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Exploring patterns in risk factors for bark beetle attack during outbreaks triggered by drought stress with harvester data on attacked trees:

A case study in Southeastern Sweden.

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Abstract

In recent years, bark beetle outbreaks have intensified causing damage to forests in many parts of the world. Forest ecosystems of Northern Hemisphere are considered more vulnerable because of their tree composition. Vast areas are covered by spruce forests which is a favorable type for the specific pest. Forest ecosystems provide many services and secure the wellbeing of wildlife and citizens. Protecting their structure and functionality is of the utmost importance. Other factors may contribute to the damages caused to forest ecosystems like outdated forest management policies. Furthermore, land use systems and guidelines that are not adjusted to the specific characteristics of a region. Another factor to consider is the percent of privately-owned forests, in some cases, which makes it difficult to communicate the hazards and follow some harmonized standards.

Physical characteristics of a region and topography are parameters that can enhance the potential risk if other factors coexist as well. An event like a storm damage or a drought stress is usually the triggering factor for the beginning of the outbreak. The predisposing factors contribute to the rapid spatial propagation of the outbreak among with favorable climate conditions like temperature and drought. Southeastern Sweden is a region considered to fit the abovementioned description. Extreme events initialize a bark beetle outbreak which results in greater damages due to higher number of bark beetle. Climate crisis favors the breading process of bark beetle which results in higher number of bark beetle during their lifecycle.

In this study, we focused on the environmental perspective of the bark beetle outbreaks. GIS techniques were used to analyze the risk factors associated with bark beetle outbreaks. By mapping trees that were attacked by bark beetles, we were able to identify patterns and trends in the risk factors. Data about attacked trees were provided by Skogsstyrelsen (Swedish Forest Agency). Landcover data were given by Naturvårdsverket (National Landcover Data). Soil moisture and topographic data were used which were provided by Lantmäteriet and Swedish Agricultural University (SLU). The goal was to investigate intervals of risk factors that elevate the potential bark beetle. Furthermore, a risk map was created indicating high-risk regions which could help to allocate preventive measures and resources.

As mentioned above forest management and bark beetle outbreaks are multidimensional concepts that require cooperation of many professionals and specialists. Sustainable management and policies are required to mitigate and tackle the outbreaks that are favored by climate conditions like temperature and water shortage. A model that incorporates various types of criteria (social, environmental, financial), data-driven decisions and location-specific management is the way to proceed in the future.

Keywords: Geography, GIS, Geographic Information Science, Forest ecosystems, Bark beetle outbreak, Southeastern Sweden , Predisposing factors, Triggering factors, Drought stress

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1. Introduction

Changing climate is a crucial parameter that shapes physical and human environment. Based on the recent report of the intergovernmental panel on climate change (IPCC AR6 2021), measures to tackle and avoid 1.5 degree increase in temperature are of the utmost importance. Some consequences of climate change are prominent in various locations on earth’s surface. Severe events like heavy rainfalls resulting in floods and heat waves are becoming more intense and frequent. When external influence of climate parameters is sufficiently low the ecosystem will provide services for people persistently through self-regulation. Since an ecosystem's ability of self-adjustment is limited, once external influence exceeds the threshold, the ecosystem will become vulnerable and may even collapse, which will seriously limit the benefits of people (Liu et al., 2017). The natural carbon sinks are important contributors to tackle and reduce carbon emissions. The provision of services of the ecosystems is consistently tested by climate variability. Warming favors various disturbances for the ecosystem balance. Climate directly affects ecosystem functions such as growth, reproduction and migration of a tree species, whereas it indirectly controls natural disturbance regimes such as fire, insect outbreaks and diseases (Dital et al., 2015).

The carbon cycle is an important process for the conservation of the biosphere. A key role in this procedure is attributed to forests and the oceans. Forests are important sinks of carbon. Boreal forests cover an extensive area of the northern hemisphere and provide important ecosystem services that support societal wellbeing at local, regional and global scales: wood supply, biological diversity, water quality, climate regulation, cultural inspiration, and recreation (Campbell et al., 2019) but the risk of disturbances increase with climate change. Climate variability creates indirect hazards for the forest ecosystem. High temperatures and droughts increase the intensity of wildfires. In both Europe and North America, large disturbance events have become more frequent in recent decades. The future rate of carbon uptake by forests depends on how ambient temperature, land use and resource management practices evolve (Holmberg et al., 2019).

As mentioned above forests are threatened mainly by temperature, land use and unreasonable management. Temperature consequences cannot be avoided but a realistic goal is to stabilize the existing climate conditions to avoid future deteriorations. Land use is an equation with many economic and political variables. The forest management can be a multidimensional solution by mitigating direct and indirect climate risks. Forest management incorporates many aspects ranging from tree species to environmental, economic and social criteria. Pest disturbances is a common cause of forest mortality. This obstacle is enhanced by climate crisis. One cause is the increase in the proportion of mature, often planted conifer stands, which are particularly susceptible to bark beetles (Lehnert et al., 2013). Spruce bark beetle outbreaks are major disturbances that can cause the mortality of over 90% of the mature spruce within a stand and over extensive areas (Hart et al., 2013). Increasing sizes of bark beetles’ populations can cause massive outbreaks. These outbreaks result in extensive tree mortality which could impact the ecosystem and impede various of its services. Adopting another management approach could reduce the risk of disturbances. Managing a bark beetle outbreak involves both proactive and reactive measures. In terms of reactive management, monitoring and early detection of a bark beetle outbreak is very important. Another measure could be salvage logging. Removing infested trees as soon as possible to prevent the spread of the outbreak to healthy trees could also help to reduce the number of bark beetles to the area. In terms of proactive management, there are many options and perspectives. One could be to incorporate various environmental and climate criteria to select tree species that are more resilient to these circumstances in forest management. Promoting tree diversity and reducing stand density could be some measures of proactive management. Another option could be to create zones of adaptable trees inside the forest. The extent of the interference in the forest ecosystem will be examined spherically. The landscape and the ecosystem's processes must not be disrupted. The impact of various management options and measures should be evaluated. Clear cut practice for example could have negative impact in the ecosystem functioning as well. Soil erosion, water quality and wildlife habitat could be affected. The ultimate goal is to incorporate management strategies to prevent or mitigate a possible outbreak by maintaining the overall health of the ecosystem.

In 2018, an extreme drought triggered a severe outbreak in Sweden which resulted in high forest mortality rates (Müller et al., 2022). However, it is important to note that this does not necessarily mean that drought stress was the only contributing factor. Bark beetle outbreaks can be triggered by a combination of environmental and ecological factors. Some these factors could be: drought stress, temperature variations, composition of tree species, and previous disturbance events such as storms. This situation has been dramatically worsened by climate change, which has further compromised tree defense abilities and favored bark beetles (Hlásny et al., 2019). This study has two main aims. The first aim is to examine how the studied risk factors influence the risk of bark beetle attacks to guide the forest management (avoid planting spruce in areas with elevated risk of bark beetle attacks) to mitigate bark beetle attacks and outbreaks. This study will focus on proactive risk management, i.e. identifying areas of high risk for bark beetles attacks and manage these to reduce the risk of attack. The second aim is to create a risk map based on the findings of the analysis. This thesis will investigate if there are any type of correlations between type of forest as well as topography and soil wetness, and bark beetle attacks. The comparison will be made between pure spruce forest and mixed types of forest. The results can be used to implement a forest strategy which can lead to a more sustainable and resilient future. The results should also be communicated to the (private) forest owners and decide in conjunction with them for actions and measures. The two main research questions are:

1. Which type of forest is more susceptible to spruce bark beetle outbreaks? (Spruce forests versus mixed forests)

2. How does topography and soil wetness of a region affect the risk of bark beetle outbreaks in a drought-stress (triggering factor) scenario?

2. Background

This chapter provides the theoretical concepts that are necessary to better understand and evaluate forest management operations. The first section describes the consequences of climate change to ecosystems and their services. Then the importance of forest ecosystems in biogeochemical cycles is examined. Their contribution in carbon cycle is a vital process to mitigate and tackle uncontrolled warming. The third section emphasizes on bark beetle attacks and their effects. These attacks touch the activities of the entire social spectrum. Local communities face economic and environmental difficulties. Finally, forest management concept is introduced as a possible solution. The focus is on management framework and proactive policies that can reevaluate the current approaches.

2.1 Climate change and ecosystems

Ecosystems and their services play an important role in the well-being of living creatures. Human health and welfare are highly dependent on the "health" of nature. The concept of ecosystem services has become widely used and serves to highlight the dependency of human society's welfare on natural ecosystems (Holmberg et al. 2019). Nature provides essential services to humans including material and economic services (i.e. ecosystem services) as well as cultural, experiential and recreational services, which, in turn enhance human psychological and physical health (IPCC 2022).

Climate change disturbs the balance of terrestrial ecosystems. Ecosystems are rapidly changing in response to climate change and other global change drivers, not only in response to temperature changes but also associated changes in precipitation, atmospheric carbon dioxide concentration, water balance, ocean chemistry, and the frequency and magnitude of extreme events. Ecosystems vary in their sensitivity and response to climate change because of the complex interactions among organisms, disturbance, and other stressors. Changes in natural ecosystems threaten biodiversity worldwide, and have implications on global food production (Malhi et al. 2020).

