kellomäki et.al. (2005) largely agreeing with these statements, also note that the current insect pests in Finnish forests, while not necessarily attributed to climate change, will also have a higher success in a warmer climate. An example of an insect pest already somewhat established in Finnish forests is the European spruce bark beetle, *Ips typographus*, which Kellomäki et.al. (2005) mention will benefit from the higher mean temperatures. They also note that newly introduced pest outbreaks may be difficult to predict, and the long-term effects on forest ecosystems are poorly known.

Vapaavuori et al. (2010) also add that forest pathogens which may, for example, cause root rot, are expected to thrive in the future. The reason for this scenario is partially due to other abiotic factors, such as increased deadwood due to wind damage. Kellomäki et.al. (2005) mention that species of fungi may also benefit from the changes that occur, which will increase the loss of timber and affect the productivity of the forests. Since the prevalence of some fungi is related to soil moisture, in case of increased precipitation, such species may also succeed. Another risk as a consequence of extreme weather and increased precipitation is flooding, according to Ministry of Agriculture and Forestry (2020). This risk, however, is not as prevalent in other sources of academic literature.

2.1.2 Changes for Finnish forestry

Mäkelä et al. (2010) state that the growth potential of Finnish forests is likely to increase in the boreal zone due to longer growing seasons, but existing forests must also adapt to these changes so that their productivity levels do not decrease. Mäkelä et al. (2010) also note the risk of forests in northern regions having trouble adapting to the climatic changes, partially due to the change in season length, as well as the underlying changes in the characteristics of the winter season. Extreme weather events, such as the factors seen in Figure 1, may also disturb the natural regeneration of forests and may, for example, lead to pest outbreak occurrences due to deadwood, spreading to healthy forest stands (Mäkelä et al., 2010).

Another factor worth mentioning is the climate change's impact on soil compositions, such as when the soil is frozen and unfrozen, which may affect harvest schedules, since forestry has relied on frozen, hardened soil to support heavy machinery during winter harvest (Mäkelä et al., 2010). The frozen soil also affects the sturdiness of mature trees, reducing the chance of windthrow during winter months.

A report by Ministry of Agriculture and Forestry (2005), "Finland's national Strategy for Adaptation to Climate Change", states that while the knowledge of climate change's effect on forestry is good, little adaptation research has yet to have been conducted. The report also mentions that the identification of potential risks plays an important part in the adaptation to climate change. Identifying the potential threats can help mitigate the impact of these disturbances. The research into risk assessment is important, since it will help Finnish forestry adopt new measures to these circumstances, while the practice itself still remains profitable.

Ministry of Agriculture and Forestry (2005) mentions that suitable species which may adapt to changes in climate and soil conditions will be essential for forestry, and also emphasizes the need of adaptive forest management to reduce the damage from environmental risks, while keeping forests profitable. The report states "Adaptation research in the forest sector should be directed at developing advance warning and monitoring systems for climate change." (Ministry of Agriculture and Forestry, 2005). It does not, however, offer any further information about potential systems that may assist forest managers. Mäkinen et al. (2020) further highlight the need for research and development of risk assessment tools with regard to climate change in another published report "Implementation of Finland's National Climate Change Adaptation Plan 2022 – A Mid-term Evaluation". They also state that risk assessment tools are needed for both local and regional actors, as well as companies, and that this also includes training and advice of risk assessment.

2.1.3 Forest ownership and managers

According to Parviainen et al. (2009), about 3/4 of all forests in the principal forest area of southern and central Finland are in private ownership, while state-owned forests are mostly located in northern and eastern Finland. Parviainen et al. (2009) also note that private forests produce most of the timber purchased annually by the forest industry.

According to Mäntyranta (2019), private people (including parties of several shareholders) own around 60% of the productive forest land in Finland, while the state owns 26%, forest industry companies 9% and other entities 5%. While the private sector tends to own more productive forest areas, all parties do contribute timber to the Finnish forest industry that further refine the raw material. This means that information and knowledge to educate forest managers of climate change risks may need to be distributed to multiple different parties, including to those selling forest management services as well as potentially to private forest owners. This also includes potential tools and understandings on how to use those solutions in mitigating risks. Since the forest industry is reliant on timber volumes from all parties, finding solutions for the sector that are adoptable by any party involved to ensure future production of raw material is essential.

Another important factor is that due to the reliance of the forest sector, decreases in forest productivity also have socio-economic consequences, since the Finnish society is heavily dependent on the success of the forest sector (Mäkelä et al., 2010). As previously mentioned, the entire forest sector is responsible for around 20% of Finland's total value of export goods, but Lier et al. (2018) also note that the forest sector accounted for over 4% of the Finnish GDP back in 2017 as well as employed around 60 000 people.

2.2 Geographical Information Systems (GIS)

GIS are computer systems used for managing spatial data and their attributes. As the name implies, the data related to these systems are geographical items and values, such as location-based details in the form of, for example, coordinates. GIS use several different components contributing with different factors and functions, as well as user interfaces integrated with the software package allowing manipulation, analysis and visualization of datasets. GIS are essentially collections of a wide range of components in the form of hardware, software and data that collectively perform these tasks. They are also capable of integrating other geographical technologies in accomplishing their objectives (Peggion et al., 2008). This offers the possibility to make a fairly accurate conclusion regarding an area that would prove difficult by simply observing a map or a satellite image of the area itself. GIS offer users a more accurate overview of the area, since the systems are created to combine the use of maps or other remote sensing (RS) imagery, with more detailed information such as topography, water depth levels, and definition of local vegetation (Bonham-Carter, 1994).

2.2.1 Key Components

Defining the components of GIS may prove difficult, since the systems often differ both in structure and in level of complexity. The common key components found in most systems, according to Peggion et al. (2008), are:

- The tools used for entering and manipulating the data
- A database and its management system (DMBS)
- The tools used to create, analyze, and query for information
- A graphical user interface (GUI)

Worboys & Duckham (2004) take a more systematic approach to the structure of GIS and highlight the relationship between the components and external sources that exist in the form of data. Since GIS essentially represent real and actual geographic areas or phenomena in what could be described as a simulated environment, both quality and up-to-date data that resemble reality are needed if any conclusion made through analysis using GIS tools is to be accurate.

2.2.1 Data and data collection for GIS

2.2.1.1 Spatial and non-spatial data

Spatial data exist in a variety of different formats. They are often represented as pixels, points or lines, which when combined creates a representation of a location or an area. In comparison to data associated with a physical object, spatial data are essentially associated with a particular location. The meta-data can be more detailed descriptions of the traits associated with a certain coordinate. Stacking spatial data together offers the possibility to create shapes or “polygons”, which can visually draw representations of an area. This is common with coordinates, or “points”, which can be bound together as “polylines”, which forms a closed nonself-intersecting loop represented as a polygon (Prieto et al., 2019). This, however, is only one way of representing spatial data, since more complex representations are available depending on the sort of data used.

Describing both the data and the combination of using spatial data can generally be made in two different ways. Examples of these data can be seen in Table 1. Vector data, being the more common ones, consist of points, polylines, and polygons (Janipella et al., 2019). They can be used to represent objects or areas that exist on the surface of the planet or even on another object in space. Vector data can be further connected to either create more polygons or to simply expand an already defined polygon. Raster data refer to data presented as generalized grids of pixels referenced by rows and columns (Janipella et al., 2019). Each pixel contains a certain attribute of data, often displayed as, for example, a particular color or as a unit of measurement tied to the datapoint. A common usage of raster data is elevation, where a value connected to a pixel defines the height above sea level. Raster data often refer directly to an image, such as orthophotography, or to already defined vector data.

Spatial data alone are not necessarily useful or easy to handle unless some forms of non-spatial data or attributes associated the data are present. This also offers querying of data, as non-spatial data generally exist in the form of nominal data, ordinal data, interval data or ratio data. (Janipella et al., 2019). Spatial datapoints and their non-spatial attributes can be used for several different purposes. Within forest management, they are applicable to analyzing, for example, the number of trees within a certain area, estimating natural resources or creating boundaries for effective plantation terrain. They can visually represent roads, rivers, lakes, and landmarks, all taking the shape of points, or polylines while the boundaries of the entire area are represented as a polygon (Janipella et al., 2019). Meanwhile, raster data pixels may offer information about, for example, elevation or water depths in the area. This can be further combined with a RS imagery, as for example a satellite image, to help visualize the data in relation to reality. Spatial data and their attributes are the foundation of the data input of GIS, which through an interface framework offer users to store, manipulate, combine, summarize, and analyze the data (Janipella et al., 2019), both visually and statically. Their output may come in forms of maps or models as well as statistical analyses.

Table 1 Spatial- and non-spatial data with examples

Data	Example of data	Example of representation	Description
Spatial Data			
Vector data	Point	Coordinates	Points create polylines. Polylines create polygons
Raster data	Pixel	Elevation	Pixels contains value. Creates grid of pixels
Non-spatial data			
Attribute	Integer/Text/Image	Name of forest	Any data describing additional information

2.2.1.1.1 Representation

The data used in GIS can be used to represent a wide variety of objects and phenomena. The representations are largely based on the objective of what is studied or its narrative to visually display the results. This requires combining layers of information graphically, which can later be manipulated, or as Harder & Brown (2017, p.73) state: "GIS enables you to work with these layers to explore critically important questions and find answers to those questions.”.

The components that interest forest management are those that can easily allow users to visualize the natural features of an area. Features may range from road networks to elevation to land cover. Sonti (2015) mentions that forest managers may use different sorts of maps to assist their work. Plantation maps, which combine features such as road access, compartment boundaries and planted species are used on a daily basis. Sonti (2015) also highlights that other features such as vegetation cover, soil, and air quality as well as general climate factors may be included in case of purposes such as fire management. The forest sector is therefore reliant on both the GIS capabilities of mapping boundaries visually displaying the areas, but also more specific information and attributes that describe the characteristics of the forest. Figure 2 displays an example of how GIS layering may be combined to represent forest areas. As previously mentioned, this is only one combination of layers, and other aspects may be included if needed.

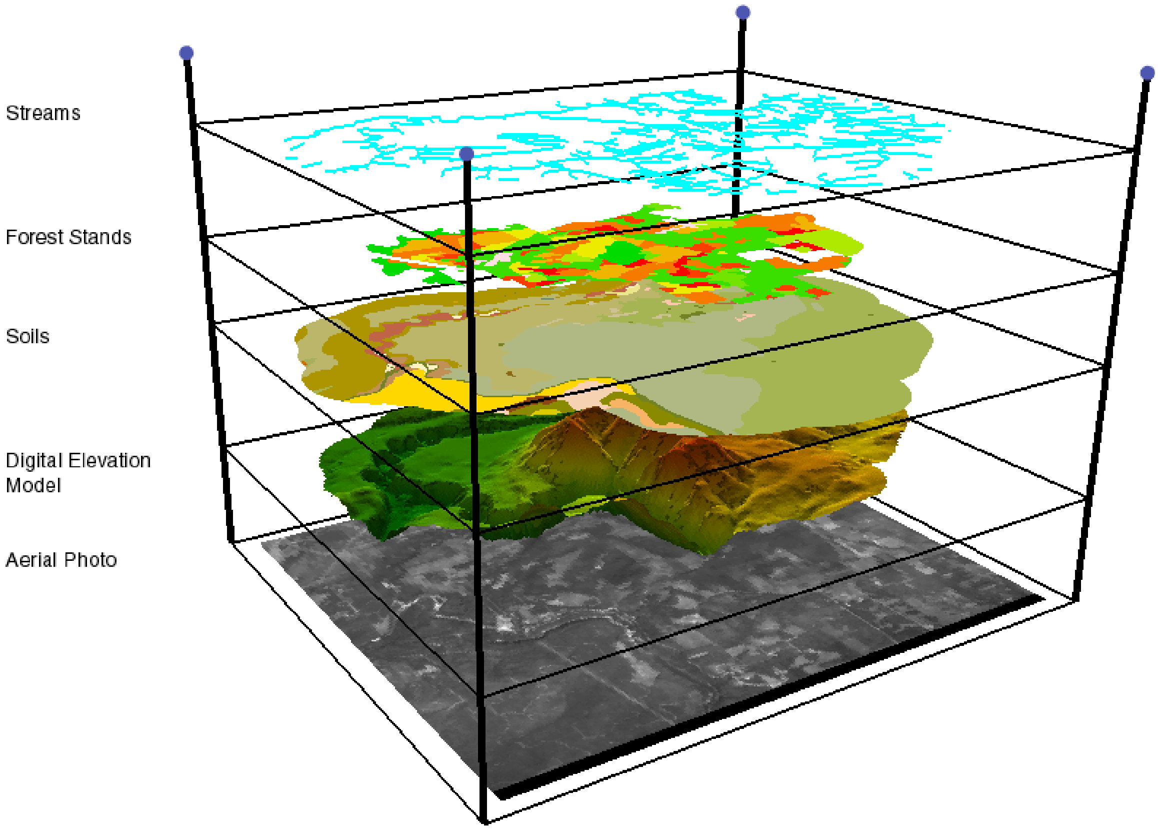

Figure 2 Example of GIS layers in forest areas (University of Washington, 2010)

2.2.1.2 Collecting Data

The collecting of spatial data and their attributes has been practiced for thousands of years in the form of maps, handwritten notes, and illustrations, which constitutes what is referred to as an analogue format of spatial data (Oguchi et al., 2011).

Oguchi et al. (2011) mention that with the development of new technologies, spatial data have transformed into a digital format. This format has essentially superseded the traditional analogue format. Since the collecting of new spatial data often require at least some previous data, the process is often dependent on itself. For example, to gather data of a forest area, one must know the boundaries of the area in question, which has previously been designated through data collecting. The collection of spatial data is, therefore, often a process of updating previous data, which allows for analysis of historical data.

GIS can use many different sorts of data. The methods of collecting the data can differ from one another, and while plenty of reasons for manually collecting certain types of data still exist, some processes have been largely superseded by new high technology methods to both speed up the process and enhance the quality of data. A common way to gather vector data is the use of global positioning system (GPS) receivers communicating with satellites, offering accurate coordinates of their locations (Keeler & Emch, 2017). Regarding forests, the optimal methods for gathering raster data and attributes are those that do not require constant surveillance, due to the large geographic areas as well as the changes that occur over long periods of time. Multiple different solutions are available today and many of them are using RS techniques. RS is a method of providing information about the earth's surface or atmosphere but can even be applied to other objects in space, often through images captured by objects such as satellites or drones (Read & Torrado, 2009).

2.2.1.2.1 Technological advancements

Spatial data collecting methods are constantly improving concurrently with technical advancements. The most noticeable advancements are made in RS methods, which may effortlessly provide both up-to-date, high-quality data and high-resolution imagery of forests, negating the need for more tedious surveying methods of manually mapping forests and their characteristics. Oguchi et al. (2011) mention that the shift from analogue to digital formats has reduced the time for map production. Jung et al. (2021) also note that improvements in artificial intelligence (AI) is simultaneously benefitting RS methods, due to their capabilities of processing big data.

Jung et al. (2021) also highlight the potential use of Unmanned Aerial Systems (UAS) in digital agriculture. These systems may provide a cost-effective method to monitor factors such as plant specific data, biotic and abiotic factors as well as soil properties. Jung et al. (2021) note that the literature on Unmanned Vehicle solutions have been increasing rapidly since they may be used in a multitude of different disciplines and for a large number of purposes.

While Jung et al. (2021) mention the use of technologies such as sensors when monitoring and collecting data, other solutions such as LiDAR or "light detection and ranging" methods are also available. Kellner et al. (2019) state that light-weight airborne laser scanners are becoming commercially available and also suitable for installment on UAS. Almeida et al. (2019) discovered that LiDAR was effective in monitoring forests due to the capabilities of distinguishing between features such as different types of trees and observing attributes such as canopy heights. Advancements in other high-technology solutions, such as Airborne Hyperspectral Imagery are also able to achieve these results (Dian et al., 2015).

With high quality RS methods becoming more accessible and commercially available, accuracy of analysis will simultaneously improve with clearer and more up-to-date representation of the areas studied.

2.2.1.3 Forest inventory data

Besides mapping the general features of areas, another sort of data is needed for understanding the underlying characteristics of a forest. Forest inventory data that include further information about forest stands, such as height, diameter, age, and the dominant tree species are important for accurate analysis. Ministry of Agriculture and Forestry (2021b, para. 1) defines the data that the forest inventory monitoring system Finnish National Forest Inventory (NFI) collects as "volume, growth and quality of growing stock, land use structure and forest ownership, forest health, biodiversity of forests and forest carbon stocks and their changes".

The techniques for gathering such data are essentially very similar to other forms of spatial data, such as with the use of RS techniques, for example, LiDAR, which have been found to be effective (Zhang & Lin, 2017). Natural Resources Institute Finland (2011), which has been conducting research into collecting data for the NFI also used RS methods such as Synthetic Aperture Radar (SAR) and Airborne Imaging Spectrometer (AISA) when gathering forest inventory data.

Forest inventory data can be integrated into GIS, and further accurately designate the position of the data points using GPS. This also allows integration of photographs of tree stands as a form of attribute of a certain geographical location (Spencer et al., 1997). An important feature regarding more specific forest data is that they also allow for analysis of the health of the trees, which may prove useful in risk assessment studies when screening for damage.

2.3 Decision Support Systems (DSS)

DSS that use different methods, such as simulation models and statistical methods to assist with decision-making have found their place both as a strategic management tool for financial and corporate use, and in the form of improving and managing natural resources (Reynolds et al., 2005).

DSS are versatile tools that can optimize processes within forest management due to being able to use computing power when calculating expected outcomes. Simple mathematical models can be calculated directly by humans, but well-configured DSS may take complex mathematical models and swiftly make calculations using multiple factors that directly assist decision-making. They may also improve transparency in their results, since DSS allow for multiple parties to understand their reasoning behind the results and disclose the information input used in the decision outcome (Menzel et al., 2012).

The primary users of DSS can vary, but users are often in higher or mid management positions where more crucial decisions take place (Hogue & Watson, 1985). Eom et al. (1998) mention that DSS should, however, provide decision support tools for decision makers at all organizational levels.

Eom et al. (1998) also state that DSS are meant to only support decision makers and not replace them. The output of the system is not deterministic, but instead offers assistance based on its evaluation. Keen (1980) also mentions that DSS are meant to support the cognitive process of the decision maker, such as with the capability of solving problems with varying degrees of structure (Eom et al., 1998).

2.3.1 GIS-based DSS

DSS have increasingly become more accepted and implemented into GIS technology. By combining the DSS functions into GIS, the potential power of the systems and their data input increases due to the possibilities of using more complex mathematical models when analyzing spatial information (Reynolds et al., 2005). These systems are sometimes referred to as Spatial Decision Support Systems (SDSS), but they are essentially GIS implemented into DSS or vice versa. This does, however, complicate the terminology used when referring to these systems. Keenan & Jankowski (2019) state that the concept of SDSS have essentially been developed independently from DSS, since their purpose is combining spatial and non-spatial data, as well as providing the analysis and visualization functions found in GIS. The term "GIS-based Decision Support System" is still often used for the very same purpose in literature.

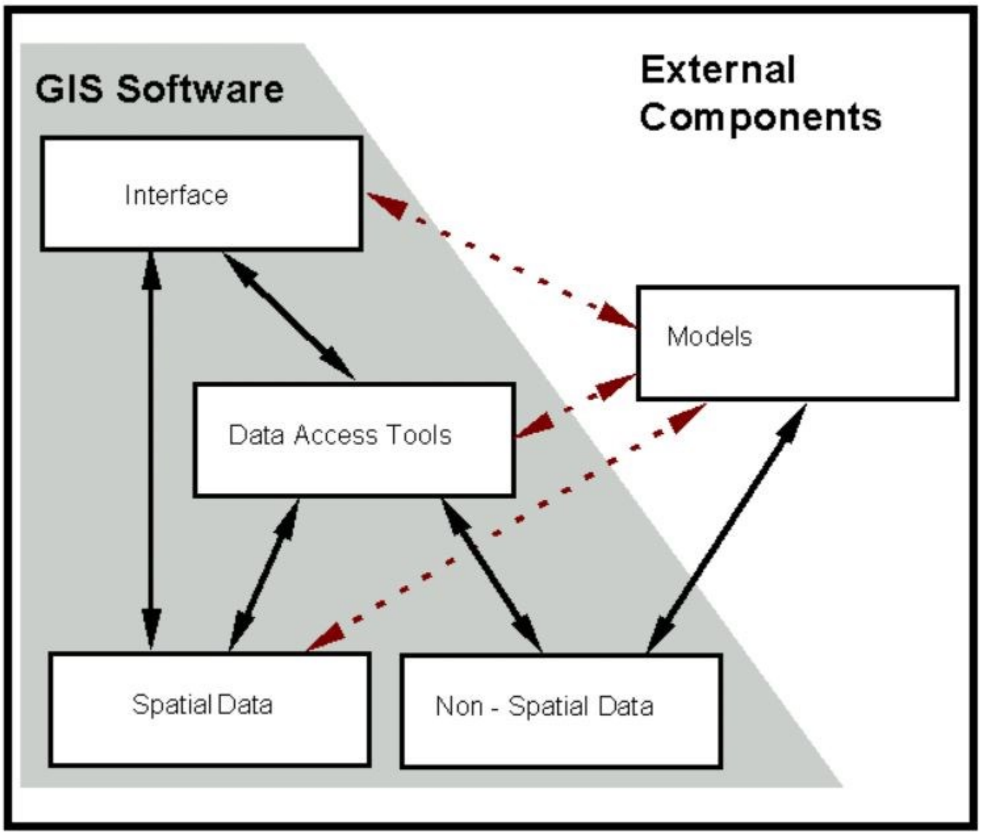

Figure 3 Example of how a DSS component interacts with GIS (Keenan, 2004)

Figure 3 represents a simplified example of how DSS interact with the GIS software. Keenan (2004) states that in simpler and less effective systems, DSS only utilize non-spatial data or attributes, while a fully integrated system is utilizing all features of GIS. Moderns GIS-based DSS are often fully integrated, allowing for features such as visualization and mapping.

2.3.2 Forms of DSS

A wide variety of different systems can be considered DSS. The systems may vary depending on their tasks, objectives and field of use. Power (2002) categorizes DSS in five different categories based on their process and output:

- Communication-driven
- Document-driven
- Data-driven
- Knowledge-driven
- Model-driven

In modern day forest management, the majority of the systems are considered model-driven (Segura et al., 2014). These systems are based on simulations, such as Monte Carlo simulation methods, as well as growth and yield models. Segura et al. (2014) note that model-driven DSS within forest management may also implement certain risk models.

Another common category of DSS in forest management is knowledge-driven DSS, which implement direct problem solving methods using, for example, data mining and machine learning (ML) models ranging from regression analysis to artificial neural networks (ANN). Segura et al. (2014) define these as statistical methods DSS. Segura et al. (2014) also claim they are not as commonly used within forest management as simulation models, but that they do have their field of use. Traditionally, regression analysis and multivariate models have been more common, but the use of data mining and ANN methods are increasing. Segura et al. (2014, Conclusion section, para. 2) also mention, “Regarding statistical methods there is a need to develop and integrate spatial models in GIS tools, which will be a requirement to tackle spatial problems and also to involve stakeholders in participatory processes, among other applications.” They mention that many systems are in fact using associated information systems (IS) such as GIS.

The definition of certain DSS can sometimes be confusing. For example, the functions of knowledge-driven DSS can be compared to a form of Expert Systems (ES), "computer programs, which provide expert advice, decision, or recommended solutions for a given situation" (Lukasheh et al., 2001, Expert Systems section, para. 1). Meanwhile knowledge-driven DSS using AI may also fall under a category of intelligent decision support systems (iDSS), not to be confused with interactive decision support systems with the same acronym. In this thesis, the systems will simply be referred to as DSS or decision support systems without further specification unless stated otherwise.

2.3.2.1 Multi-criteria decision-making (MCDM)

A fundamental factor within GIS-based DSS for forest management is being able to deal with countering factors. Not only do economical and sustainable solutions often counteract each other, but other factors such as resource management, geographical and political restrictions often add further complications for decision-making. Multi-criteria decision-making (MCDM) is an approach that takes different aspects into account and assists decision makers by modelling trade-offs between multiple or conflicting objectives (Reynolds et al., 2005). The research and development of new ICT tools and the improvement of both the quality of the data and the models used, can be integrated into more effective multi criteria support systems (Reynolds et al., 2005).

MCDM is sometimes distinguished from other methods, as mentioned by Segura et al. (2014), but Kartal et al. (2016) state that, for example, ML algorithms can in fact be integrated with MCDM. Ananda & Herath (2009) mention that MCDM has been a part of solving forest resource management problems for the last three decades. They also note that it does have its use in other forms of forest management planning and echoing previous statements claiming MCDM can indeed be combined with other methods. Ananda & Herath (2009) mention multiple different MCDM techniques that have found their way into forest management but highlight methods such as Analytic Hierarchy Process (AHP) and Multi-Attribute Utility Theory (MAUT) for risk assessment purposes.

2.3.3 GIS use in risk assessment and DSS

While Segura et al. (2014) mention that many forest management DSS are using GIS technology, they do not identify any systems that individually incorporate GIS-based DSS into risk assessment. Their study does, however, discuss risk assessment DSS, mainly ForestGALES and GeoeSIMAeHWIND, but not as systems individually based on GIS. They mention that GeoeSIMAeHWIND, using the individual models SIMA and HWIND, can in fact be integrated into a GIS framework. GeoeSIMAeHWIND is a wind risk assessment system, but Segura et al. (2014) also indicate that forest fire risk assessment should also benefit from GIS but does not identify a DSS associated with this particular scenario.

Indications of GIS-based risk assessment DSS being viable in forest management do, however, exist but they are not always specified in academic studies. In the case of Finnish forests, taking the risk mentioned in section 2.1.1 into account, studies would have to include both methods applicable to forests, as well as methods applicable to the specific risks.

GIS-based DSS appear within risk assessment research in a wide variety of areas. For example, Thumerer et al. (2000) describe a GIS-based risk assessment system incorporated into DSS for mitigating coastal flood risks. Systems designed for flood risk purposes using similar technology and methods are found in a multitude of academic literature. Other areas where these systems have been implemented are within risk management of chemical emergencies (Hormdee et al., 2006). A common occurrence in these studies is that the definition of DSS deviates, and DSS are sometimes not specified while still being a component of the product, but only described as, for example, a risk management system. Risk management, however, can be vastly different from decision management. The objectives of these systems are often still consistent with decision-making in regard to a certain risk, but risk management on the other hand, would imply a more specific focus on just the risk itself.

3 Methodology

Kothari (2004) mentions the importance of identifying the research question and isolating the problem before defining the methodology of the study. In the case of this thesis, the research question is fairly broad and is not meant to be solved definitively with one particular answer. The problem in question is the lack of knowledge and consensus on the possibilities around a proposed solution.

3.1 Assessment of methods

Kothari (2004) states that the method of data collecting can either be based on the collection of primary data, meaning fresh data or original in character, or secondary data, referring to data that have been collected by someone else. Primary data collecting is not feasible for the topic of this thesis, due to the broad subject in question. Another problem with primary data collecting methods such as interviews or questionnaires, is that the forest sector is made up of both private parties and corporations, both with different needs and understandings, complicating the process further.

Due to the broad scope of the research question, some secondary data collection methods are also insufficient. Quantitative methods such as statistical studies lack any answer of implementation of the proposed systems into the digital ecosystem of the Finnish forest sector. Based on the results of quantitative research, there would be little conclusion on the general viability of the system, only on certain aspects of its functions and the data requirements.

The critical issue with the mentioned methods also includes the lack of consensus from academic sources on the topic. Research mostly exists as individual studies, only handling a particular environmental issue using a custom-made solution. The optimal solution for a qualitative study is, therefore, to gather data that combined are capable of creating a consensus on the topic, instead of focusing on individual aspects.

The method of this thesis is, therefore, secondary research in the form of a systematic literature review to draw conclusions over the possibility of implementing GIS-based risk assessment DSS to assist forest managers with decision-making when combating the consequences of environmental changes. The consequences in this scenario are the ones mentioned in section 2.1.1, which are directly risk affecting Finnish forests.

3.2 Chosen method

The key aspect of conducting a systematic literature review is finding a clear consensus on the possibility of implementation and the absence of potentially critical information, for example, solutions that are proven beneficial but not fully addressed in previous research. Okoli (2015) notes that the theory behind systematic literature reviews within the field of IS have been implemented from other academic fields, for example, health science, but has since proven to be a valuable method in IS research. It offers a solution for conducting a broader study on a topic, instead of focusing solely on a certain aspect, as is often the case with quantitative and other forms of qualitative studies.

Since the objective of the review is to create a foundation and consensus that can be used to form a conclusion on the research question, the review must be systematic, explicit, comprehensive, and reproducible (Fink, 2019). This means that the reviewer must be explicit in their way of conducting the study, ranging from search strategy to techniques for analyzing the findings. By being comprehensive in presenting all the relevant material, the results in the review are reproducible by anyone following the same approach in reviewing the topic (Okoli & Schabram, 2010). This also improves the possibility of conducting further research directly based on the results of the study.