Climate change further affects the ability of ecosystems to adjust to various modifications. Biogeochemical cycles are disturbed and ecosystem adaptability is under constant pressure. Warming and heavy rainfalls have an impact on the defensive mechanisms of the biodiversity. Furthermore, it can extend or shrink habitat of innumerable beings (United Nations Climate Action 2022). Finally, risk of various disturbances is increased. This type of disorder can damage all type of ecosystems and especially terrestrial ones.

2.2 Carbon cycle and forest ecosystems

Terrestrial ecosystems play a significant role in the greenhouse gases (GHG) cycles. The ability to consume vast quantities of these gases helps the ecosystem to retain its balance. Forest ecosystems contribute by absorbing large amounts of carbon dioxide from the atmosphere resulting in reduced concentration of carbon dioxide. The ability of forests to act as carbon sinks can compensate for other human emissions that are produced from various activities. There are however, substantial uncertainties in predicting boreal forest response to climate change due to the uncertainty in climate change predictions and differences in ecological models' structure and mechanism (Huang et al. 2021).

In recent years the term "irrecoverable carbon" is coined. This expression is used to describe amounts of carbon that are stored but can be potentially released to the atmosphere due to a variety of reasons. The source of this loss is related with human activities and disturbances. Effective strategies to reduce the risk of catastrophic climate change will need to locate large irrecoverable carbon reserves that are at risk due to anthropogenic action and prioritize their protection and sustainable management, alongside efforts to phase out fossil fuel emissions and restore degraded ecosystems (Noon et al. 2021).

Forest ecosystems are threatened by different causes. Their coverage is reduced along with the ability to store carbon. The main cause is deforestation (Gatti et al. 2021). Deforestation can be the result of human activities (logging) as well as natural disturbances such as wildfires. Mediterranean ecosystems are expected to face repeated fire events during the summer season (Duguy et al. 2013). Furthermore, disturbances will also intensify during the coming years. There is increasing evidence that human actions through management and climate change have altered the interactions between insects and forests, resulting in more widespread insect outbreaks (Senf et al. 2015). As an example, severe summer droughts can result in lowered tree defense capacity, thereby increasing the risk for subsequent infestations of bark beetle (Jönsson et al. 2012). Land management can be a tool to mitigate risk and prevent rapid spread of these hazards. A sustainable forest management should incorporate social and environmental variables. An ecosystem-friendly approach could address future issues and alleviate the ongoing emergency.

Another origin that deteriorates forest coverage and their ability to consume are pest disturbances. Increasing numbers of bacteria and other microorganisms are using trees to breed and expand in significant number. Global warming already has influenced insect distribution and phenology. Understanding how insects will respond to continued climate change is important for predicting how ecosystems will function in the future (Adamo et al. 2012).

2.3 Forest management and climate adaptability

Recent research indicate that climate adaptability and efficient management is the way to proceed to reduce the risk of disturbances. Many unfavorable stand characteristics and local factors are caused by past forest management strategies, which, at the time it was implemented, were considered to be the most economical approach (de Groot et al. 2019). There is still a lack of information regarding the role of forest management in the case of bark beetle epidemics in protected areas, particularly whether the effect of ongoing changes in the ecosystem caused by primary disturbance is stronger than the stand and site features of the location (Mezei et al. 2017). Adaptation of forest management, aiming at sustainability, requires that a range of environmental, economic and social goals are taken into account (Jönsson et al. 2013). Forest management will most likely change to adapt to a warming climate and changed demands from the market and society. This will probably lead to the implementation of new methods and strategies affecting rotation time, harvesting systems and the use of new tree species and genotypes (Björkman et al. 2015). Gross (2016) presented an adaptation framework where the adaptation policy is summarized in four key steps (Figure 1): (1) identify conservation targets, (2) assess vulnerability to climate change, (3) identify management options and (4) implement management options.

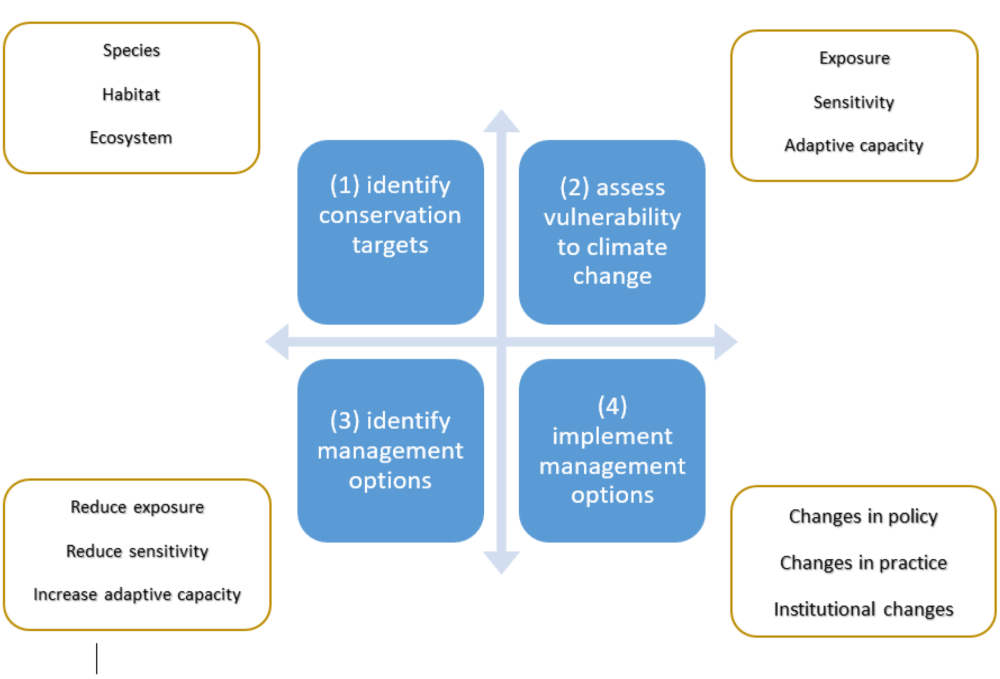


Figure 1 Adaptation framework to achieve a more sustainable forest management (Gross 2016).

Sandler (2013) argues

that rapid and uncertain ecological changes undermine traditional justifications for both reserve oriented and restoration-oriented ecosystem management strategies. Rapid and uncertain ecological change requires rethinking ecosystem management goals, not just developing novel strategies (such as assisted colonization) to accomplish traditional goals. Under conditions of rapid and uncertain ecological change, species preservation ought to be deemphasized as an ecosystem management goal. Park and reserve-oriented ecosystem management remains well justified under conditions of rapid and uncertain ecological change, but the goals of such management strategies must be revised to reflect the new realities of rapid and uncertain ecological change.

The current disturbance management approach in many parts of Europe exhibits features of the command-and-control pathology which describes a problematically large degree of authoritative centralization and control in a governance system

(Hlásny et al. 2021). As it is adopted in other land management projects a fit for purpose solution should be preferred over a “fit for all” plan. The management policy must have clear and specific target-groups tailored to the needs of the specific region. A decentralized strategy can be more effective. Local authorities that face the consequences can propose more accurate and precise actions. Furthermore, forest management should include legislative measures as well. Cooperation of various technical fields and scientific backgrounds will usually yield a better outcome. The main idea is to result in a continuous and complete climate risk and adaptability framework. Rapidly changing conditions due to climate variability demand a management strategy that will equally focus on each stage. Resources should be allocated in prevention and conservation of the outbreaks in a context-depending way.

To summarize climate crisis, natural disturbances ecosystem services and forest management are variables of the same equation. Climate conditions increase the risk of insect outbreaks and disturbances. Climate change patterns are not expected to improve, the only realistic target is to stabilize temperature and avoid warming consequences. The viable approach is to implement sustainable land use and land management policies. There are many suggestions that human factor is deteriorating outbreaks. Adopting general regulations that are legislated by central authorities can be a possible cause. Another explanation could be the absence of a rigid and efficient legal framework. As mentioned above, the management process should include predefined stages and targets. This is very important because some objectives can have societal contradictions. In some cases, the created value is reduced by alternative goals.

2.4 European spruce Bark beetle attacks and consequences

Ecosystems are facing more frequent droughts. This reality increases the hazards for forest ecosystems around Europe. A warmer climate will favor the development of insects such as the European spruce bark beetles (*Ips Typographus* L.) and allow more frequently the completion of two and even three insect life cycles per year leading to potentially rapid population build-up and subsequent damages in host trees (Norway spruce; *Picea abies* (L.) Karst) (Pasztor et al. 2013). The bark beetle life cycle contains four main stages. The first stage is the swarming in which bark beetles create a colony in order to attack trees. The next stage is the attempt to attack new hosts (trees). The next stage is the creation, by laying eggs, of a new “adult” bark beetle generation which is ready to attack. The cycle closes with a new swarming stage. The bark beetle has multiple means of spreading, which include wind-assisted dispersal where the beetles are carried by the wind to new locations, human-assisted transport such as the movement of infested wood products or transportation of infested trees. Bark beetle outbreaks are usually triggered and enhanced by some common factors. The most common triggering factors are drought stress and storm damage (Müller et al. 2022). Furthermore, there are some predisposing and contributing factors that favor bark beetle outbreaks. Some of these factors are: tree age, forest tree composition, sanitary and continued drought stress.