A systematic literature review is essentially an evidence-based study following structured and predefined steps to ensure transparency in the process and the results. Munn et al., (2018) mention the indications for systematic reviews as the following:

1. Uncover the international evidence
2. Confirm current practice/ address any variation/ identify new practices
3. Identify and inform areas for future research

4. Identify and investigate conflicting results

5. Produce statements to guide decision-making

Munn et al. (2018) also mention the multiple ways that a systematic review can portray its results based on the research question and its narrative, for example, if a current practice is feasible and based on relevant evidence, establishing the quality of such evidence, assess uncertainties in practices, as well as identifying gaps and deficiencies in current evidence. All these narratives are suitable for assessing the research topic of this thesis, but since the general functions of GIS-based risk assessment systems have already been implemented for a wide variety of other purposes, the key aspects of this thesis are identifying deficiencies in evidence that as well as assessing uncertainties that would void the usefulness of these systems for the Finnish forest sector.

3.3 Adapting method to thesis

The angle of approach on the systematic literature review in this thesis is based on "Lessons from applying the systematic literature review process within the software engineering domain" (Brereton et al. 2007), while the review protocol is based on "A systematic mapping study on API documentation generation approaches" (Nybom et al., 2018). Since IS research may differ from other disciplines in a variety of ways, certain steps and phases may, therefore, be attuned to the narrative of this thesis and its topic.

The central aspect of conducting a systematic literature review is extracting previous research and documents of studies made on the topic in question, based on predefined research questions, followed by grouping their conclusions and synthesized results to answer a more global question. This includes defining a thorough search strategy for the research and studies required, as well as defining both the inclusion and exclusions criteria for the studies in question. Okoli & Schabram (2010) mention the difficulty of searching for literature in systematic reviews and that the initial search will undoubtedly return a large number of studies. Limiting the search strings so that the number of irrelevant studies is minimized is, therefore, important. This restricts and defines the selection of previous research to include only relevant data. Conducting a quality assessment on the studies identified is fundamental for ensuring that the conclusion and synthesis of the findings is based on clear evidence. This requires a clear and thoroughly thought-out protocol that documents each phase of the study, which consequently makes the study easy to reproduce.

The choice of conducting a systematic literature review over standard literature review is largely because of the field of research. A valid argument can be made for conducting a literature review to assess the possibility for implementing a system for a particular purpose, but it does not offer the same magnitude of evidence-based data that can be achieved in a systematic fashion and is therefore the inferior option for this study.

4 Systematic literature review

The planning of the review, including the full protocol used for the review is presented in this chapter. Each step of the protocol is clearly defined and includes an explanation of the thought process up to that point. The inclusion and exclusion criteria, as well as the screening process is assessed with an explanation regarding how they are contributing to the objective of the review. The objective of the review in regard to the thesis itself, will also be further defined and clarified under the research question and search string section.

As mentioned in section 3.3, the protocol is partially based on the method used by Nybom et al. (2018), unless stated otherwise. Since this review was made by only one researcher, it may affect both the validity and the also include a certain bias to the protocol. The validity of both the review and the results is discussed further in this chapter as well as in section 6.6.

4.1 Review planning and protocol

A. Research questions (RQ)

The research questions for the review were defined as the following:

RQ1: What evidence exists of GIS functioning as risk assessment tools within DSS for forest management?

RQ2: Which consequences of climate change in Finnish forests can be assessed by GIS-based risk assessment?

RQ3: Can GIS-based risk assessment help forest managers plan for the future?

RQ4: Does GIS-based risk assessment offer long- or short-term solutions for forest managers?

Since the objective of the review is to gather data that can be synthesized to help explain a much broader scenario, the research questions must cover enough ground to help identify studies from different areas and disciplines. Worth noting is that the potential primary studies are not expected to necessarily answer every question.

RQ1 is concerned with connecting GIS-tools to DSS within forest management in regard to risk assessment. The RQ is meant to identify whether, and how such an implementation is made, regardless of purpose, offering better insight on how GIS-based risk assessment can be combined with decision support tools. The reason for specifying DSS is to try finding studies that separate decision management methods from risk management. The purpose of RQ2 is to identify how GIS-based risk assessment methods are dealing with climate change risks. This, of course, includes certain risks already observed in Finnish forests, meaning the research question is not excluding studies not concerned with risks that have not yet been realized. RQ3 is meant to identify studies that specifically address how GIS-risk based risk assessment can assist forest managers with planning ahead and mitigating potential future risks. This leaves space for a wide variety of potential methods, since the objective is to identify what is, and potentially, what is not possible. The last research question RQ4 could possibly be split into two different questions, but it would not affect the outcome of the results. The research question is concerned with the time frame that the solutions offer. In later stages of synthesizing the results, the question is split into short- or long-term solutions.

The choice of not restricting the research questions to GIS-based solutions using DSS, is because GIS-based risk assessment can already be a form of decision support. The purpose of the questions is to identify both the possibilities that GIS-based risk assessment offer, as well as how it may play a role in DSS for forest management.

B. Strategy to find primary studies

1. Search terms

The search strategy was made to reflect both the research questions and the topic of the thesis. The strategy for finding the right search terms was based on preliminary searches trying to identify literature, as well as trail searches as mentioned by Kitchenham & Charters (2007). Through the trial searches, “DSS” or “Decision support system” was added to reflect the first research question. Specific search terms of “climate change” or “environmental change” were also added to include studies specifically mentioning future events. “Risk assessment” was combined with the term “hazard”. The use of an “OR” operator was chosen to not exclude studies due to the use of abbreviations or different definitions. This was also the case of “GIS” or “Geographic information system”. The search terms “forest” and “forest management” were added to ensure relevance for certain searches.

The main risks from section 2.1.1 as identified by previous literature were also added as search terms. Due to the results returned in trial searches, forest fire was excluded as a separate search term due to it already being more established in literature. The relevant studies concerning forest fires for the purpose of the thesis are found through search terms “climate change” and “forest management”.

2. Search strings

Since most search terms would return thousands of results, they were combined to only return results that included all relevant terms, as seen in Table 2.

Through the trial searches, the choice of including “DSS” or “Decision support system” separately in the search strings from specific risks was made. As mentioned in section 2.3.3, DSS is not always specified in literature, adding to the incentive of also separating it from other search terms that directly address the specific risks. The term was, however, included in the first two search strings that address climate change and forest management, which also added further certainty to include relevant forest fire literature, as it did not receive its own search string.

Table 2 Search strings

#	Search strings
1	(“GIS” OR “Geographical Information System”) AND (“DSS” OR “Decision support system”) AND (“risk assessment” OR “hazard assessment”) AND (“forest” OR “forest management”)
2	(“GIS” OR “Geographical Information System”) AND (“DSS” OR “Decision support system”) AND (“risk assessment” OR “hazard assessment”) AND (“climate change” OR “environmental change”)
3	(“GIS” OR “Geographical Information System”) AND (“risk assessment” OR “hazard assessment”) AND (“forest*”) AND (“wind damage” OR “storm damage”)
4	(“GIS” OR “Geographical Information System”) AND (“risk assessment” OR “hazard assessment”) AND (“forest*”) AND (“pest*”)
5	(“GIS” OR “Geographical Information System”) AND (“risk assessment" OR “hazard assessment”) AND (“forest*”) AND (“frost damage” OR “freeze injury”)
6	(“GIS” OR “Geographical Information System”) AND (“risk assessment" OR “hazard assessment”) AND (“forest*”) AND (“snow damage”)

3. Databases

The search strings were modified to fit the databases used in the study. This included wildcards, which were used when possible. However, due to the choice of search terms, wildcards ended up being non-essential. The operators “AND” and “OR” were also changed to “&&” and “||” when necessary.

Two databases were selected for the study:

- Science Direct
- ACM Digital Library

C. Inclusion criteria for primary studies

The inclusion criteria for the primary studies were identified as the following:

- Article was written in English
- Article was published in a journal, conference proceeding or conference workshop of relevant area
- Article addresses one or several of the predefined research questions directly or indirectly

In case multiple studies addressing the exact same concept, both in research method and their presentation of the results, the most recent study would be included unless the contributions of the studies were different.

D. Title and abstract screening

The inclusion criteria identified in 4.1.C were applied to the title and abstract of the search string results. Since the screening was made by a sole researcher, the potential of search bias must be noted. Despite a large number of search results, both the title and abstract were screened in all cases. Since there was a possibility of differences in definition of certain concepts, due to studies originating in several different disciplines, the choice of screening the abstract regardless of title was made to avoid accidental exclusion of relevant literature.

E. Full text screening

The studies that were included from the previous phase were subject to full text screenings to analyze their core material and their relevance to the study. The inclusion criteria were once again added, focusing on how the identified studies responded to the research questions.

F. Quality Assessment of primary studies

Studies that passed the full text screening phase were subject to a quality assessment to ensure that all primary studies met the minimum quality to be included in the review. The quality assessment analyzed both the quality of the research in the studies themselves as well as their relevance to the review.

Table 3 represents the questions used in the quality assessment. The system was based on the method used by Nybom et al. (2018), functioning as a three-level point system, where the answer:

- Yes = 2 points
- Partially = 1 point
- No = 0 points

The maximum points that a study could score was 32. The minimum requirement for inclusion was the first quartile (32/4 = 8), meaning studies with 8 or less points were excluded, and those with at least 9 points passed.

The quality assessment was constructed to ensure that even well-written studies were excluded if they did not prove relevant for this study. Contrarily, studies that were relevant were excluded in case the overall quality of their research did not meet the minimum requirements. This phase ensured that the primary studies for the review are all beneficial for its purpose.

Table 3 QA questions. Partially adopted from Nybom et al. (2018)

#	Questions
	Theoretical contribution
1	Is at least one of the research questions addressed?
2	Was the study designed to address some of the research questions?
3	Is a problem description for the research explicitly provided?
4	Is the problem description for the research supported by references to other work?
5	Are the contributions of the research clearly described?
6	Is there sufficient evidence to support the claims of the research?
	Experimental evaluation
7	Is the research design, or the way the research was organized, clearly described?
8	Is a prototype, simulation, or empirical study presented?
9	Is the experimental setup clearly described?
10	Are results from multiple different experiment methods included?
11	Are results from multiple runs of each experiment included?
12	Are the experimental results compared with other approaches?
13	Are negative results, if any, presented?
14	Is the statistical significance of the results assessed?
15	Are the limitations or threats to validity clearly stated?
16	Are the links between data, interpretation, and conclusions clear?

G. Data extraction

The studies that passed the quality assessment were chosen as the primary studies for the review. Their data were extracted using the form in Table 4. During this phase, individual keywords and themes related to the research questions were also extracted for use in the next phase.

Table 4 Data extraction table. Partially adopted from Nybom et al. (2018)

Data item	Value	Notes
General		
Data extractor date		
Study identifier		
Bibliographic reference (title, authors, year, journal/conference/workshop name)		
Author affiliations and countries		
Publication type		
Research content		
(RQ1) What evidence exists of GIS functioning as risk assessment tools within DSS for forest management?		
(RQ2) Which consequences of climate change in Finnish forests can be assessed by GIS-based risk assessment?		
(RQ3) Can GIS-based risk assessment help forest managers plan for the future?		
(RQ4) Does GIS-based risk assessment offer long- or short-term solutions for forest managers?		

H. Synthesizing the data

Using the keywords and themes identified during the data extraction phase, the primary studies were categorized in subcategories for further analysis. The extracted results are presented in chapter 5. Due to broad research topic, the choice of categorizing the studies based on themes as well as keyword, instead of solely on keywords, was made to better reflect their relevance in regard to the research questions.

5 Results

The initial results from the search strings (from Table 2) yielded a total of 1257 studies. This number does, however, include duplicates from search strings and databases. The studies were subjected to screening of both the title and abstract, after which there were 76 studies remaining. After a full text screening, 36 studies remained.

Noticeable exclusions at this stage were articles that included methods that incorporated DSS, but which were not using any form of GIS technology, since they did not fully reflect the purpose of the review. Other exclusions were GIS-based risk assessment that were not relevant enough for the Finnish forest environment. Since this stage also included screening by only one researcher, the potential bias involved must be stated.

The remaining 36 studies were subject to quality assessment (as described in section 4.1.F), further excluding 8 studies, resulting in a total of 28 primary studies selected for the final review. The elimination process of the studies can be seen in Table 5.

*Table 5 Number of studies per phase. *Number includes duplicates*

Phase	No. of papers
Number found on initial search*	1257
After title and abstract screening	76
After full text screening	36
After quality assessment	28

The data of the primary studies were extracted using the form seen in Table 4. The results of the extraction are visualized in Table 6. Each study was given a study identifier which the study is referred to in this review (except for direct quotations). The reference for each study is connected to their entry in the reference list of the thesis. The last column shows which research questions that the studies answered.

Table 6 Study ID, reference in list, and RQ answered

Study ID	Number in reference list	RQ
1	**[1]**	RQ2, RQ3
2	**[2]**	RQ1, RQ2, RQ4
3	**[3]**	RQ1, RQ2
4	**[4]**	RQ2, RQ3
5	**[5]**	RQ1, RQ2, RQ3
6	**[6]**	RQ2
7	**[7]**	RQ2, RQ3
8	**[8]**	RQ2
9	**[9]**	RQ2, RQ4
10	**[10]**	RQ1, RQ2, RQ3, RQ4
11	**[11]**	RQ2, RQ4
12	**[12]**	RQ2, RQ3, RQ4
13	**[13]**	RQ2
14	**[14]**	RQ2, RQ3
15	**[15]**	RQ2
16	**[16]**	RQ2
17	**[17]**	RQ1, RQ2, RQ4
18	**[18]**	RQ2
19	**[19]**	RQ2, RQ3, RQ4
20	**[20]**	RQ1, RQ2
21	**[21]**	RQ2, RQ3, RQ4
22	**[22]**	RQ1, RQ2
23	**[23]**	RQ2, RQ4
24	**[24]**	RQ2, RQ3, RQ4
25	**[25]**	RQ2, RQ3, RQ4
26	**[26]**	RQ2, RQ4
27	**[27]**	RQ1, RQ2, RQ3, RQ4
28	**[28]**	RQ2

The themes of the studies were further subcategorized as can be seen visualized in Table 7. These subcategories created the foundation for the results of the review.