Forest ecosystems in various regions encounter many difficulties. Forest ecosystems of the northern hemisphere are susceptible to pest disturbances. In the forests of Sweden, 43% of the standing volume is Norway spruce, i.e. 1279 million cubic meters, and forest owners consider the spruce bark beetle as one of the major threats to forest production (Jönsson et al. 2007). While bark beetles are responsible for 8% of the forest damages in Europe, storm damage is the most significant disturbance causing up to 53% of the total damage (Stadelmann et al. 2014). In Central Europe, the scale at which forest managers are currently tackling the impacts of global change on disturbance regimes is primarily the tree to stand scale, while large-scale drivers pertaining to the scales of regions or landscapes (e.g. spatial connectivity and contagion) are frequently neglected in considerations of management (Seidl et al. 2016).On the other hand, plants have evolved myriad chemical and structural mechanisms to protect themselves from damage, which can be altered by environmental conditions such as climate (De long 2016).

Bark beetle attacks result in multidimensional damages and cost. As mentioned above a forest ecosystem provide many services and return profits to humans and other biodiversity. Humans can gain economic revenues. Timber and wood harvesting can be a good source of income. Tourism and recreational experiences add psychological and economic value. Maintaining habitat is also an important process of an ecosystem. Key provision is the temperature and climate regulation that makes a location viable for humans and other living things. From a management perspective, timely identification of sites at most risk of tree mortality during outbreaks is a challenge. Thus, development of robust risk-rating models and maps could help managers to prioritize stands in which to apply preventive and mitigation measures (Kärvemo et al. 2014).

2.5 Risk factors for bark beetle outbreaks

In this section some theoretical concepts about risk factors for bark beetle outbreaks will be explored. These features affect and exaggerate outbreak dynamics. Considering variables that increase the possibility of a pest attack will also designate the necessary variables for the analysis part. The risk factors that will be examined are: Soil moisture, topography and Landcover category.

2.5.1 Topography

Topography is an important parameter that influences the capability of spruce trees to defend themselves from bark beetle attacks. Furthermore, the conditions for the bark beetles are affected. Bark beetle population numbers are related to some characteristics of the physical landscape. Some researchers indicated that larger trees at higher elevations on south-facing slopes were targeted most frequently, particularly during the later stages of the outbreak. Aspect, elevation, and slope were the best predictors of tree mortality, demonstrating moderate forecasting ability (Kaminska et al. 2021). The topography and the structure of each region is a perspective that should be included in any attempt to mitigate pest risk.

2.5.2 Soil moisture

Climate change is expected to intensify in the coming years with anticipated consequences such as wildfires, droughts and heatwaves depending on the location in the earth’s surface. Regional drought often acts as a catalyst for bark beetle outbreaks, as water-stressed trees have lower rates of growth and carbon assimilation, which may compromise host defenses and result in large amounts of tree mortality over short periods of time (Robbins et al. 2022). Extremely low values of soil moisture can be ideal for massive bark propagation. The correlation between soil moisture and natural disturbances’ presence should be inspected and examined. Drought is usually described as a prolonged precipitation deficit. The co-occurrence of drought with other conditions such as higher temperatures (warming), specific intervals of slope and aspect could result in creating a favorable environment for bark beetle breeding process. The effect of heat and drought on bark beetle breeding system are not clearly understood. Netherer (2019) pointed out that challenge remains for such risk assessment systems to translate the occurrence of heat and drought events into meaningful tree stress proxies and infestation probabilities. Precipitation deficits interpreted as drought have repeatedly proved significant in explaining timber volumes salvaged due to bark beetle attack. The “Rosalia Roof experiment” for the first time provided strong empirical evidence of the negative impact of drought stress on Norway spruce defense against the European spruce bark beetle; yet, distinct differences in attractiveness of stressed and control trees were not observed. Notably, proportions of prevented attacks were higher among trees exhibiting low water stress and high resin flow, while proportions of successful attacks increased with drought stress.

2.5.3 Land cover

Natural disturbances cause a gradual increase of the land cover heterogeneity, the number of land cover types and fragmentation of landscape (Falt’an et al. 2021). Various metrics can quantify changes that emerge in the landscape. Investigating landcover categories that are susceptible to the bark attacks is an important step in the design policy process. Identifying vulnerable locations can lead to more efficient management options and operations. Land use is related with land cover under the prism of human activities. Information about vulnerable land cover categories can drive human-ecosystems interaction to a more sustainable and knowledgeable administration.

2.5.4 Tree age

There are other parameters that favor bark beetle infestation. Tree age can be a condition that leads to a rapid spread of the specific pest. Bark beetle attacks are often concentrated on stands with dominating spruce cover. Trees older than 60 years that have a diameter at breast height > 20–25 cm are favored, but during epidemic outbreaks also younger trees are attacked (Müller et al. 2022). Coexisting with other factors, this parameter can create a preferable environment for the proliferation of insects. Tree age was not included in the analysis since there was no age data available.

2.6 Outbreak history

In the last 50 years (1960-2009) three spruce bark beetle outbreaks have occurred (including the current one started in 2018) in Sweden. The triggering factor of these outbreaks was a storm damage or a drought stress. In the fall of 1969 southern and central Sweden were struck by large storms which initiated the largest Swedish outbreak documented so far. During eleven years of outbreak (1971-1981) bark beetle killed about 4.5 million m^3 trees. Damage levels were highest in the province of Värmland and adjacent provinces in central Sweden (Öhrn 2012). Several warm and dry summers may have contributed to the long duration of this outbreak. A period of increased spruce bark beetle activity in southern and central Sweden started after the warm and dry summer of 1992 (Kärvemo et al. 2010). As it is indicated by the historic data, warm and dry summer entails a possible outbreak. Southern Sweden faced a strong wave of bark beetle attacks during the years 2005-2009. The catalyst of this outbreak was considered the storm Gudrun which hit Southern Sweden in 2005. The outbreak of 2018-2020 (still ongoing in 2022) is considered one of the worst in the history of Southern Sweden. During these three years bark beetle killed about 17 million m^3 trees. Drought stress trigger this outbreak along with other factors.

3. Methods

This section describes the methodological framework that was adopted to answer the two main research questions that were stated. Firstly, the study area is examined. Some historic climate data are presented that incentivize the selection of the specific locations. The next part of this section describes the datasets that were used to answer the research questions. The source of these datasets and other metadata are presented. The final part extensively analyzes the workflow that was used to evaluate the specific risk factors. Finally, the process to create the risk map is designated.

3.1 Study area

Southeast Sweden is selected to be the study area for this project (Figure 2). The study area is divided into six tiles.

Southeastern Sweden is considered an area with elevated risk for bark beetle outbreaks due to dry and warm weather during the summer season. These circumstances enhance insect outbreaks possibilities. Furthermore, the fire risk is extremely high (SMHI 2022). Higher temperatures are also a parameter that can set a location to the vulnerable category. This is also observed in the chosen region. The final piece of the risk equation is drought and water shortage. During summer season, parts of the study area are facing severe water shortage events (Swedish Portal for Climate Change Adaptation 2022). Major and minor groundwater resources are diminished. This can increase the risk of water shortage in specific regions of the study area. Some regions that all the mentioned risk factors co-occur are: Östergötland County, Jönköping County, Kalmar County and Kronoberg County. These four individual regions comprise the study area for this project. The following table (Climate Change Knowledge Portal 2022) presents mean temperature, and mean annual rainfall for the corresponding 10-year periods for the specific counties.

Table 1 Historic climate data for the counties of the study area (Southeastern Sweden).

County	**Annual mean temperature (°C)**				**Annual precipitation (mm)**			
	1981-1990	**1991-2000**	**2001-2010**	**2011-2020**	**1981-1990**	**1991-2000**	**2001-2010**	**2011-2020**
Östergötland	6.07	6.63	6.97	7.47	653.08	613.04	621.14	593.11
Jönköping	5.88	6.33	6.63	7.19	714.7	752.8	751.23	743.52
Kalmar	6.65	7.16	7.46	8.02	573.62	590.77	597.1	577.33
Kronoberg	6.49	6.94	7.19	7.81	723.22	751.61	746.98	746.62

The abovementioned data about the climate variables in the specific areas indicate some patterns. Annual mean temperature is progressively increasing. This observation was verified in all four regions of the study area. Based on the projection scenarios increasing temperatures and warming are expected to insist in near future (IPCC 2021). Increasing temperature creates a favorable environment for natural disturbances. Precipitation values do not display a clear pattern. Based on presented values one can observe that the amount of water is following a descending direction which can lead to more frequent drought events in the specific locations.

Figure 2 Study area with the six tiles for the evaluation of bark beetle risk (W1, W2, W3, E1, E2, E3).

3.2 Data

Based on the risk factors and the methodological framework the data selection process was performed.

Table 2 Data list for studying the risk of bark beetle attacks

Dataset	Source	Data type	Products
Harvester data (2018)	Sveaskog, Södra; Skogsstyrelsen.	raster format(10×10 meters)	bark beetle attacks
Harvester data (2019-2020)	Sveaskog, Södra; Skogsstyrelsen.	raster format(10×10 meters)	bark beetle attacks
soil wetness	Swedish Agricultural University (SLU)	raster format(10×10 meters)	soil moisture value
Landcover 2018	National Landcover Data(Naturvårdsverket)	raster format(10×10 meters)	forest type
DEM	Lantmäteriet	raster format(10×10 meters)	slope,aspect

3.2.1 Bark beetle data

The locations of attacked trees was the main dataset used in the study. The dataset included bark beetle attacked trees from the years 2018 2020, with the locations obtained from the harvester machines cutting the attacked trees. Harvester data were retrieved by machines that were equipped with GNSS systems. The coordinates of the attacked trees were based on the harvester machine body or crane. This could result in identical coordinates for some attacked trees, and uncertainties in the actual position of the attacked trees. Furthermore, harvester data included records from trees that were removed because of their proximity to an attacked tree. Those records were not separated.