Table 7 Identified themes and keywords

Theme	Count	Primary studies
RQ1		
Exists/has been tested and verified	4	S2, S17, S20, S27
Structure of system	7	S2, S3, S4, S10, S17, S22, S27
Information requirements	5	S3, S5, S17, S20, S27
Implementation	5	S2, S3, S10, S20, S22
RQ2		
Storm damage	13	S1, S4, S6, S7, S8, S10, S13, S15, S16, S24, S25, S27, S28
Pests	8	S5, S9, S11, S12, S18, S21, S23, S26
Forest fire	5	S2, S3, S14, S17, S20
Disease	2	S19, S22
Indirect damage	4	S2, S15, S18, S24
RQ3		
Planting and spatial aid	7	S1, S7, S10, S14, S19, S24, S25
Timber volume loss	3	S4, S5, S24
Species planning	5	S10, S12, S21, S24, S27
RQ4		
Global long term risk modelling	2	S11, S23
Local long term risk modelling	8	S9, S10, S12, S19, S21, S24, S25, S27
Short term detection of risk	2	S17, S21
Response planning	2	S2, S26

5.1 What evidence exists of GIS functioning as risk assessment tools within DSS for forest management? (RQ1)

DSS have been implemented in a variety of different areas and disciplines. Research into GIS-based DSS does exists, but as mentioned in section 2.3.3, not a substantial amount in the use of GIS-based risk assessment DSS in forest management. Functioning systems that support decision-making in forest management using GIS data or functions, are not as clearly defined in previous research, in comparison to the general concept of decision-making methods and geospatial analysis. This section addresses the existence of GIS-based DSS for risk assessment in forest management, as well as proposed systems or methods that comprise of decision support tools and systems.

The studies included in this section are those identifying either a complete system that combines risk assessment and GIS which assists decision makers, in the form of a complete DSS, or a method that incorporated decision-making for higher hierarchy of management, meaning decision management instead of only addressing the aspect of risk assessment.

5.1.1 Exists/has been tested and verified for a purpose

By using the methods defined in the protocol of the review, there were four primary studies, [S2, S17, S20, S27], that specifically mentioned the existence of GIS-based risk assessment within DSS and its use within forest management. Three studies, [S2, S17, S20], were related to systems incorporated into forest fire management, while one, [S27], was being used to assess the risk of wind damage.

All studies base their research on systems that are either already in use or have already been tested in their field of application. The common motive of the systems is to assist decision-making by either visualizing or quantitatively describing the results, as well as giving insight into the process behind the results. While not every study has a clear description of the end users of the systems, indications that they ultimately are forest owners, forest managers, or natural hazard managers can be found. [S2] addresses the significance of outputting the systems information and results to forest managers as well as to the public regarding potential risks identified by the system, since the study is referring to the risk of forest fires. This, however, is not clearly stated, nor discussed in the other studies.

The way that DSS and GIS functions in relation to each other varies in the studies. Several different forms of systems are identified. [S27] describes the DSS being implemented as a toolbar into GIS, while [S2] refers to an independent software tool using an integrated framework of image processing, GIS, and regional data. [S17, S20] reviews several different systems that have been developed independently for more specific purposes within forest fire risk management, varying in methods used to combine DSS with GIS. No clear consensus on an optimal way of implementing the systems is identified in the studies, as well as no mentioning of any downsides to a particular format.

No clear consensus on the scope that a particular GIS-based DSS can cover was identified either. Some of the identified forest fire DSS can cover multiple functions within the area of forest fire risk, but decision support through assessment of multiple risks of different variety by one single system is not addressed in any of the studies.

5.1.2 From the structure of the system to output

The identified studies included in this section either have a thorough technical explanation on how DSS is combined with GIS or includes an overview on how the structure of their respective decision-making methods translate into decision support and output. A total of seven studies, [S2, S3, S4, S10, S17, S22, S27], discussing these themes were identified.

While all identified studies mention running their methods using either GIS data, functions, methods or both, the specifics of what kind of GIS software is used is not clearly stated in every study. ArcGIS or some customization of an ArcGIS component is used in [S3, S4, S27], while [S22] uses GRASS GIS. A stronger consensus, however, exists on the use of a structurally sound GIS databases capable of easily transferring information.

The technical aspect on how to integrate GIS and DSS is lacking in most studies, except for [S27], which gives a clear description of this integration. In this study, two different models, one as a forest growth and yield model, the other a mechanistic wind damage model, are combined into a DSS module, integrated as a toolbar into ArcGIS to assist with decision-making in regard to the risk of wind damage. While not explicitly mentioned, this resembles the method mentioned by [S3] which would utilize a toolbar "ArcFuels" in ArcMaps, a component of ArcGIS, which can be applied to assess wildfires. [S3] also mentions WFDSS (Wildland Fire Decision Support Systems), which is a standalone web-based DSS, used with the economic model RAVAR (Rapid Assessment of Values at Risk), and indicates that this combined model can be used to spatially project fire growth under different weather scenarios, and offer a value-at-risk analysis. The study itself lacks the explanation of how geographic data are used in this circumstance.

[S22] takes a slightly different approach, which is not explicitly described as a DSS, but essentially functions as one, since one can interact with the system outside the limits of the risk assessment method itself. The study describes the creation of an interactive model, by projection the landscape onto a physical model. The model can then be interacted with physically, which simulates the user response and visually projects the results of adaptive risk management.

Most studies are accompanied by a description of their method, such as a simulation model or statistical method, and how that method is connected to the risk assessment method used and the output of the DSS. Some studies rely on external sources for their models. [S2] describes using multiple external modules that combined constitutes the decision support tool. [S22] and [S27] are both using preexisting models and datasets, the former using PoPs (Pest or Pathogen Spread), a library with GIS and R interfaces for pest risk assessment, and the latter combining HWIND, a mechanistic wind damage model with SIMA, a forest growth and yield model for wind damage assessment. This is in fact the same model identified in previous literature mentioned in section 2.3.3. These models compose the foundation on which the simulations are run, as well as the results the decision support tool is based on. [S4] utilizes a decision tree analysis based on GIS data and InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, used for quantifying and valuing ecosystem services.

Studies [S10] and [S17] both state the importance of MCDM for more accuracy in the results. While other studies are partially deploying similar strategies, no specific mention of such practice exists. [S10] (referring to MCDM as MCA or multi-criteria analysis) does, however, mention that the problem with MCDM is that the factors and weights of the model are subject to judgment by the decision maker. The study utilizing an algebraic function in a GIS environment, combining maps based on risk factors for flood and rainfall intensity risks, validates the results with historical data to analyze the weights used in their function. [S17] assesses multiple model structures in forest fire risk assessment. Using RS imagery and GIS as foundation, the models utilize different methods, ranging from comparing RS imagery from previously affected areas, to more complex functions such as running neural networks (NN) based on historical data. The study reviews multiple decision-making methods for forest fire risk assessment, dividing them into groups of four:

- Statistical and data-mining methods
- ML methods
- MCDM methods
- Ensemble methods (combination of methods)

According to [S17], each model has its own advantages and disadvantages for decision-making, and the models should therefore be calibrated depending on where they are used. Generally, little consensus exists within the identified studies on a best-choice model for GIS-based decision-making for forest management, but a multitude of options are available.

The output of the proposed systems in the studies varies depending on their purpose. Some offer multiple different ways of displaying the results. [S2, S10, S17, S22, S27] display their output visually, more specifically in the form of maps. [S2, S3, S17, S27] display the output as quantitative or numerical results, for example as probability or estimation of risks. The results of [S4] while also quantitative, offer output in the form of economic loss due to risk, as well as visual damage risk maps. [S2] also offers estimations on the costs of combating risk, as well as assessing destruction from risks. Some consensuses can be identified on the concept that output should relate to probabilities instead of deterministic predictions, which agrees with literature on general aspects of DSS mentioned in section 2.3.

It may be worth mentioning that [S10] did utilize MCDM methods in its decision-making approach and essentially describes the structure of a GIS-based DSS, but also mentions that its approaches can be incorporated into an already existing DSS, which is an anomaly in comparison to the other studies identified.

5.1.3 The problem with information

A general need for high quality information certainly exists in risk assessment, but when combined with DSS, this becomes even more crucial. The entire process of identifying a risk, assessing the risk, and outputting probabilities and evaluations based on input data require a large amount of quality information for the output to be deemed relevant and reliable.

A few studies discuss the issue with information. [S3, S5, S17] explicitly mention the problem with information gaps and deficiencies when making evaluations or calculations for decision support. Worth noting is that since the studies evaluate different risks, some risk assessments methods may rely more heavily on data that are harder to obtain.

[S5] mentions the lack of sufficient information available when assessing risks in the first place, which would require further research to fill any identified information gaps. The information gaps may not always be in form of spatial data, but in lack of other information regarding the scenario. [S5] mentions that an indirect risk of a symbiotic fungi associated with a certain pest may be perceived as a threat to a forest, but due to the lack of information on the potential impact from the fungi on trees in general, a conclusion regarding the threat cannot be assessed. This form of insufficient information can make implementation of DSS that rely on these assessments deemed unreliable. In the case of study [S5], risk assessment was made difficult due to the difficulty of accurately forecasting climate change, which in turn makes decision support for future events impractical.

[S20] mentions that evaluating wildfire spread, with or without suppression or human interaction, often requires an extensive amount of information, which often may not be available. While one can assume that the designer of a decision support system generally is not the party collecting information, [S20] notes that even an accurate DSS is limited to the quality of the input data, meaning issues with information is indirectly impacting the quality of even a well-designed DSS. The study also emphasizes that information can be costly, meaning both the designer and the decision maker (as the end user of the system), should have a clear understanding over the balance between input data errors and model accuracy, in addition to the different sources of uncertainty and the potential impact on losses.

[S3], however, states that while insufficient information is an issue, internet information sharing has improved, and complex decision support models are therefore made possible. Other studies, while not directly assessing the issue with information and its acquisition, do indeed mention the improvements of data quality that are being made. [S17] mentions the importance of updated satellite information and other forms of RS methods, such as drone-based photogrammetry, which has become progressively more essential for risk assessment. The quality of the information that these tools offer is constantly being optimized and function as direct input data into GIS, which consequently results in more accurate evaluations within GIS-based DSS.

[S27] also highlights the issue of information within the system itself. The system designed in this study is noted to be time-consuming. This includes the work of handling the data correctly as well as the adjustments made, for example, having to update the spatial database after the DSS is run.

5.1.4 Implementation of the system

Several studies discuss the implementation process of GIS-based DSS. Studies [S3, S20] assess several issues disrupting the implementation of DSS for the end user, in their case regarding forest fire risk assessment. Meanwhile study [22] identify a different approach of implementing the system, more easily engaging with the end user. Worth noting is that the problems during implementation and adoption may be somewhat unique depending on which sort of risk is researched, but some general standpoints can be found.

[S3] reviews several barriers to implementation of risk assessment systems. Since the study is based on forest fire risk frameworks in the United States, some of the barriers identified may differ in the case of other countries such as Finland. The study mentions there being social, political, and economic pressures that may influence implementation of risk assessment systems, and further, decision-making tools, meaning the problems are not necessarily restricted only to the private or public sector. The study mentions that the incentive to allocate funds for implementing a new risk-based decision process by a sitting manager may be non-existent, since the consequences and potential realization of the risk is likely to occur under future managers. [S20] addresses a similar issue, and states that more research should be made on management's insight of the implementation of DSS, since it could help enhance the perception of the system's positive impacts and reduce the negative impacts. [S3] also highlights the possibilities of conflicting long- and short-term management responses to decisions based on risk assessment. The options for short-term management of a risk do not necessarily agree with the optimal long-term strategy. [S20] make similar statements and notes that there may be conflicting management strategies as a result.

[S3] also mentions the process of risk management training, not only when adopting new methods, but also for training staff to understand both the negative and the beneficial consequences of implementation. Similar statements are made by [S20], also mentioning that misalignments between DSS and the users adopting and implementing the system may often occur. The implementation of a decision-making process must be delicate, to be done correctly. [S20] argues that the success of the implementation of the systems is largely based on opinion leaders and their views. [S20] claims that DSS falls under a broader concept of risk management, known as "risk governance", as visualized in Figure 4, where risk management and assessment are included. This can cause discrepancies in an individual's view of risk assessment from a decision-making standpoint and may lead to a misperception of the perceived risk or value at risk. The study states that the development of these systems started with risk management approaches but has transformed into the broader concept of governance with time.

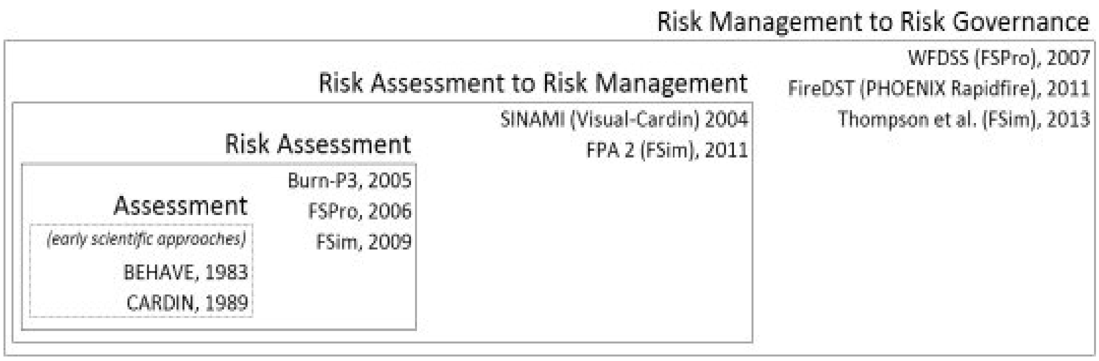

Figure 4 From management to governance with examples (Pacheco et al., 2015)

[S22] states that the implementation of a more interactive management approach would be more easily accessed and understood by the users. They argue that this model better represents reality and allows users and managers to ask better and more realistic questions about decision-making in forest management.

[S2] and [S10] discuss the extension of their proposed DSS for implementation. [S2], which presented a finished system, explicitly mentions its open architecture and permitted expandability which would allow for further configuration. This is also stated by [S10], noting that the system and the approaches themselves may be incorporated into other systems and applied to areas outside of the studied location. [S20] does, however, emphasize that DSS, and in the case of [S10], its approach, must always be configured to the local context for them to be effective.

5.2 Which consequences of climate change in Finnish forests can be assessed by GIS-based risk assessment? (RQ2)

Most of the primary studies identified include GIS-based risk assessment relevant to the Finnish forest sector. The studies included in this section address risks, some of which are more relevant, and others that are not considered as crucial for the Finnish forest sector, but nevertheless, whose solutions are still considered beneficial and offer a clearer consensus of what is possible, and how GIS data and functions contribute to risk assessment. Some practices are more established using GIS, while others are not.

Of all the potential risks identified in section 2.1.1, two were not identified in any of the studies included this review. No indication of GIS-based risk assessment for frost or snow damage was found, and the potential reasons for the lack of studies is further discussed in section 6.5.

The terminology of risk assessment and risk management is sometimes used interchangeably with decision management in the identified studies, confirming the initial intuition mentioned in section 2.3.3 and 4.1. The systems described in several studies are not described as DSS, but essentially function in the very same way. They are, however, only described as risk assessment methods, indicating a general lack of consensus on the definition of such terminology.

5.2.1 Storm damage

Storm damage is a theme covering all forms of risks related to storms or heavy weather. The main consequence of concern is increasing wind speeds, causing wind damage in the form of uprooting, windthrow or other forms of abiotic damage. Other potential risks also related to storms are those caused by increased precipitation, which may, for example, cause potential flooding in low-lying areas. The potential of GIS-based risk assessment of wind damage was identified in a large portion of the studies, [S1, S4, S6, S7, S8, S13, S14, S16, S24, S25, S27, S28], while risks related to increased precipitation was only identified in study [S10].

5.2.1.1 Wind damage

The effects of high wind speeds on tree stands and forests have been studied well over the past few decades, but based on previous literature uncertainties still exist whether and how wind patterns are expected to change in the future. A general agreement, however, that wind damage in general is expected to increase does exist. [S1] states that the need of decision support tools for handling wind damage risks is greater than other hazards in raw material production. While this statement is not echoed directly in other studies, the general need of proper risk assessment is mentioned in most identified studies. [S7] also states that high wind speeds are one of the main causes of damage in forests.

The methods of assessing wind damage risks are relatively similar, with most studies using wind damage models combined with spatial data and GIS computations. Forest inventory data are also needed for specific information about tree species in the studied area. While the wind damage models may vary and are often configured to fit the purpose of the study, the most commonly mentioned models are HWIND or GALES, mentioned by multiple studies [S7, S8, S13]. Some studies, [S1, S6, S25, S27, S28], either use these models directly or in the form of a modified version of the models.

[S27] use the HWIND model with GIS to predict wind damage on certain species of trees under critical wind speeds representing storms. [S28] is largely based on the same method and utilizes the model to predict the threshold wind speeds, lasting 10 minutes, at which trees will be uprooted. The study also states that differences in direction relative to the forest (up- or downwind) may also be crucial. [S1] uses a model modified version of HWIND, "WINDA", for calculating the stand-wise probabilities of wind damage, uprooting and breakage of trees. The models were all considered to predict wind damage well. [S1] notes that any errors may be decreased with proper forest inventory data. [S25] also partially utilizes the HWIND model, but its use is not thoroughly specified in the study. The study essentially also uses GIS-based spatial data coupled with the wind model, in a similar fashion to studies [S27, S28, S1]. While the results were promising, [S25] states that more information would be needed on the differences in individual stands for more accurate predictions, essentially echoing the need of higher quality forest inventory data.

[S6] uses the GALES model (referred to as ForestGALES in the study) for quantitative risk estimation. By integrating the model with spatial data and GIS functionalities, it may be used to calculate wind damage risks in isolation. The study also notes that by assessing isolated risks, it could lead to other potential risks that are not accounted for as a consequence of trying to mitigate the risk, for example, changing the density of stands to reduce wind damage may leave the trees exposed to other forms of abiotic and biotic damage.

Studies [S7, S8, S13, S15, S16, S24] utilize other methods mainly based on statistical models, but the methods are generally fairly similar to one another. [S7] evaluates limb loss risk under high winds using the model "TREEFALL", utilizing a PostgreSQL, "PostGIS", database as spatial data storage. The study notes that the wind damage risk may also affect surrounding areas due to limb loss from trees. [S15] utilizes GIS-based data used to calculate damage risk on stand level, with a wind damage classification "WINDARC". The study utilizes wind directions combined with wind speeds for its calculations and emphasize that damage is also based on soil risk, since it can affect how resistant trees are to uprooting and breakage. This statement confirms the mentions of soil state in previous literature, being a key factor in wind damage. Soil state may therefore also be considered in other studies, but not specifically mentioned since it may already be included in GIS datasets. [S16] focuses on assessing edge exposure resulting in windthrow damage. Several studies note the increased damage risk near forest edges, but [S24] contradicts this statement, claiming that while open stand edges increase risk of damage, the risk is not as high as earlier research has stated.

The statistical models used in the studies are often based on logistic regression models, but [S24] mentions that more advanced ML methods may outperform simpler logistic models in some situations. [S8] utilizes an ANN approach and presents similar results. The study also states that ML, or training-algorithms are promising approaches, but with some uncertainties in their results. Regardless of statistical approach, if the input data are based on spatial datapoints and attributes, the model may interact with any GIS-functions with relative ease. [S24] assessed different statistical models and did not find more improved results in complex models compared to a generalized linear model.

The approach of [S4] in its entirety may not be fully adoptable in Finnish forests, but it does offer an alternative method of assessing the risks as well as consequences of wind damage. The study assesses timber loss from hurricanes in North America. The circumstances naturally exceed those experienced in Northern Europe, but the method is still somewhat valid since it relies on hurricane wind risk information. The approach is highly reliant on GIS and forest inventory data to grasp forest characteristics. The assessed damage of the risk is quantified as timber volume loss, essentially risk of economic loss in case of wind damage. As mentioned by [S28], however, Finnish wind speeds have never exceeded 40 m/s in speeds (except for gusts), and storms usually range between 14 to 27 m/s. The alternative of expressing output is, however, still relevant and implies GIS may assist with the assessment of economic impact as well.

Most studies embrace the concept of critical wind speeds, often defined as the wind speeds required to break, uproot trees, or cause windthrow. A relatively clear consensus can be found implying it being a key indicator when making predictions. The general effectiveness of GIS-based wind damage risk assessment is also implied it be good. While some methods may experience slight errors, there seem to be overall accurate results when predicting potential future events. The output is often easily configured when using GIS compatible data, by simply changing the input data. [S24], however, notes that uncertainties appear when using GIS-data from multiple sources, meaning data from the same source is important for the predictions. Several studies assess or discuss the quality of the data and their effect on the results. Some studies also state that higher quality data will be needed for more accurate predictions.

5.2.1.2 Intense rainfall and flood

[S10] researches a method of assessing the risk of flooding in forests in Crete, Greece due to geographical features such as slope, elevation in combination with intense rainfall scenarios. While this risk is not considered as crucial in Finnish forests, flooding is still a potential issue in low-lying forest areas. Since increased precipitation during certain times of the year is considered to be a factor that may become more common in the future, the study does offer a way of assessing this risk with the help of GIS. The method mentioned in the study is based on mapping geographical features that may affect how water is cumulated as well as rainfall intensity and combining these factors into a map, visualizing areas where flooding may become an issue. The study validates the results using historical data, which was in good agreement with the initial predictions. Assessing future risk scenarios may therefore be possible by keeping the geographical data constant, but increasing the rain intensity, simulation the effects of caused by climate change.

5.2.2 Pests and invasive species

A total of six studies, [S5, S9, S12, S18, S21, S26], were identified assessing pest risks related to forests, and two studies, [S11, S23], discussing other sorts of pests but utilizing methods relevant for the same topic. While some of the studies are directly related to the same form of risks identified in Finnish forests, others use methods that are adaptable to a variety of different forms and species of pests. [S5] states that climate change is expected to increase the outbreak frequency and intensity of forest insects in the future. Similar statements are echoed by [S12, S21], with [S12] mentioning that bark beetle outbreaks have increased in both Europe and North America and is likely to continue due to climate change. Concern from [S23] about invasive species in general being increasingly introduced to new locations due to the changing climate is also expressed.

These statements confirm statements in previous literature on the topic, as mentioned in section 2.1.1.

Studies [S5, S9, S12, S18, S21] research GIS-based risk assessment concerning beetles such as the North American Mountain pine beetle and European spruce bark beetle. [S5] discusses the risk of North American Mountain pine beetle spreading in Canadian boreal forests. The study uses a three-step method, beginning with assessing the likelihood of the pest being introduced to a new ecosystem and how such an introduction would take place, followed by the use of forest inventory data and GIS to estimate the area and volume of timber at risk, and lastly produces quantitative probability outputs and maps evaluating the impact. [S9] uses similar methods when assessing risks related to the European spruce bark beetle in Polish forests. The study focuses on habitat and stand factors affecting the severity of outbreaks in spruce, using GIS to map the dynamics of stand mortality, and identifying characteristics of hotspots of infestations and initiation points for outbreaks.

[S12] also researching the European spruce bark beetle in Sweden, maps the location of infestation spots using GPS, and proceeds in a similar fashion to [S9] by predicting the risk of future infestation spots, and using GIS functions to map the graphical results. The study utilizes RS data such as satellite imagery and aerial survey to assess forest characteristics. The study also establishes that the risk is affected by the variety of tree species in stands and emphasizes how the diversity may affects the infestation. [S18] analyzes the same species of pest, and the stand characteristics influencing the probability of damage by predisposition assessment, essentially drawing similar conclusions to other studies. [S21] also models the probability and intensity of bark beetle risks on a stand-level, with the use of regression models, combined with climate data and GIS software. Regression models, such as boosted regression trees and other statistical methods using spatial data were commonly used in all studies with good results.

The consensus on the usefulness of GIS-based risk assessment of beetle pests is positive, with no real contradicting statements in the identified studies. Another aspect commonly mentioned is the need for knowledge of the geographical location, as well as information not necessarily in the form of ex. Spatial data, like characteristics of pests and their behavior. This is implied to be crucial in accurate pest risk assessment, meaning decision-making based on the results may require more expertise of the risk in question than what is mentioned in, for example, wind risk studies.

Studies [S26, S23] take different approaches, by scaling the risk to larger areas. [S26] also researches a beetle pest, the North American emerald ash borer, but focuses on mapping the effect of preemptive quarantine efforts of the risk. The study relies on GIS to map larger areas than just stand-scale. It also compares the estimated benefit of quarantining with the cost of preemptive quarantine. [S23] studies invasive weed species, but discusses other forms of pests as well, which may be introduced and affect local ecosystems. The study combines distribution models with GIS to estimate distribution of species due to climate change. Since the method predicts climatic suitability, the results are answers to questions regarding "whether" or "when" the climate in a particular location is hospitable for new species of pests.

[S5] notes that the estimation of vulnerability of forests is reliant both on the understanding of individual trees, as well as characteristics on stand level, meaning while GIS and spatial data are important for the evaluation, it may be difficult to obtain specific data of the expected quality needed for high accuracy. [S5] also mentions the uncertainties appearing in existing information about pests despite it being a looming risk for the forest sector. Information for risk assessment can be costly, and study [S21] adds that the overall management costs are expected to increase in the future. It also mentions that unplanned management activities may disturb data input.

[S11] also discusses how GIS-based risk assessment in the form of spatial mapping may help identify the introduction of new pests in areas that may become hospitable due to climate change. The content of this study is discussed further in section 5.4.1.

While some studies imply that their methods should prove possible in cases of different species of pests, no clear proof of this assumption can be found, which can be further emphasized by statements regarding the need of information about the characteristics of the pests, as previously noted. A consensus on GIS-based risk assessment for mitigating bark beetle infestations does, however, exist in the identified literature.

5.2.3 Forest fire

Five of the studies identified, [S2, S3, S14, S17, S20], discuss forest fire risk assessment utilizing GIS. Forest fire or as some studies referred to it as, wildfire risk assessment, includes estimating the probability of fire that may be visualized as, for example, risk hotspots, as well as risks associated with economic damage.

[S2] evaluates the risk of forest fire occurrence based on attributes such as moisture content of soil, atmospheric stability, and wind speed as data input in the spatial data raster cells, meaning the data input of the method is easily compatible with GIS modelling. The study utilizes forest fuel distribution and weather patterns, which is a common occurrence in the other identified studies, [S3, S14, S17, S20] as well. Fuel mapping, i.e., vegetation, combined with wind data is commonly the foundation when evaluating potential spread of forest fires.

[S2] notes that GIS tools are capable of assisting response planning in case of wildfires as well, something that is echoed in other studies. Another possibility is estimating the cost of destruction due to fire, which can be calculated based on fire simulations. As previously mentioned in section 5.1.2, the study states that the final output of these evaluations should be based on probabilities instead of deterministic predictions.

[S3] mentions there being three major quantitative elements of wildfire risk assessment:

- Estimation of the probability of fire and intensity through landscape scale fire simulation modeling
- Spatial identification of the resources that may experience value change due to fire
- Estimation of resource value change in response to fire intensity level

The study discusses three different models of forest fire risk assessment, which all differ in scale, type of fire, and purpose, but a general agreement that forest fire risk assessment with GIS capabilities is both effective and viable can be found. Based on the risk assessment systems [S20] reviews, those incorporating GIS technologies are often able to use weather related inputs as well as mapping abilities in aiding the analysis of fire behavior, probability and fire spread. [S17] also reviews multiple different systems for assessing forest fires using geospatial technologies. The study notes that GIS and RS techniques are becoming increasingly more beneficial and essential in risk assessment, since they are capable of not only assisting in making predictions, but also visually project the results, and map out the risks.

In contrast to other studies, [S14] researches the wildland–urban interface, where forests meet urban areas. The potential risks in these areas are affected by each other, but the methods and data are fairly similar to other studies. An exception that can be found, which is that when assessing forest fire risks in these areas, the identifying critical variables that can be used to determine the risk of fire occurring may differ, since one must consider urban factors as well. [S14] also states that "modeling wildfire potential via GIS is a form of prescriptive analysis that relies on the ability of GIS to direct the analytical manipulation of data" (Lein & Stump, 2009, Introduction section, para. 3), and that "data manipulation patterns emerge connecting the problem to a 'realization' that provides a solution. "(Lein & Stump, 2009, Verification and validation section, para. 1).

Commonly mentioned in the identified studies regarding cause of fires, is that forest fires can be triggered by both external (human interaction) and internal (natural) sources, meaning risk assessment often includes both probabilities, risks of destruction, and response analysis in cases that the risk cannot be predicted. [S17] does, however, state that man-made or industrial risks are in fact more predictable than natural ones.

Forest fire risk assessment relying on GIS is generally an established practice. [S17] also mentions that the creation of a GIS database is essential for contemporary practice. Few contradicting statements can be found, but the methods used are often related to very specific purposes and comparisons are therefore harder to make. In fire management, the possibility of mapping becomes an essential asset that GIS can offer. [S3] does, however, note that some difficulties, such as that the increased risks due to climate change may not always be considered in the methods, and that the relevant information needed is defined on local scales, making large scale assessments difficult.