The year 2018 was considered a drought year whereas 2019-2020 were more normal years from a meteorological perspective. Bark beetle data were provided for the years 2018, 2019 and 2020. Datasets comprised of “presence” data and “count” data. The presence dataset was a mixture of harvester and inventory data. Count data described the number of attacked trees (derived from harvester data) in each pixel. These datasets provided information about the locations and number of bark beetle attacks. The 2018 dataset did not need any major cleaning operations. Presence and count datasets were used to create a single dataset for 2018. These operations will be described in the Methods section of this thesis. 2019 and 2020 bark beetle attacks datasets were decided to be grouped into a single bark beetle attack dataset. The reason for this decision was that some months of attacks could not be specifically identified. There were uncertainties in the harvester data what year a tree was attacked so it was better to merge data from years 2019 and 2020 since both years were considered more “normal” from a meteorological perspective. This decision will ensure we get “cleaner” data and a more robust result. All bark beetle data were provided in raster format with a spatial resolution 10×10 meters. Only data on attacked trees were used.

3.2.2 Geodata

According to the risk factors that were stated in a previous section, the data collection process was performed. A dataset containing landcover information was collected and imported in the analysis model. This dataset will help to answer the first research question of this thesis. The influence of landcover categories on the risk of bark beetle attack will be quantified and assessed. This dataset contained information about forest types and landforms. This dataset was provided by the National Landcover data (Naturvårdsverket 2018) and created in 2018. This dataset was in a raster format with a spatial resolution 10×10 meters. Another dataset that it was used it was about soil wetness. Soil wetness values about the study area divided into the corresponding study tiles. Soil moisture value was retrieved by Swedish Agricultural University (SLU). This dataset provided soil wetness percent (value range 0-100%) for each location of the study area. It must be pointed out that the soil wetness index is a static index which means that it does not give the actual soil moisture during the attacks. Furthermore, it does not differ between 2018 and 2020. Soil wetness dataset was also in raster form with a spatial resolution of 5×5 meters. Performing some resampling operations was a necessary process for this layer. Transforming the cell size of this layer to 10×10 meters (as the other layers) would yield better and precise results. Finally, elevation data were used. The source of the dataset was a Digital Elevation Model (DEM) from Lantmäteriet that was used to create the slope and aspect products that were incorporated to the analysis. The DEM dataset was in raster format with a spatial resolution of 10×10 meters.

3.3 Thesis workflow

The workflow can be divided into three stages (Figure 3). The first stage was the creation of bark beetle attack layers for the years 2018 and 2020(the latter will be referred as a 2020 dataset to avoid any redundant repetition). Harvester, count and inventory data in the extension of the study area were used to create bark beetle attacks datasets.

The second step in the workflow was to evaluate the influence of each of the risk factors. Overlay analyses was performed to examine effect of risk factors. The two main layers of the overlay operations were attacked trees for years 2018 and 2020.

The second input in the overlay computations was each one of the risk factors as mentioned in the previous part (3.2.2 Geodata) of this section.

The final stage of the analysis was to create a risk map of the study area. The method to create this map will be thoroughly analyzed in this section. The tool that was used to construct the map was weighted overlay analysis. Three numerical values were used (1, 2, 3) which were linked to corresponding categorical values of risk (low, medium, high).

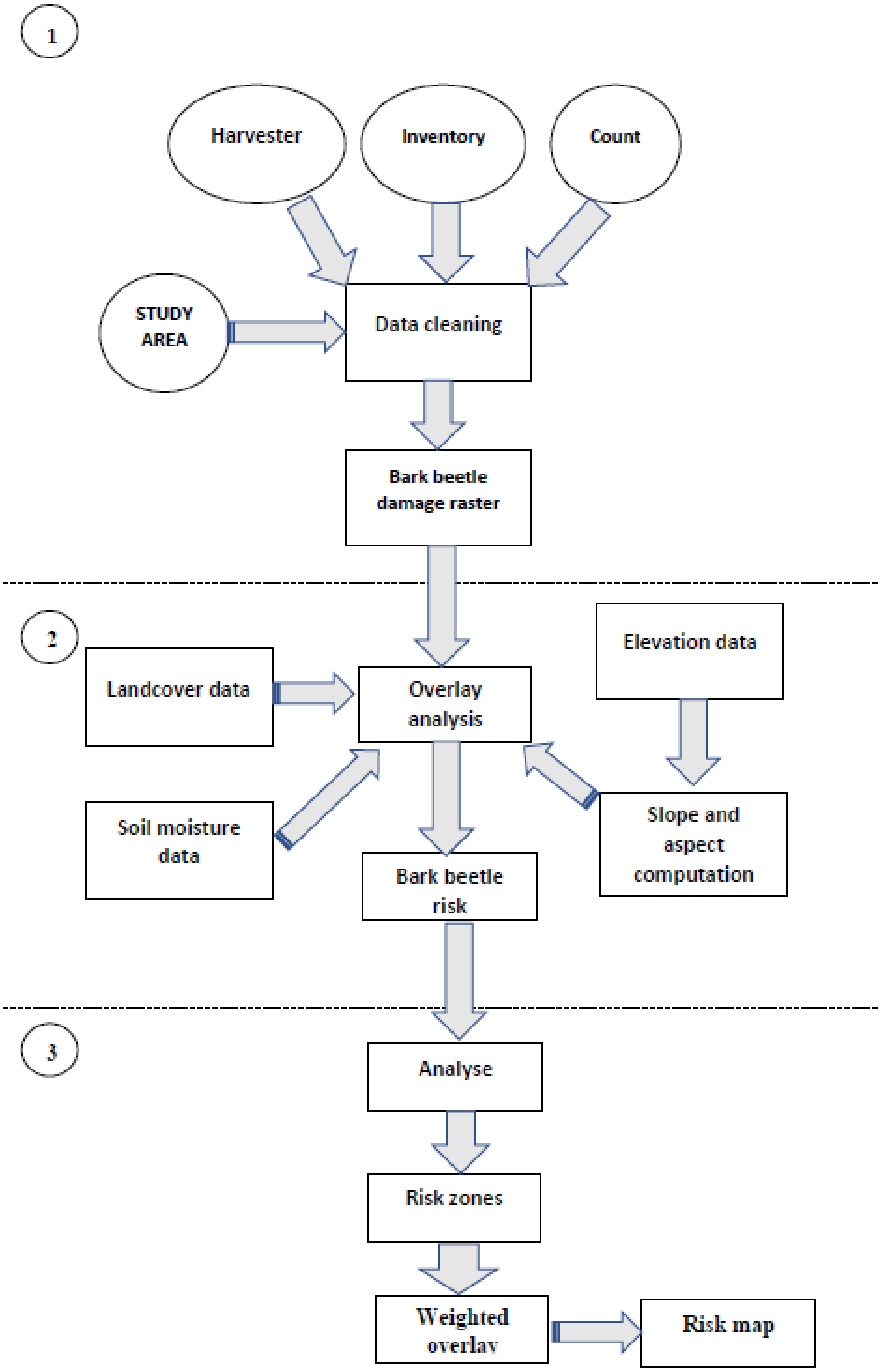


Figure 3 Complete workflow describing the stages and the steps to evaluate the risk factors and create the risk map

3.3.1 Creating bark beetle attack layers

In this section the first stage of the workflow will be described. The result of the specific process was two datasets (damage data 2018 and 2020). All available data (inventory, count, harvester) of bark beetle presence were incorporated to identify the regions that suffered bark beetle attacks. The final dataset displayed the bark beetle attacks over the entire study area. The process to create the dataset for the year 2018 was straightforward. The dataset for the year 2020 required some cleaning operations as mentioned in a previous section (3.2.1 Bark beetle data). The final product (Bark beetle damage raster) in each case was a binary dataset indicating healthy and attacked locations in raster format.

3.3.2 Analysing risk factors

The final products of the previous stage were bark beetle damage raster for 2018 and 2020. These were two binary raster datasets one for each year of study. The second stage of the workflow involves the analysis and evaluation of the risk factors. The overlay analysis was performed between the bark beetle damage raster and each one of the risk factors. The first parameter was a landcover dataset. This dataset contained various forest types ranging from spruce forest to mixed coniferous and deciduous forest. Furthermore, vegetated and arable land categories were included. Finally, some artificial surfaces were also incorporated in the analysis.

The second factor that was analyzed was soil moisture. Soil wetness dataset provided static soil wetness over the entire study area. Using the bark beetle damage raster and soil wetness dataset, the mean soil wetness for each tile was calculated (ArcGIS Zonal statistics). This resulted in corresponding mean soil moisture values for healthy and attacked locations for 2018 and 2020. Furthermore, number of attacks per soil moisture value was calculated which was used in the creation of the risk map.

The next step in this section was to incorporate slope and aspect into the model. Based on the elevation data that were provided, slope and aspect were computed. Slope was calculated as percentage slope. The lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain. Percentage slope is calculated as the tangent of a cell multiplied by 100(ArcGIS help page 2022). Aspect is the compass direction that the downhill slope faces for each location (ArcGIS help page 2022). Slope and aspect were calculated by executing ArcGIS algorithms. Then the study area was classified in slope and aspect classes. The slope and aspect classes that were used are presented in Table 3. Finally, bark beetle damage raster was overlayed with these slope and aspect classes.