5.2.4 Diseases and fungi

Only two studies identified, [S19, S22], directly discuss GIS-based risk assessment of different forms of pests other than insects in forests.

[S19] highlights the threat that non-indigenous pathogens such as fungi or bacteria pose to forests and utilizes a method relying on quantifying the propagation velocity of infections for this purpose. In the method of the study, GIS is essentially used to map and create boundaries using coordinates and identify the characteristics of the area studied. The study ran simulations checking for the infections spread and behavior in different quantifications of tree density.

[S19] notes that the objective of this form of risk assessment is to analyze the spread of a forest disease and predict the occurrence of it, in order to create countermeasures in case of an outbreak. The study also mentions the problem of factors responsible for forest disease being extremely complex and unpredictable, making accurate risk assessment difficult. The study does, however, mention the necessity of long-term RS data, as well as high quality GIS forest datasets as a factor that may improve the accuracy of these predictions.

[S22] uses a library, PoPS (Pest or Pathogen Spread), capable of simulating pest and pathogen spread with the use of its R and GIS interface. While the study focuses on simulation steering for adaptive management, the scenario studied was an incidence of a forest disease, known as Sudden Oak Death (SOD). The study gives some insight into the capabilities of GIS-based risk assessment, with the possibilities of estimating the effects of management of the disease, and predicting outcome based on treatment. This is also mentioned by [S19], noting that risk assessment may assist in countering the onset and progression of diseases. This, however, is the only clear consensus in the studies analyzed due to the lack of identified literature.

5.2.5 Indirect and combined risks

Several mentions of combined or indirect risks were identified in the studies, as well as situations where a method is partially reliant on the same data and results from the assessment of another risk. While this assumption is not directly brought up as a theme in the studies, the results of the studies as well as evidence presented in literature mentioned by the studies does support it. Studies [S2, S15, S18, S24] all mention either variables or effects that can be connected to other risks than the ones focused on in their respective studies.

[S2] emphasizes the effect that wind patterns and wind speed intensity have on forest fires. Wind is very much a contributing factor to both the spread and behavior of fire, meaning forest fire risk assessment also requires some magnitude of wind risk assessment.

[S18] reveals that in the results of the study, an increased frequency of forest pest infestation in stands affected by storm damage was found, and that it may in fact function as a trigger of bark beetle mass outbreaks. This statement is echoed by [S24], mentioning that "wind disturbances are strongly linked to other processes of the forest and, therefore, should be considered in larger context." (Suvanto et al., 2019, section 4.4., para. 5). The study also states that wind damage strongly correlates to pest outbreaks as well as fungal disease, and this occurrence is becoming more commonplace due to the changing climate. Wind damage itself may also be based on other risks. [S15] mentions that tree decay in the form of fungi may increase the chances of damage from increased wind speeds over large areas.

While no substantial amount of evidence of these phenomena can be found in the identified studies due to their focus mainly being on specific risk assessment, the arguments can be seen echoed in external literature cited by the studies. Despite this occurrence, no mention exists of systems capable of assessing multiple risks or taking the results of other risks into account.

5.3 Can GIS-based risk assessment help forest managers plan for the future? (RQ3)

The third research question was included to identify studies that discuss how GIS-based risk assessment methods may help forest managers plan for the future. Three themes were identified, the first one being spatial aid and plantation planning, mainly referring to how to identify if a certain location is suited for planting new trees and any indications of the optimal layout of stands. The second theme addresses the question regarding economic planning, for example, quantifying timber volume at risk. The third theme is related to questions regarding species distribution and if species that may fare better or worse under future scenarios can be identified.

5.3.1 Forest planting location and spatial aid

The studies that research the use of GIS-based risk assessment of wind damage, are quite clear about the differences in risk depending on areas and locations. The use of GIS to map and visually present the output over susceptible zones aid forest managers in terms of planning new locations to plant forest.

Since the variables describing the location and overall characteristics of the area are not likely to change rapidly, the estimates that are made through risk assessment today should hold true in the future, with the possible exception of climate data. The critical wind speed factor offers an overview of which wind speeds in a certain area may cause damage to a particular species, or combination of species, under different stand densities. Wind damage risk assessment also assist with the issue of exposed stand edges, allowing for measures to plan against this risk. [S24] notes that this sort of risk assessment may help analyze disturbance probability over large areas. [S1] also mentions that it may help benefit spatial harvest planning, since GIS-based risk assessment does offer indication of when factors such as age and height as well as the location of the tree may be susceptible for wind damage and, therefore should be harvested.

[S19] highlight that stand density can affect how diseases spread within forests. The use of GIS-based tools can help plan for optimal stand density as well as help design the layout of the forest during planting to diminish the impact of disease spread. While disease spread may be accelerated due to high density stands, [S25] on the other hand, claims that lower density stands may leave the forests more susceptible to wind damage.

[S7] brings up another issue regarding planting locations, since under critical wind speeds, trees may cause windthrow or limb loss that can affect nearby infrastructure, such as roads or buildings. GIS-based risk assessment offers an excellent opportunity to assess these issues by providing mapping of both stands and infrastructure. These statements are also made by [S24], which further mentions the risk windthrown trees cause to powerline infrastructure. [S7] also notes the considerable potential of utilizing GIS-based risk assessment in this scenario for forestry since it may assess the risk posed by trees adjacent to utility and transport networks.

A similar approach in benefitting from this form of GIS-based analysis is addressed by [S14], which studied the problematic urban–wildland interface. The risk from wildfires may not only be contained to forests, but also risk affecting urban settlements nearby, which requires accurate forest planning and countermeasures to avoid these risks. The climate change’s potential to increase the frequency of forest fires due to drought, may very well pose an increased future threat to urban centers near both managed and unmanaged forests.

[S10] mentions that GIS-based risk assessment is quite useful in identifying areas which are more at risk of flooding due to increased rain intensity and storms. This also offers some possibilities to prepare identified areas for the potential risk. As previously mentioned in section 5.2.1.2, the study analyzed and mapped the different factors that may contribute to a potential flood risk and combined the maps into one that visualized areas where risk is more common, identifying areas where flood risk is more likely to occur. Due to the uncertainties of future flood risks as mentioned in section 2.1.1, the actual relevance, and benefits of this method for Finnish forests may be questioned.

5.3.2 Timber volume and economic loss

A few studies identify resource planning in the form of timber volume loss and economic loss as the results of GIS-based risk assessment.

[S4] studying the effect of storm damage due to hurricanes, mentions that risk assessment methods utilizing GIS and forest inventory data are also capable of estimating the risk of timber loss volume as well as carbon storage loss in tree stands, meaning both economic and environmental consequences. The study uses, as previously mentioned, a decision-tree analysis and an InVEST model, “a GIS spatially explicit tool used for quantifying and valuing ecosystem services based on ecological production functions and economic valuation methods” (Nelson et al., 2009; Tallis et al., 2011, as cited in Delphin et al., 2013, section 2.2.3). The method itself does not differ significantly from other methods designed for wind damage risk assessment, which would indicate that other solutions should be able to provide similar outputs. [S24] verify this assumption by noting that through mapping of wind risks combined with more specific spatial information, such as tree volumes, it should be possible to assess economic risks due to wind disturbances.

[S5] focusing on assessing the risks posed by invasive forest pests, made similar statements: “data from forest inventory and GIS systems can be used to estimate the area and timber volumes at risk and to produce maps to help decision makers in evaluating the potential impacts.” (Fuentealba et al., 2013, section 2.2). This would indicate that information of economic risk would be obtainable when assessing different kinds of risk, as long as enough quality forest inventory data are obtained and combined with features of GIS.

5.3.3 Species planning

GIS-based risk assessment may assist with identifying how different species of trees experience different levels of risks. The information may prove useful for planning efforts when deciding which trees to plant. Due to the long time period that it takes for trees to fully grow, obtaining information about which species are more resistant to future risks may greatly reduce future management costs.

[S12, S21] found indications of the difference in tree vulnerability though pest risk assessment. [S12] performed large scale risk mapping of bark beetle outbreaks and mentions that spruce volumes were identified as the most important variable when predicting outbreaks. Both the result of [S12] as well as earlier research referenced in the study, found a positive relationship between the risk of tree mortality by European spruce bark beetles and proportion of spruce trees in the area. The study also mentions that the presence of birch in spruce stands did not necessarily lower this risk as commonly hypothesized, but it did affect the results depending on the volume. [S21] also mentions that the probability of bark beetle risk is higher in old, highly stocked stands dominated by Norway spruce. The study does, however, state that the area studied includes locations that are highly elevated, which are more populated by spruce and more strongly affected by wind damage, which may lead to pests due to the abundance of dead wood. Despite this fact, the study does still mention that decreasing the share of spruce in stands may be a viable pest management solution.

[S27, S24] mention similar results through wind damage risk assessment. The area studied by [S27] included Norway spruce, Scots pine as well as birch and broad-leaved stands. Through the method of assessing and mapping critical wind speeds for a certain stand, the study notes that different species are more resistant than others. Birch, for example, can withstand higher wind speeds than Scots pine and Norway spruce. These results may, however, differ depending on which species are located near stand edges where they are more susceptible to wind damage, as well as the time of the year, since broad-leaved trees such as birch are leafless during later autumn and winter which may impact the critical wind speeds. [S24] also claims Norway spruce stands to be more susceptible to wind damage compared to Scots Pine, which may be due to lower height-to-diameter ratio.

While [S10] also mentions species planning in the form of identifying areas susceptible to flooding, which would allow for planting of trees that are more tolerant to those effect, it may not necessarily be applicable to Finnish forests, due to the lack of variation in tree species available, as well as lack of species exceptionally resistant to repeated exposure to flooding and constant soil moisture.

5.4 Does GIS-based risk assessment offer long- or short-term solutions for forest managers? (RQ4)

Ten studies, [S9, S10, S11, S12, S19, S21, S23, S24, S25, S27], discussing how GIS-based risk assessment is benefitting forest managers on a long-term scale or as an early warning indicator were identified, and four studies, [S2, S17, S21, S26], discussing short-term risk detection or handling as well as response management to risks in case of occurrence. These themes are somewhat tied to the kind of risk observed and, therefore, not necessarily explicitly stated as a long- or short-term solution. This section sorts these themes into categories based on similarity to the timescale of assistance their methods provide forest managers.

5.4.1 Global long-term risk modelling

The methods used by studies [S11, S23] are far more globally scaled and address risks on a longer timescale than what is identified in other studies. [S11] attempts to predict the introduction of invasive pest species in new areas of the world due to climate change. This method would allow us to indicate risks of newly introduced pests depending on our current knowledge of climate change and may be used to show indications of when the climate is hospitable for a certain pest. This method, however, is far larger in scale than what an individual forest manager would find useful on a daily basis but does provide some indications of future scenarios. Study [S23] offers a similar solution, also addressing the issue on the global scale, with the argument that both pests and invasive weed species can be analyzed in a method of combining GIS and climate data. Since both studies are outside the area of direct forest risks, the studies lack information on how to actually mitigate these risks, but they do offer a solution on how to identify the potential risk of invasive species being introduced and a prediction on when the climate is hospitable for a permanent population.

5.4.2 Local long-term risk modelling

Studies included in this section address long-term risk modelling but on a smaller scale compared to the previous section.

[S10] utilizes GIS mapping feature in flood risk assessment to offer a more locally scaled solution of long-term planning, since the geographical features of an area do not change over the course of time, which allows for planning long before a risk occurs. This sort of risk modelling may help address the risk of flooding in low elevation forests, for example, near lakes. The study also takes into account the effects of rain intensity and how geographical features in an area affect the potential risks.

Through the method used by [S9] of creating a hot-spot analysis, arises the possibilities of assessing and mapping the risk of initiation points for pest outbreaks in forests before they occur. The characteristics and key-factors of such an outbreak can be analyzed based on historical data of previous occurrences. [S12] presents similar results by identifying important variables predicting the risk of infestation spots, and mentions that by providing risk maps, it may allow forest managers to focus on mitigating risks in stands at risk. [S21] also provides similar statements, claiming that GIS-based pest risk assessment can help long-term planning and mitigating the risks before they occur.

Similar benefits can be found in wind risk assessment studies. [S25] reports that by combining the "stand characteristics such as tree height, stem taper and stand density" (Talkkari et al., 2000, section 2.4, para. 2) and information about the local area, i.e., local wind extremes and topology, it provides good indication of areas at risk, allowing forest managers to focus on mitigating risks in the identified stands. [S27] also mentions that through their wind risk assessment method, it would be possible to assist forest managers to evaluate the effects of management, for example, aggregating the cuttings to mitigate long-term risks near forest edges. The method used by [S24] of testing which forest characteristics increase probabilities for wind damage, also allows forest management effort to focus more heavily on these factors to prevent future damage. Some examples of the variables identified are the effects of thinning and how the height affects damage probability. A fairly good consensus can be identified on wind damage risk assessments usefulness for long-term effort of forest maintenance, due to the benefits it provides both location and stand based factors as well as the particular variables that may affect individual trees.

While [S19] does discuss the possibility of predicting early warning signals for plant disease outbreaks, the study does not fully offer enough information of identifying an actual outbreak in advance. The study does, however, offer a method to identify areas where an occurrence of a tree disease would thrive, by taking into account factors that contribute to the survival and spread of disease, such as stand density.

While the long-term possibilities are not always thoroughly discussed in most of the studies identified, the predictions made through most GIS-based risk assessment methods generally prove beneficial for the future. How the information would affect decisions made within forest management is, however, not always mentioned, with the exception of wind damage risk studies where authors are more in agreement over the long-term benefits it may offer from a management standpoint.

5.4.3 Short-term detection of risk

Since [S17] researches multiple methods of wildfire risk assessment, the results and benefits differ from one another. The general benefits of the methods mentioned are, however, expressed as short-term risk detection in regard to the timescale. This includes identifying key variables that tend to be characteristic to forest fires moments before the fire occurs, for example, a certain level of forest moisture a week before wildfire occurrences. A certain level of planning is, however, involved in identifying the areas where fires are more likely to occur, but more as observations than as predictions. While the use of risk mapping to analyze areas where forest fires are more likely to occur and the identification of variables that are connected to potential forest fires are made in advance, and may, therefore, offer some long-term strategies, forest fire risk assessment, as [S17] notes, is reliant on RS data or in some cases even simple observation towers to monitor areas, since long-term predictions are generally considered hard to make. GIS-based risk assessment offers more effective short-term solutions in the form of identification and response to occurrence within wildfire risk assessment.

Similar statements are made by [S21] when detecting risk of pest outbreaks. The study also mentions the use of RS techniques for monitoring and observing areas at risk. The study states that in cases of bark beetle disturbances, options that forest management may use to mitigate the risk short-term exist, but the problem is that they are not necessarily effective short-term solutions and may therefore be irrelevant, since it may take a significant amount of time before any of these adaptative measures become effective. The benefits of detection do, however, provide the possibility of response planning.

5.4.4 Response planning

In addition to assessing the potential damage and occurrence of risks, studies [S2, S26] also discuss the use of GIS-based risk assessment when planning response operations. While risk response planning is its own field of practice, the information from these studies is beneficial in identifying the link between risk assessment and the actions taken in case of a realization of the risk.

[S2] discusses the potential of analyzing access time for vehicles in the scenario of forest fires concurrently to forest fire risk assessment. Given the information available in GIS, in the form of infrastructure, terrain, and types of vegetation, it would be possible to make preparations in case of a risk being realized. This ties risk management into the broader concept of risk governance, in a similar fashion as mentioned by [S20] in section 5.1.4, and as [S2] also notes, that being able to simulate fire spread can be useful for the response planning effort.

[S26] mentions the use of GIS-based risk assessment to calculate effective preventive management in order to slow the spread of pest outbreaks by preemptive quarantine in case little is known about the pest. This method being especially useful in case of invasive species. Response planning in these scenarios may also offer some notion of economic value at risk if combined with accurate forest inventory data, and the risks may be compared to the cost of response, as discussed by both [S2] and [S26].

6 Discussion

The results of the review provide an overview of which of the risks in Finnish forests that are either caused or amplified by climate change can be assessed by utilizing GIS, as well as how GIS-based risk assessment functions when integrated into DSS. Some other aspects touched upon is how GIS are utilized in different methods, what functions they provide managers in terms of planning, if they offer short- or long-term solutions, and their use within forest management and decision-making. This chapter will discuss the synthesis of the results and their relevance to the research questions and to previous literature.

6.1 Benefits of GIS-based risk assessment

Based on the results regarding which risks GIS can help assess, a wide variety of different outcomes depending on the risk in question were identified. More clearly established practices can be found within wildfire and wind damage risk assessment. The utilization of GIS in these areas is well researched, and the purpose of the studies also reflect the same problems that are identified in previous literature as discussed in section 2.1.1.

GIS and forest inventory data are valuable assets for assessing wind damage risk since these components combined with either statistical methods or simulation models are quite capable of outputting accurate probabilities and predictions without any external components and information being required.

An aspect worth noting is that systems using statistical methods are seemingly functioning well with little need for more complex models, meaning GIS-based risk assessment is largely based on the quality of data, as was also noted by the identified studies. While some uncertainties, such as how wind patterns will change in the future and which areas are more at risk, can be identified, the overall consensus on the actual methods used for wind risk assessment is more robust. For management aspects and decision-making, GIS-based risk assessment does offer long-term solutions on a local stand scale through calculations of critical wind speeds and how thinning may affect damage probability. There may, however, be some uncertainties on how efficient it may prove in the terms of spatial planning. Based on previous literature and the statements made in the primary studies, the uncertainty of wind patterns may cause somewhat incorrect results that could potentially affect planning efforts and is, therefore, in need of further research if these methods are to be proven reliable.

Forest fire or wildfire risk assessment is also heavily reliant on GIS and forest inventory data, especially for vegetation in the form of fuel mapping, since they offer a good indication of the magnitude of fires that may occur and may help assess the potential spread. Weather data similar to what may be used for certain wind risk assessment methods are also important, meaning multiple data that are used in both wind damage and forest fire risk assessment, mainly geospatial data, climate data, and forest inventory data are being used. The use of GIS-based risk assessment for wildfires is seemingly an already somewhat established practice, and due to the effectiveness of the methods for shorter timescales, they would likely offer the same benefits in a warmer climate. Since the benefits mainly indicate short-term detection of risks, it may not provide forest managers with as many benefits for long-term planning. Effort for mitigating the risks of wildfires can, however, be made through response planning. Based on the results of the review, one can assume that GIS-based forest fire risk assessment does not necessarily offer ways of avoiding the risks but does help reduce the damage from an occurrence. This argument is backed up by the fact that forest fires are not only started by natural means, but also by human interaction. In these scenarios, having a well-maintained GIS-database is essential for both assessing the spread, severity and the response.

The results on the use of GIS in pest risk assessment, did include a fair amount of evidence on the existence of beneficial methods. GIS especially prove useful when assessing beetle infestation on a local stand scale due to the ability of finding forest characteristics leading to outbreaks, as well as those affecting the severity of outbreaks. The methods do, however, require plenty of external information on the pest in general. Based on the results one can also note that GIS prove practical for larger scale assessment of pests, for example, to identify when areas have become suitable for certain species. These methods, however, are hardly useful for forest managers in daily operations and does not necessarily offer any added value, except for some indications of potential upcoming threats that may be considered in long-term planning. Another problem with these methods is that they do not rely on the same form of local data as other forms of risk assessment.

As mentioned in previous research, it will be important to identify tree species that have a higher chance of survival in the future. The primary studies, [S12, S21], note the indications that some species, in this case spruce trees, are considered to be more susceptible to bark-beetle outbreaks than others, as was identified through the risk assessment methods used in the studies. Wind damage studies, [S27, S24], offer a similar conclusion, that mainly spruce trees happen to be more susceptible to wind damage in comparison to other species. The problem in these studies, however, is that there were a few factors that may impact this assumption as, for example, [S21] mentioning that the area studied had higher elevation, meaning that the causality may be questioned. Nevertheless, one can still conclude that GIS-based risk assessment may offer some indications of the difference in future vulnerability of tree species.

Pathogen and disease risk also offered some promising results when utilizing GIS, mainly as by mapping and identifying characteristics of forest areas at risk. A noticeable problem, however, is introduced when comparing management decisions based on forest disease risk assessment with the results based on other risks. As noted by [S19], the stand density plays a role in the spread of disease. The solution to mitigate the risk of disease spreading would, therefore, be to lower the stand density and planting trees further apart, but by lowering the density, it would contradict the potential solution to mitigating wind damage. As mentioned by [S25], lower density may actually increase the risk of wind damage. These contradicting statements are still somewhat understandable, since the studies are focusing on their own field of research, but it does also mean that while the results of GIS-based risk assessment are promising, they may not individually provide a reliable solution for forest managers.

6.2. Conflicting statements

A common problem identified in the primary studies is that a risk assessment or risk management tools are sometimes referred to as a form of decision support tools. While these tools may in some cases be designed as decision support tools, as also mentioned in previous literature (see section 2.3.3), this does introduce some of the potential problems mentioned in the previous section. Despite the commonly indistinguishable use of risk assessment and decision-making in terminology, flaws are exposed when including multiple risks, which justifies the use of some form of separate decision support system that may account for these conflicting statements. However, no indication of a system with these capabilities was identified.

While one can conclude that GIS-based risk assessment does offer beneficial solutions to forest managers in case of climate changes, decision-making may require additional tools. This argument is backed up the fact that several risks are actually affecting the probabilities of other risks. For example, based on previous research and the literature in the primary studies, wind damage is considered one of the most threatening factors for timber loss. High density tree stands may protect against wind damage but may also lead to the potential spread of disease, which in turn may lead to root damage and weaken trees' resistance to high wind speeds, once again resulting in an increased risk of wind damage. Low density stands on the other hand. may directly lead to wind damage which in turn may, for example, trigger pest outbreaks. Calculating or simulating these scenarios require far more advanced tools that are capable of both outputting predictions based on individual risk probabilities and weighing these individual factors with the results from other risk assessments. Beside the direct risks, another aspect that may also have to be accounted for is the potential timber volume at risk. The benefit of using GIS-based solutions for individual risks, however, is that they do offer some form of foundation, since many methods use similar data which would help weighing and comparing the risks. It would also be possible to offer some alternative solutions such as assistance in response planning in case of low probability occurrences.

6.3 DSS role in risk assessment

As previously mentioned, some studies refer to risk management interchangeably with decision management. Since risk management is essentially a form of decision-making support, the issue in terminology is somewhat understandable and may be more common in certain disciplines that focus on narrowing down risks to only one aspect, instead of observing multiple scenarios. The choice of not including DSS in every search string of the initial query for primary studies proved beneficial for this exact reason.

DSS can both be perceived as simplified risk assessment tools for people without the technical knowledge and expertise of the risk themselves, or as systems capable of superseding the output of risk assessment models, or simply as a risk management system with a particular kind of output. The primary studies, however, often identify them by the first definition. However, with this definition several of the studies that did not specifically mention DSS, directly referenced either systems or methods that should essentially be considered DSS. This may once again be a case of differences in disciplines. DSS in the context of risk assessment for forest management can almost be considered management tools that are partially irrelevant from the point of view of an expert, or someone only focusing on a particular risk, but this should not be the case. The discrepancies in definition identified in the studies may also be a question about the time of publishing. The idea of separating decision-making tools from risk assessment models may not have been a practice in earlier years but appeared later. For example, [S6] describes ForestGALES, which is actually a decision support system, the one originally identified in previous literature as mentioned in section 2.3.3 but combined with GIS. The system, however, is not identified as a decision support system in the study. This confusion over definitions may, therefore, have affected the results and the primary studies identified for the review, and does require further research on how these terms are used in forest management. Regardless of the definition, however, one can still claim as highlighted in the previous section, that forest management would still require DSS that can supersede the output of individual risk assessment models and are in some way capable of handling multiple risk assessment models at once. GIS-based DSS would also offer several benefits in terms of compatibility due to the matching data foundation.

In study [S6], published during 2000, the authors mention the hope that systems developed in the future will be capable of assessing multiple risks. Several of the risks mentioned in the study are highly relevant to Finnish forests. Study [S20] also mentions that wildfire management and other forms of forest management have previously been carried out independently from each other, and that efforts are being made to help integrate these functions further. If this is the case with other forms of risk assessment, one can assume that there may not be enough research based on functioning systems to achieve this implementation. Since [S20] was published as recent as in 2015, one would expect improvements in the near future if research on the topic continues. No decision support system with these capabilities, however, was identified in this study. If the target group of users is as large as right now, considering the number of people owning forest in Finland requiring forest management services, not to mention elsewhere in the world, one would assume there would be some incentive to develop a unified system capable of accounting for all risk aspects integrated into one decision support tool.

Creating and maintaining GIS databases is also considered important, and are mentioned to be valuable assets, whether private or public, to assist DSS. Considering the advancement made in methods of collecting quality data, such as through RS, risk calculations are expected to become more and more accurate. As identified in previous literature, RS methods are becoming both more effective and economically viable, offering the collecting of more accurate forest inventory data as well as other spatial attributes. The data collected through these methods can cover a large number of different sorts of risk assessments. Improved forest inventory data may also increase the knowledge of economic value at risk. Several of the primary studies still relied on data often available via external parties in the form of databases and data libraries, implying that the party designing the DSS may not necessarily be worried about the data or information deficiency, but low quality or quantity of data would make the system obsolete, since the entirety of the system from top to bottom (identifying a risk, assessing the risk, and outputting probabilities and evaluations) is relying on these data. This further justifies the recommendation of creating and improving internal GIS databases.

Possible issues may occur due to the number of disciplines involved in the process of creating DSS for forest management. The primary studies were conducted in a multitude of different academic areas, ranging from forest sciences, environmental engineering to information technology (IT) and studies in AI. Risk assessment systems created based on the knowledge of forest researchers may not necessarily be difficult to create on a technical level, but other factors such as implementing the correct statistical methods, analyzing the optimal datasets, or simply creating a user-friendly interface may require cooperation with other areas of research in order for the system to benefit the average forest manager. Since even the primary studies had discrepancies in terminology that may be due to differences in disciplines, one can assume that any attempt to create a unified

DSS accounting for multiple risks would require much more interaction between disciplines.

6.4 Implementation

Implementing GIS-based risk assessment into DSS may already be considered somewhat complicated. As mentioned in section 5.1.4, however, persuading users to implement the DSS offers additional issues. Since this is seemingly the case with DSS dealing with individual risks, one can assume that more complex DSS would complicate matters even further.

The problem is partially caused by the expected user of the system. An expert or field manager may see the benefits of the systems, but if implemented for higher managerial positions, they would also need a deeper understanding of the systems, their use, the benefits, and the potential flaws and restrictions. As [S20] stated, the success of the systems is largely based on opinion leaders and their views. Another aspect mentioned in the primary studies, is that the effectiveness of the system is highly dependent on how much users dare to rely on the system. This also includes the monetary budget, as well as the time spent on obtaining information and implementing the proposed actions.

DSS are after all support systems, and as both identified in previous literature and primary studies, used to assist with decisions instead of making deterministic decisions, but they do add a multitude of options for governance. Implementing an interactive model would be easier for a large number of users to understand, and also reduce time spent learning. While study [S22] created a physical interactive map, the solution may not have to be as complex. An interactive software would already help users find more realism in their evaluations. GIS does provide these possibilities. Also being configured to output economic value at risk is seemingly possible in most models as long as forest inventory data are available. Economic value at risk does add incentive to implement these systems, despite risks not being imminent.

6.5 Missing research

Unfortunately, no indication of studies discussing GIS-based frost or snow damage risk assessment were found by using the search strings in this review. One would assume that GIS in the form of mapping would be useful for snow risks, just by combining it with climate data, yet no studies were identified. There may be several explanations for the lack of studies, but they are mostly considered speculations:

- The search strings may not have been compatible with studies on the subject
- There may not be enough research on the topic
- There may be other methods achieving the same objective
- Snow damage risks assessment may not benefit from GIS directly

Worth noting is the uncertainties of frost damage, since previous material, as mentioned in section 2.1.1, indicated that no snow cover during certain seasons may lead to frost damage of saplings, but [S24] also confirmed the benefits of frozen soil in its study by stating “When the soil is frozen, trees are well anchored to the ground and less vulnerable to windthrow and, therefore, forests located in areas with longer periods of soil frost are less likely to be damaged during winter storms” (Gregow et al., 2011; Laapas et al., 2019 as cited in Suvanto et al., 2019, section 4.2, para. 5). Frozen soil may, therefore, offer more benefits than drawbacks.

6.6 Validity analysis

Since the study was made by one researcher, highlighting the risk of bias in the study is important. Systematic literature reviews are under optimal scenarios conducted by multiple researchers to avoid these risks.

Threats to the validity of the study may have appeared due to the difficulty of narrowing down search terms for the purpose of the study. All of the terms yield a large number of studies, due to them being fairly ordinary word and phrases. This bias, however, is difficult to assess and mitigate, since as mentioned in section 6.3, several different disciplines are researching similar subjects, and terminology and definitions, therefore, tend to differ. For example, as previously mentioned, some DSS are sometimes being described as general risk assessment tools, when other studies separate the definition of the two. The same terminology used in this study may be defined in a wide variety of ways, and while different disciplines may partially be the reason for the difference in definition, the assumption is hardly certain. As mentioned in section 6.3, the definition of certain terminology may have changed with time, which may also have an influence on the outcome.