Table 3 Slope and Aspect classes that were used for this analysis

Slope Classes(percentage)		Aspect classes(degrees)
1	0 - 2.5	1-Flat (-1)
2	2.5 - 8.4	2-North (0-22.5)
3	8.4 - 16.0	3-Northeast (22.5-67.5)
4	16.0 - 25.2	4-East (67.5-112.5)
5	25.2- 38.7	5-Southeast (112.5-157.5)
6	38.7 - 62.2	6-South (157.5-202.5)
7	62.2 - 214.3	7-Southwest (202.5-247.5)
		8-West (247.5-292.5)
		9-Northwest (292.5-337.5)

	10-North (337.5-360)

The final product of this stage was the influence of the bark beetle risk factors. This was further evaluated in order to create the risk map in the final stage of the workflow.

3.3.3 Creating a risk map over the study area

Before performing the final overlay operation, some preparing processes were executed to the risk factors. Each one of the parameter intervals was reclassified. Identical values (1, 2, 3) were used to group various intervals into three categories. These categorical values indicate the degree of bark beetle attack risk ranging from lower (1) to higher risk (3). This process was executed for all the above-mentioned risk factors. Each group of the risk factors was attributed the categorical value based on the number of attacks that were suffered. For example, soil wetness parameter was attributed risk values based on Figure 9 and Figure 10. If we observe these two graphs, we can see that the highest number of bark beetle attacks are noticed for soil wetness values 0-7. This group was attributed the highest risk value (value 3). Similarly, all parameters were attributed risk values based on the results. The risk factor Landcover category was grouped according to table 4.

Table 4 Landcover classes with their bark beetle attack risk group values for the creation of risk map

LANDCOVER CLASSES	RISK VALUE
Open wetland (2)	1
Arable land (3)	1
Non-vegetated other open land (41)	1
Vegetated other open land (42)	1
Artificial surfaces, building (51)	1
Artificial surfaces, not build ay (52)	1
Artificial surfaces, road/railway(53)	1
Pine forest not on wetland (111)	2
Spruce forest not on wetland (112)	3
Mixed coniferous not on wetland (113)	2
Mixed forest not on wetland (114)	1
Deciduous forest not on wetland (115)	1
Deciduous hardwood forest not on wetland (116)	1
Deciduous forest with deciduous hardwood forest not on wetland (117)	1
Temporarily non-forest not on wetland (118)	1

Pine forest on wetland (121)	1
Spruce forest on wetland (122)	1
Mixed coniferous on wetland (123)	1
Mixed forest on wetland (124)	1
Deciduous forest on wetland (125)	1
Temporarily non-forest on wetland (128)	1

All parameters were reclassified to categorical values ranging from 1 to 3 with a similar process. Attributing risk values to soil moisture factor performed according to table 5. Attributing risk values to Slope and aspect classes performed according to table 6.

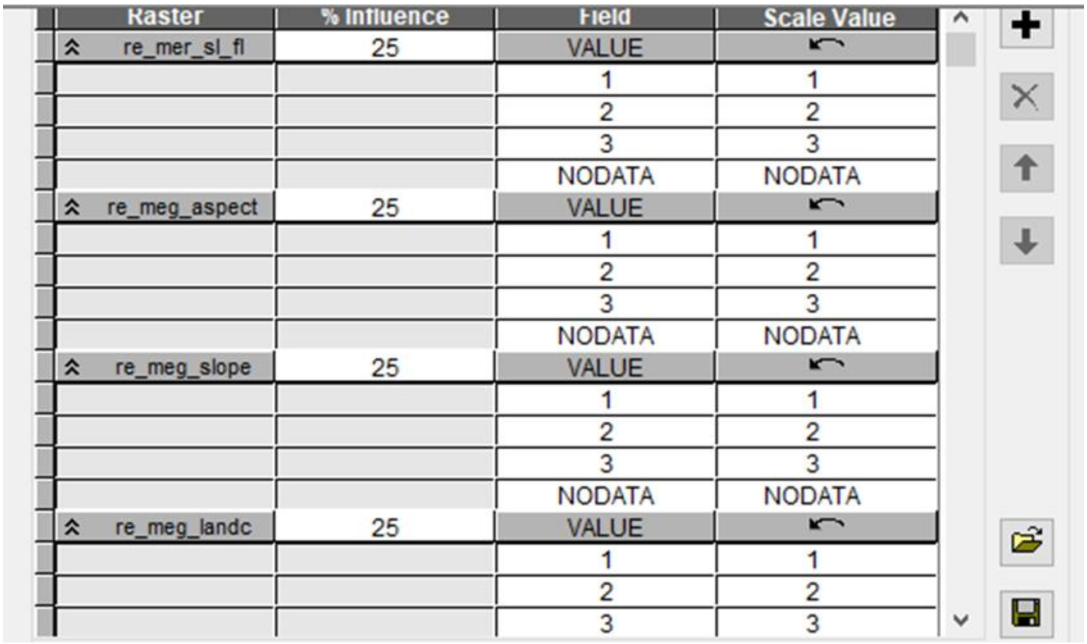
Table 5 Soil wetness classes and group risk values

Soil wetness classes (%)	Risk values of bark beetle attack risk
0-7	3
7-28	2
28-101	1

Table 6 Slope and aspect classes with their corresponding group values of bark beetle attack risk

Slope classes (%) of the study area	Risk values of bark beetle attack risk	Aspect Classes of the study area (degrees)	Risk values of bark beetle attack risk
1- (0 - 2.5)	1	1-Flat (-1)	1
2-(2.5 - 8.4)	2	2-North (0-22.5)	1
3-(8.4 - 16.0)	3	3-Northeast (22.5-67.5)	3
4-(16.0 - 25.2)	3	4-East (67.5-112.5)	3
5-(25.2- 38.7)	1	5-Southeast (112.5-157.5)	2
6-(38.7 - 62.2)	1	6-South (157.5-202.5)	2
7-(62.2 - 214.3)	1	7-Southwest (202.5-247.5)	2
		8-West (247.5-292.5)	2
		9-Northwest (292.5-337.5)	1
		10-North (337.5-360)	1

The next step was to incorporate the factors in the weighted overlay model (Figure 4). All parameters were considered to be of equal importance and influence (weight). The Weighted Overlay tool parameters are presented in the following screenshot.



Raster	% Influence	Field	Scale Value
re_mer_sl_fl	25	VALUE	↶
		1	1
		2	2
		3	3
		NODATA	NODATA
re_meg_aspect	25	VALUE	↶
		1	1
		2	2
		3	3
		NODATA	NODATA
re_meg_slope	25	VALUE	↶
		1	1
		2	2
		3	3
		NODATA	NODATA
re_meg_landc	25	VALUE	↶
		1	1
		2	2
		3	3

Figure 4 Slope, aspect, soil moisture and landcover parameters imported in weighted overlay model according to predefined risk values

The final product of this stage was a raster dataset with categorical values of estimated risk of bark beetle attack. This dataset can be displayed as a risk map.

4. Results

4.1 Landcover distribution in the study area

The five dominant landcover classes for each tile are presented in Table 7. The landcover dataset which was provided by the National Landcover Database was the input for this initial analysis. We can see that in W1 the inland water and arable land cover most of the area. Next are pine forest and temporarily not forest. Fifth in the list is spruce forest not on wetland. Temporarily non-forest on wetland is the most dominant landcover category in W2 and W3 tiles. Spruce forest is the second class in these tiles. Pine forest is the most dominant class in E1 and E2. Marine water covers the most area in the last tile of the study area. In the last two tiles temporarily, non-forest is the second most dominant category. This table will further clarify if a land class is vulnerable in bark beetle attacks. Overlay operations between attacked trees and landcover layer will be presented in the next section.

Table 7 Area coverage of dominant landcover classes for each tile of the study area ("ar. land" is arable land, "other veg. open" is vegetated other open land, "inl. water" is inland water, "mar. water" is marine water, "pine, not wetland" is pine forest not on wetland, "spruce, not wetland" is spruce forest not on wetland, "mix. for. not wet." is mixed forest not on wetland, "tem. non-for. not wet." is temporarily non-forest not on wetland)

W1	**Value**	**Area (km2)**	**W2**	**Value**	**Area (km2)**	**W3**	**Value**	**Area (km2)**
	inl. water	1687		tem. non-for. not wet.	1215		tem. non-for. not wet.	1358
	ar. land	1466		spruce, not wetland.	1110		spruce, not wetland.	1001
	pine, not wetland	887		pine, not wetland	1055		inl. water	718
	tem. non-for. not wet.	633		inl. water	694		Other veg. open	666
	spruce, not wetland.	611		Other veg. open	569		ar. land	604
E1	**Value**	**Area (km2)**	**E2**	**Value**	**Area (km2)**	**E3**	**Value**	**Area (km2)**
	pine, not wetland	1768		pine, not wetland	1917		mar. water	1529

	ar. land	1315		tem. non-for. not wet.	1173		tem. non-for. not wet.	1054
	spruce, not wetland.	794		spruce, not wetland.	1062		pine, not wetland	1027
	inl. water	785		mix. for. not wet.	592		spruce, not wetland	960
	tem. non-for. not wet.	722		Other veg. open	486		ar. land	613

4.2 Landcover risk factor

The first research question to answer was which type of forest is more susceptible to spruce bark beetle outbreaks. For the year 2018 (drought year) almost half of the attacked spruce trees were in spruce forest not on wetland (Table 8 and Figure 5) followed by spruce trees in pine forest not on wetland. A first statement that one could make is that land cover category Spruce Forest not on wetland covers half (48%) of the total damaged area. Pine forest is the second most prone class to bark beetle attacks. The third category in this list is mixed coniferous not on wetland. 2018 is also considered a drought year from a meteorological perspective. These data are also presented in the of a pie chart (Figure 5).