While the protocol itself was followed and the selection process conducted accurately, it does not prevent the impact of biases during selection. To mitigate this risk, the abstract of each study identified during the first phase was thoroughly screened regardless of whether the title of the study showed promise or not.

Another important factor to mention is that the studies were selected from publications within the scientific community. The tools and methods that were identified may already be partially implemented or configured further by corporations or private individuals. Since this study focused on GIS-based tools regardless of user, it may lower the bias somewhat, but noting that contemporary methods used by organizations may not necessarily be published in academic research is important.

6.7 Potential of further research

The review uncovers a few questions that would need to be subject to further research. The question of whether the implementation of multiple GIS-based risk assessment methods under one single decision support system is possible would require additional research. A factor to consider is that individual risk assessment methods may differ severely. As identified in previous research and confirmed in the studies, most methods are based on statistical or simulation models, and the output may vary as well, as some are more reliant on numerical probability and others on visualization. Other issues that need to be addressed are the importance of high-quality data, and information on how our understanding of a certain risk would impact the weight of such a risk in multiple risk DSS, since as witnessed in the results of this study, the success of the system is largely based on the views of the user. Within forest management, the expertise and true understanding of the severity of a risk may come from individuals, such as experts who are not necessarily responsible for the actual decisions. This may also vary depending on the end user.

More research into the contemporary practice of GIS-based risk assessment tools and how more advanced tools for decision-making would be implemented is also required. This essentially being a fairly complex question considering the differences in parties that may be involved, namely the private sector with private individuals, the industrial sector as well as the public sector. Also, the owner of a forest may not necessarily be the one making the actual decisions. The implementation of risk assessment and decision support tools may differ depending on the party as well as size of forest area.

Since this study focuses on the general aspects of GIS-based risk assessment and decision-making, other aspects such as the response, planning and action that managers may take based on the output of these systems was only briefly mentioned. Especially regarding the subject of integrating GIS-based risk assessment with response operation as mentioned in 5.4.4, may offer a great deal of potential in mitigating more unpredictable risks and would require further research.

7 Conclusion

The purpose of the thesis was to analyze how GIS as a risk assessment tool within DSS may help Finnish forest managers reduce and mitigate the risk of damage, as well as assist with planning efforts in regard to climate change. By conducting a systematic literature review, a consensus on the topic in academic literature was formed, as well as the identification of both the benefits and the flaws of methods used. The results of the review are based on a total of 28 primary studies, which individually differ from one another but together creates the foundation for the review as 16 subcategories of themes.

One can conclude that GIS-based risk assessment does offer several opportunities for the forest sector, but the actual usefulness is highly dependent on the quality of data. Since the methods of obtaining relevant data are improving, one can expect these methods to simultaneously improve in accuracy in the future. GIS offer both a foundation for direct analysis, due to the capabilities of processing spatial data and forest inventory data, as well as a tool for visualizing the output. The benefits are both in the form of spatial planning, assessing potential timber loss as well as an indication for tree species survival under future circumstances.

Several issues were also identified through the review. Regarding the potential risks, no indication of evidence of GIS-based risk assessment was found for one of the more crucial identified risks, more specifically snow damage. Another issue was raised regarding decision-making based on the systems. While most systems offer decision support, they do not necessarily identify as DSS. A lack of consensus on certain terminology on the topic must also be mentioned, which does cause some difficulty in both comparing the systems and in conducting accurate assessments based on these systems.

Decision-making in general based on these projections is to be taken with caution. Since most methods are not accounting for other potential risks, the recommended actions based on an individual method may contradict another. One must, nevertheless, bear in mind that the systems are not made for deterministic predictions, but for projections and evaluations to assist decision-making. No system was, however, identified in this study that would be capable of making projections based on multiple risks. Some issues regarding the implementation process of risk assessment DSS for forest management were also identified, noticeably that the systems are highly reliant on the views and understandings of the decision maker which affects the effectiveness of the systems.

One can, therefore, conclude that while GIS-based risk assessment DSS for Finnish forest management are promising, and do offer a fair few solution for isolated risks, the reliability of the systems may be questioned under certain circumstances and require more research on topics such as the possibility of multiple risk DSS.

8 Swedish summary - Svensk sammanfattning

GIS som verktyg för riskbedömning inom beslutsstödsystem - en systematisk litteraturstudie baserade på de potentiella riskerna med klimatförändringar i finska skogar

Effekterna av klimatförändringen fortskrider snabbare än någonsin tidigare. Ett varmare klimat medför ett flertal antal förändringar i Finland och bidrar med nya utmaningar för den finska skogssektorn. Hittills har de finska skogarna inte märkbart påverkats av dessa förändringar, men inom snar framtid förväntas vi se allt fler konsekvenser framträda. Ett varmare klimat förväntas bidra med bland annat introduktionen av nya skadedjur, ökad risk för vindskador, ökad vinternederbörd som leder till snöskador och mer frekventa skogsbränder (Vapaavuori et al., 2010). Det är allt viktigare att lyckas finna metoder som båda kan identifiera och minimera dessa risker för att förhindra skador i skogsbestånd och bevara skogarnas ekosystem. Eftersom Finland är starkt beroende av den finska skogsindustrin, vars största del timmer utvinns direkt från finska skogsbruk (Mäntyranta, 2019), har naturliga katastrofer som riskerar förstörelse av skogar även en stark påverkan på den finska ekonomin.

8.1 Teoretisk bakgrund

Den årliga medeltemperaturen i Finland förväntas öka med 2–6 grader före nästa århundrade, närmare bestämt 1–5 grader under sommarmånader och 3–9 grader under vintermånader (Vapaavuori et al., 2010). Fastän växtsäsongen för skogar förväntas förlängas (Mäkelä et al., 2010), kommer skogarna vara av behov av allt aktivare skötsel för att behålla sin lönsamhet (Ministry of Agriculture and Forestry, 2005), Eftersom den finska skogssektorn enligt Lier et al. (2018) år 2017 ansvarade för runt 20% av det totala värdet på finska exportvaror, 4% av årlig BNP, samt anställde runt 60 000 personer, är hållbarheten av finska skogar viktigt för hela samhället.

Idag samlar skogssektorn vardagligt in enorma mängder data (Ala-Kurikka, 2017). Dessa data kan användas för att för att identifiera nya lösningar för riskerna som medförs på grund av klimatförändringen. Geografiska informationssystem (GIS) som kan förvara och bearbeta dessa data kan understöda riskbedömningsprocesser för de risker som de finska skogarna är utsatta för. De data som GIS använder sig av är i form av vektordata, rasterdata eller attribut (Janipella et al., 2019). Vektordator är punkter representerade av exempelvis koordinater, rasterdata är pixlar som exempelvis kan representera höjd eller vattendjup, medan attribut består av icke-rumsliga data. Data av dessa typer kombineras för att framställa en virtuell representation av ett område. Inom skogsområden kan man ytterligare även använda sig av mera beskrivande data i form av skogsinventeringsdata, som beskriver detaljer om skogsbestånd.

GIS-baserade riskbedömningsmetoder kan utnyttjas inom beslutsstödsystem (DSS) för att assistera skogsförvaltare att göra rätt beslut inför framtiden utgående från klimatförändringens påverkan. DSS är verktyg som genom metoder som exempelvis simulations eller statistiska modeller kan beräkna resultat eller utfallsscenarier som kan understöda beslutsfattare och används bland annat inom skötsel av naturresurser (Reynolds et al., 2005). Genom att kombinera DSS och GIS har man möjlighet att använda sig av komplexa och avancerade matematiska modeller för att analysera geografiska data (Reynolds et al., 2005). Eftersom GIS har möjligheten att visuellt framställa data, kan även denna funktion utnyttjas för att framställa resultat utgående från matematiska uträkningar.

Segura et al. (2014) identifierar flera olika GIS-baserade skogsbruks DSS, men identifierar inte system skapade för riskbedömning som uttryckligen utnyttjar sig GIS. Segura et al. (2014) lyfter dock fram riskbedömnings DSS som utnyttjar modeller som bör kunna integreras i GIS ramverk. Forskning inom GIS-baserade DSS för riskbedömning finns inom flera olika områden, men inte på samma skala inom skogsbruk och främst av all hur dessa bedömningar är kapabla att hantera riskerna som medförs av klimatförändringar. Syftet med denna avhandling är att identifiera hur GIS fungerar som ett riskbedömningsverktyg mot dessa risker samt hur metoderna kan implementeras i DSS och hjälpa skogsförvaltare med beslutsfattarprocessen.

8.2 Metod och protokoll

Metoden som används i denna avhandling är en systematisk litteraturstudie. Denna metod valdes på grund av studiens breda forskningsområde, som är möjligt att analysera genom en systematisk litteraturstudie. Målet med litteraturstudien är att identifiera och skapa en konsensus över ämnet i fråga, baserat på bevis från tidigare litteratur inom GIS-baserade riskbedömningsmetoder, samt för DSS inom skogsförvaltning. Målet är även att identifiera potentiella motstridigheter inom tidigare forskning som kan försvåra implementering av GIS-baserade riskbedömningsmetoder.

Sökprocessen för studierna uppdelades i fyra faser. Genom ett fördefinierat protokoll användes söktermer relevanta för ämnet till att identifiera litteratur i de elektroniska databaserna Science Direct och ACM DL. Vid den första fasen identifierades 1 257 studier (med duplikat). Efter genomgång av titel och abstrakt accepterades sedan 76 studier för nästa fas. En full textkontroll genomfördes på studierna, varefter 36 gick vidare för kvalitetsgranskning. Kvalitetsgranskningen resulterade i 28 kvarstående studier. Från dessa studier extraherades resultat utgående från teman och nyckelord. Dessa teman och nyckelord kategoriserades, varefter resultaten syntetiserades genom att analysera likheter, metoder och motstridigheter utgående från dessa teman.

8.3 Resultat

Huvudkategorierna baserades på fyra forskningsfrågor som framkommer i protokollet, medan teman och nyckelord utgjorde underrubrikerna. Forskningsfrågorna är de följande:

1. Vilka bevis finns på att GIS fungerar som riskbedömningsverktyg inom DSS för skogsförvaltning?
2. Vilka konsekvenser av klimatförändringar i finska skogar kan bedömas med GIS-baserad riskbedömning?
3. Kan GIS-baserad riskbedömning hjälpa skogsförvaltare att planera för framtiden?
4. Erbjuder GIS-baserad riskbedömning lång- eller kortsiktiga lösningar för skogsförvaltare?

Den första kategorin handlar om GIS-baserad riskbedömning inom DSS. Ett antal studier som behandlar fungerande system identifierades. Strukturen av dessa system kan starkt variera beroende på riskbedömningssyftet, men vanligtvis handlar de om användning av multikriterieanalys, simulerade modeller eller statistiska metoder tillsammans med GIS för att kunna ge beslutsfattande råd.

Utgående från de identifierade studierna är det tydligt att information är ett stort problem då man analyserar risker inom skogar. Systemen baserar sig även på att beslutsfattaren förstår sig på felanalyser som kan uppstå ifall data inte är tillräckliga. Det finns även indikationer av problem med implementering av beslutsfattandesystem vid riskbedömning, vilket kan bero på att beslutsfattare inte fullständigt förstår nyttan med systemen.

De resterande huvudkategorierna behandlar de risker som kan bedömas med hjälp av GIS, hur de hjälper skogsägare och skogsförvaltare planera för framtiden, samt ifall bedömningen är kort- eller långsiktig.

Användningen av GIS vid riskbedömning av vindskador och skogsbränder är redan relativt etablerad. En viss form av koncensus över hur man tillämpar metoderna existerar även. Vid analys av skadeinsekter i skogar, exempelvis av skadliga skalbaggar har även GIS varit användbart. Användning av GIS vid riskbedömning av trädsjukdomar och svampsjukdomar kunde även identifieras. Risker orsakade av ökad vinternederbörd som exempelvis snöskador kunde inte identifieras i studierna. Studierna fokuserar endast på isolerade risker, och beräknar inte resultatet från andra sorter av riskbedömningar i sina egna bedömningar.

De flesta metoder utnyttjar GIS:s kartläggningsfunktioner samt de geografiska data som kan bearbetas av systemen i kombination med statistiska metoder eller simulationsmodeller. GIS möjliggör även att man kan analysera skogars karakteristiska drag vid förekomsten av risker. Möjligheterna som denna form av riskbedömning erbjuder skogsförvaltare är bland annat hjälp med att identifiera potentiella riskområden vid plantering av skog, identifiera planteringsmönster, identifiera trädarter som är resistenta mot framtida risker, samt förutspå eventuella ekonomiska förluster av timmer vid naturliga chocker. Beroende på risken i fråga finns det både lång- och kortsiktiga lösningar. Nyttan som GIS bidrar med ger även ett incitament att samla allt mera data och bygga upp geografiska databaser eftersom effektiviteten av dessa metoder ökar med högre datakvalité.

8.4 Diskussion och slutsats

Terminologin som använts i studierna skiljer sig starkt från varandra och vissa studier beskriver beslutsstödsvektyg endast som riskbedömningssystem, medan andra specificerar de med termen DSS. Vi kan notera att fastän GIS-baserade riskbedömningar kan definieras som en form av DSS, vilket även vissa studier gjort, så kan det uppstå problem då man endast utgår från en individuell riskanalys. Somliga råd som riskbedömningar ger kan vara motstridiga med andra riskbedömningar. Det finns därmed ett behov av någon form av supersystem som är kapabelt att hantera dessa motstridigheter för att undvika beslut som fattas utan att beakta andra faktorer. Dessa beslut kan visa sig vara kostsamma i framtiden, eftersom skogsbruk tar en lång tid. Fördelen med GIS-baserade system i dessa fall är att det finns en central komponent som kan koppla ihop data samt bedömningarna genom att skapa en visuell grund, som exempelvis elektroniska kartor, för dessa bedömningar. Inget centralt GIS-baserat DSS inom skogsförvaltning som behandlar flera olika risker identifierades dock i denna studie.

Överlag visade sig GIS-baserade riskbedömnings DSS vara användbara för skogsförvaltare i scenarier med endast isolerade risker som bidragits av klimatförändringen. Systemens prestation är starkt påverkad av datakvalitet vilket förväntas förbättras i samband med att datainsamlingsmetoder optimeras. Vi kan dock notera att det finns mycket rum för fortsätt forskning inom GIS-baserad riskbedömning och DSS, men även incitament till sådan forskning.

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