The results are similar for the years (2019-2020) with more normal weather conditions. The same categories are the most prone with spruce forest covers even higher area than 2018. 55 % of the total damaged area. Pine forest is the second most exposed landcover class. The percent in this case is slightly lower (14%) in comparison with 2018. Mixed coniferous type is the third one with similar damaged area (Figure 6).

Table 8 Landcover categories and bark beetle attacks for 2018 and 2020

Landcover category	**2018 damaged areas (%)**	**2020 damaged areas (%)**	**coverage over the study area (%)**
Pine forest not on wetland	17.9 %	14,4%	11.1%
Spruce forest not on wetland	48.4 %	54,7%	7.6%
Mixed coniferous not on wetland	13.9 %	13,8%	2.8%

Mixed forest not on wetland	5.7 %	5,9%	3.7%
Temporarily non-forest not on wetland	4.7 %	2.4%	7.9%
Rest land cover categories	9.4 %	11,3%	66.9%

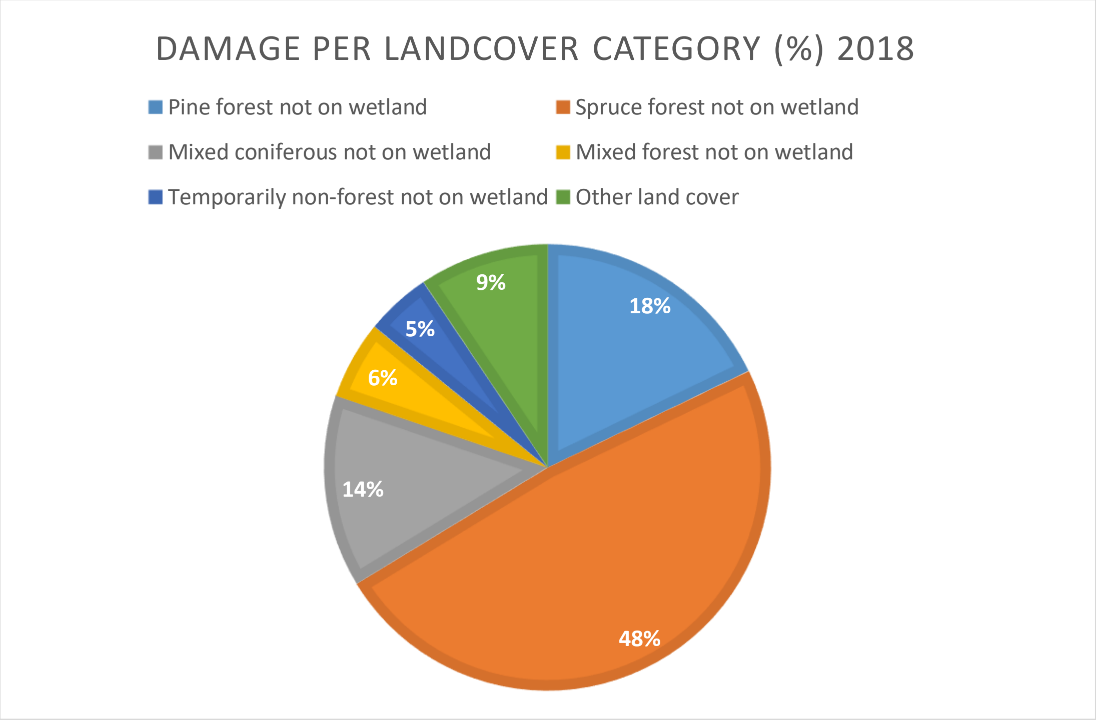


Figure 5 Landcover categories and bark beetle attacks fraction for 2018

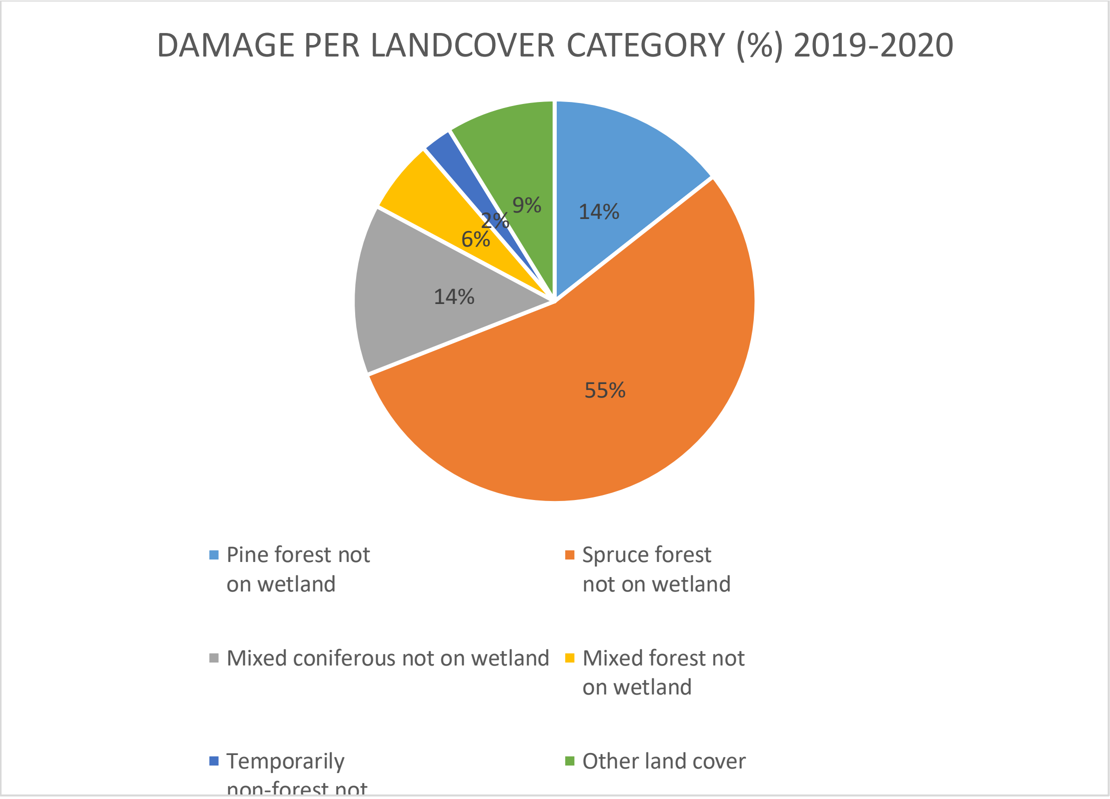


Figure 6 Landcover categories and bark beetle attacks fraction for 2020

The above tables and the graphs show that some landcover classes seem consistently more vulnerable to bark beetle attacks. In both years of study, the most attacked class was found to be spruce forest not on wetland. Furthermore, the percent of the specific class in comparison with the total percent was significantly high. In the first case spruce forest was attacked in a 48%. In the year 2020 this percent was even higher and resulted in 55%. The second most vulnerable class was pine forest not on wetland in both cases. The percentages were 18% and 14% respectively for the two years. The third type was mixed coniferous forest not scheduled wetland. The corresponding percentages in this case were: 13.9% (2018) and 13.8% (2020). The other classes that were attacked were mixed forests and various type of vegetation. The specific landcover classes are not the most dominant in the tiles of the study area as it was shown in the previous section. This fact boosts the perception that spruce forest category is considered the most vulnerable. In addition, it strengthens the perception that landcover is an important risk factor as it was observed in this section. This conclusion will be extensively discussed in the next section.

Another key operation is to investigate the pattern of the attacked trees. As we mentioned above the study area is divided in six tiles. This way it is easier to manage and inspect the regions of interest. In both study years the majority of attacked regions can be found in two specific tiles. These tiles are named E2 and E3 - respectively. As it was shown in the previous section the most dominant land cover types for these two tiles are pine forest and marine water respectively. This outcome will be further assessed. In the following sections of this paper other physical and climate variables will be incorporated. Investigating topographic conditions and soil moisture could result in correlations between attacked regions and specific intervals of the abovementioned risk factors.

4.3 Soil wetness index

In this section the effect of soil moisture in the attacked locations will be investigated. The study will focus if there is a difference in risk for trees that grow on normally drier areas (low index) compared to trees growing on normally wetter areas (high index). The first approach was to examine the mean soil moisture value for healthy and attacked locations. Then these were summarized for each year and for each tile. It must be clarified that soil wetness index is a static index and not soil moisture measured in real-time. This means that the values for the soil wetness itself do not change between the drought year (2018) and the normal year (2020).

The total mean soil wetness of most attacked cells for 2018 in the tiles is around 17(Figure 7). In tiles W2 and W3 the specific values are higher (23.7 and 28.1). The other tiles have much lower values. Healthy cells have a total mean wetness value above 25 units and soil wetness is consistently higher for healthy cells in all six tiles.

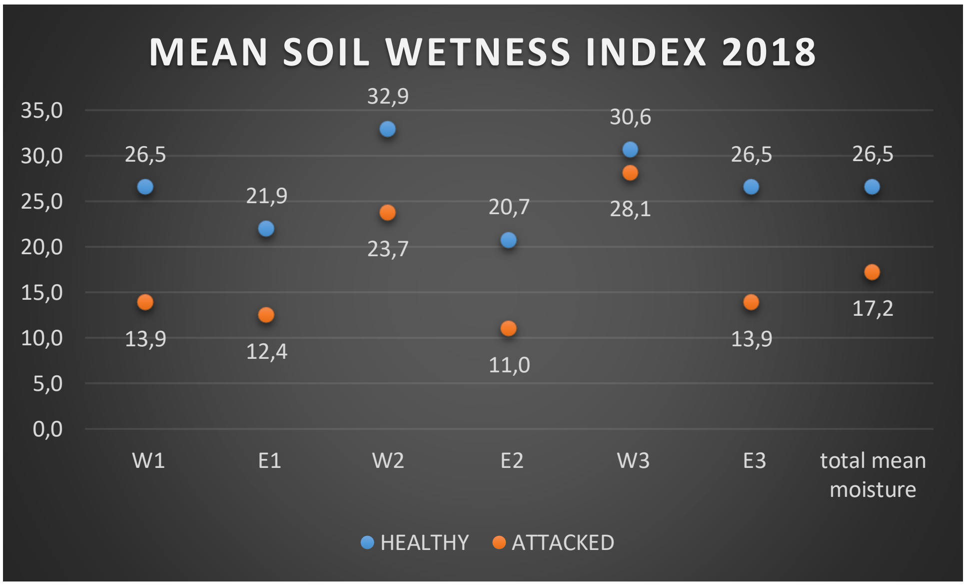


Figure 7 Mean soil wetness value (%) for healthy and attacked locations in total and for each tile of the study area for 2018

In 2020 the total mean wetness value for attacked cells is 18.2 units (Figure 8). Most of the tiles display a value lower than 20 units except one (W2). In 2020 the same patterns about healthy regions are repeated. The average total soil wetness value for the healthy cells is above 26 units. One tile presents a value higher than 30 units (W2). Mean soil wetness values of healthy trees are consistently higher than those of attacked trees for each tile of the study area.

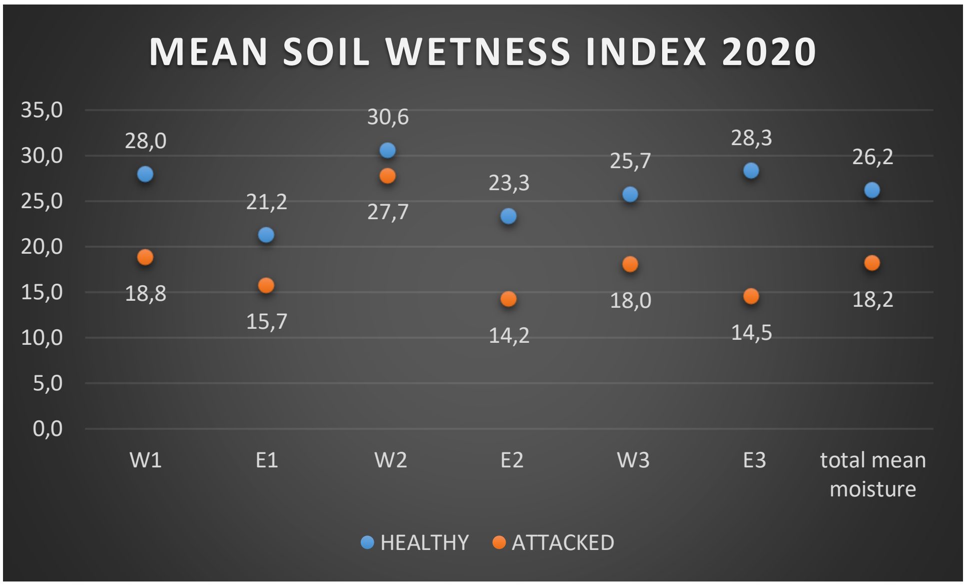


Figure 8 Mean soil wetness value (%) for healthy and attacked locations in total and for each tile of the study area for 2020

Total mean soil wetness values are similar for the two years of this study. Another observation can be made about the tiles which suffered the most bark beetle attacks. As mentioned in the previous section E2 and E3 had the majority of attacked trees in both temporal cases. If we focus in the values of soil wetness for these two tiles, we can see that that for Tile E2 soil wetness was lower for attacked pixels in 2018 compared to 2020 (Table 9).

Table 9 The two tiles with the largest number of bark beetle attacks with their corresponding soil wetness value for 2018 and 2020

Tile	**Mean soil wetness index 2018 attacked cells (%)**	**Mean soil wetness index 2020 attacked cells (%)**
E2	11.0	14.2
E3	13.9	14.5

Mean soil wetness in 2020 is almost the same for the tiles that had the most incidents of bark beetle attacks. This could be a clear pattern and was further investigated. The next operation was to consider other types of correlations for the attacked cells and specifically for these two tiles. For example, the most dominant landcover category of these tiles were pine forest and marine water respectively.

The next step was to group the mean soil wetness value of each one of the main landcover category (Table 10). The table displays the mean soil wetness value for every landcover category for every tile.

Based on the results of attacked and healthy trees we can color code this table by using a specific color for the landcover category that had a mean soil wetness value lower than 30 for the specific tile (Table 10). The last column presents the total mean soil wetness value for each landcover category over the study area. This value is calculated based on the mean value for each tile.

We can notice that categories that were the most vulnerable to bark beetle attacks like spruce forest, pine forest and mixed coniferous forest display soil moisture values similar to the ones that were preferred by bark beetles. The final table could potentially indicate other land cover classes that would be prone to pest attacks in future scenarios. Mixed forest class category manifest mean soil wetness values that were preferred by bark beetle in other cases. This result could designate forest types that would be favored by the bark beetles in the upcoming years.

Table 10 Mean soil wetness value for every landcover category in each tile and over the entire study area displaying values below 30

Landcover description name	W1 MEAN	E1 MEAN	W2 MEAN	E2 MEAN	W3 MEAN	E3 MEAN	mean soil wetness value (study area)
Pine forest not on wetland (111)	25.6	7.4	32.6	12.7	30.5	19.3	21.4
Spruce forest not on wetland (112)	26.3	15.8	31.3	19.6	28.4	21.3	23.8
Mixed coniferous not on wetland (113)	28.4	11.7	29.7	15.9	30.3	19.3	22.5
Mixed forest not on wetland (114)	39.5	23.2	45.5	29.1	39.8	29.9	34.5
Temporarily non-forest not on wetland (118)	31.4	13.2	32.0	18.1	32.6	22.2	24.9
Pine forest on wetland (121)	91.3	84.5	93.1	86.9	91.9	86.4	89.1
Spruce forest on wetland (122)	83.0	72.8	84.1	73.5	81.1	73.0	77.9
Mixed coniferous on wetland (123)	84.8	77.0	86.8	80.0	85.4	80.6	82.4

There is a similar pattern in the distribution of attacked cells over the soil wetness classes for the years 2018 and 2020(Figure 9 and Figure 10). The figures show the total number of attacks for each soil moisture value for the years 2018 and 2020. There is a higher number of attacked cells in 2020 but the distributions among the soil moisture values are similar.

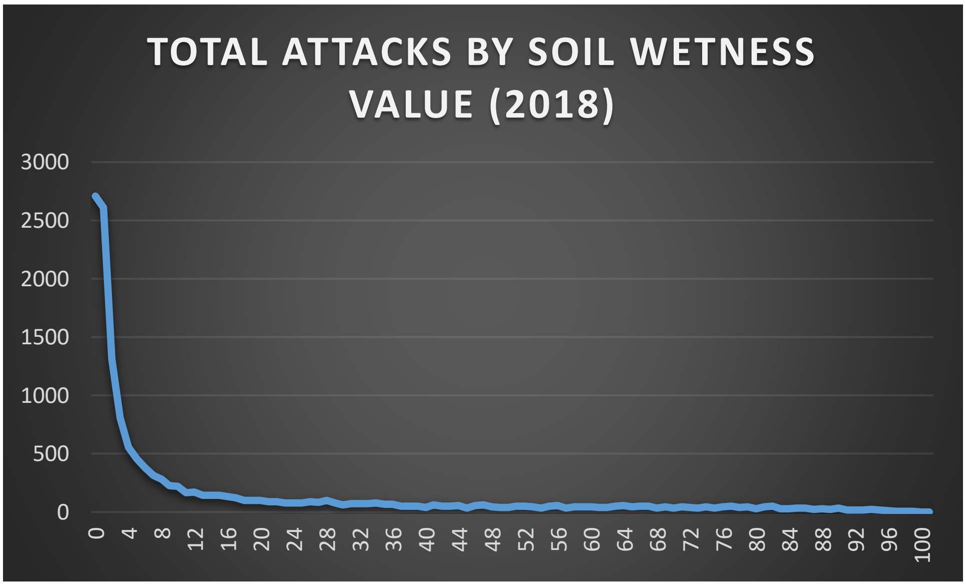


Figure 9 Total number of bark beetle attacks for every soil wetness value (%) in Southeastern Sweden for 2018

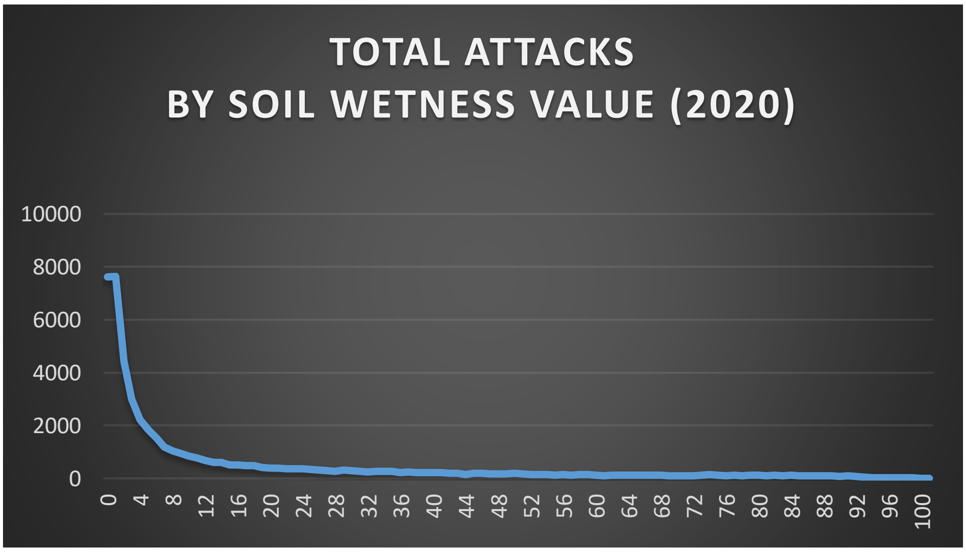


Figure 10 Total number of bark beetle attacks for every soil wetness value (%) in Southeastern Sweden for 2020

4.4 Slope results

The next step in this analysis was to examine the slope variable and its effect on bark beetle incidents. Topography is considered an important risk factor for the pest outbreaks and slope is an important parameter for describing the topography of a location.

The slope intervals with the higher proportion of cells with bark beetle attack, compared to their proportion in the study area, were in the range 2.5-25.2% (Table 11; classes 2-4). The slope interval 2.5-8.4% had the highest fraction of attacked cells for both years (Figure 11). The specific category accounts for 39.73 and 41.57 of total attacked cells for the corresponding years (2018, 2020). The slope class 1 (0-2.5%) accounts for around 25% of the cells with bark beetle attack; however, this class covers nearly 43% of the study area i.e. fraction with attacked cells is considerably lower than the area covered indicating that the risk for bark beetle attack is low in nearly flat areas. This pattern which indicates that slope is an important risk factor. Slope is a factor that should be incorporated in any forest management policy of the authorities.

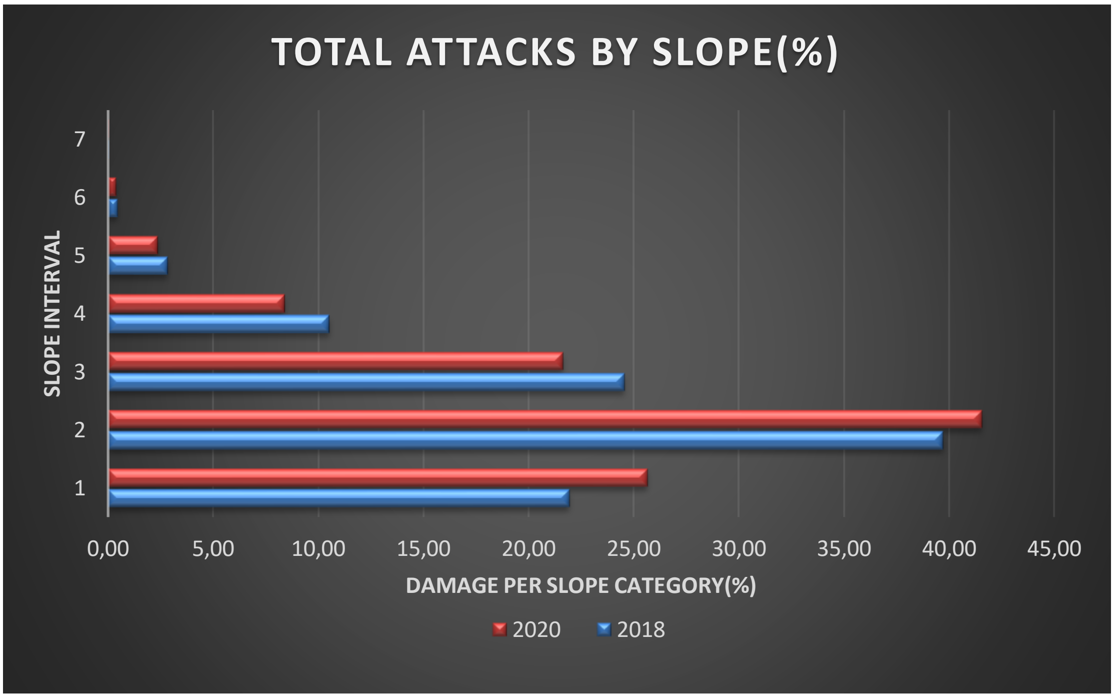


Figure 11 Fraction of bark beetle attacks for each slope interval class [1- (0 - 2.5), 2-(2.5 - 8.4), 3-(8.4 - 16.0), 4-(16.0 - 25.2), 5-(25.2- 38.7), 6-(38.7 - 62.2), 7-(62.2 - 214.3)] for the years 2018 and 2020

4.5 Aspect results

This section will examine the aspect results of the performed analysis. This will help answering the question about whether the aspect influence the risk of bark beetle proliferation. Table 11 and Figure 12 presents the results over the study area.

Most of the attacked cells are found in specific aspects in both cases. The zone with the highest risk seems to be zone 4. This zone is linked to the East direction (67.5-112.5). The corresponding percentages were 16.7% and 16.5% for the years of study. Furthermore, Northeast (3) and Southeast (5) zones seem to escalate the risk for bark beetle attack. Northeast accounts for 15.8% and 15.4% of the attacked incidents. Southeast section is responsible for 12.4% and 13.4% of the attacked cells respectively.

To summarize the aspect results of the analysis we can pinpoint some patterns that are prominent by the results. Eastern facing slopes are preferred in general by bark beetle. Eastern facing slopes contribute a 44.9% and a 45.3% of the total attacks. North facing slopes are responsible for a 37.2 % and a 36.1%. South facing slopes contribute a 34.8% and 37%. West facing slopes contribute a 32.9% and 31.9% respectively. Eastern and Northeastern slopes seem to have a higher risk than south southwest directions. One explanation for these results could be that north and northeast slopes are shaded and cooler than their counterparts which are more sun exposed. Receiving less solar radiation could explain why bark beetles prefer the specific directions.

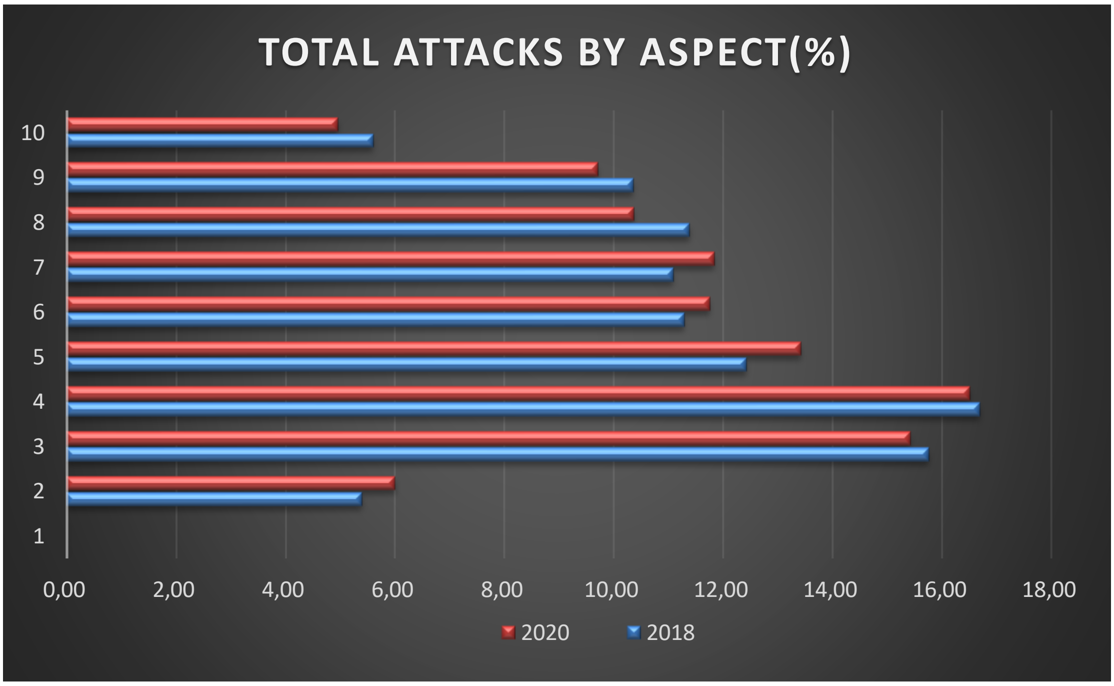


Figure 12 Fractions of bark beetle attacks for each aspect interval for the years 2018 and 2020

4.6 Risk map

The final step of the workflow was to create a risk map (Figure 13). This map can pinpoint areas of distinct risk. This product can be an important contributor to an organized schema of guidelines. The map can be a powerful tool to tackle and mitigate possible bark beetle outbreaks. The mitigation strategies should be concentrated to high-risk regions.

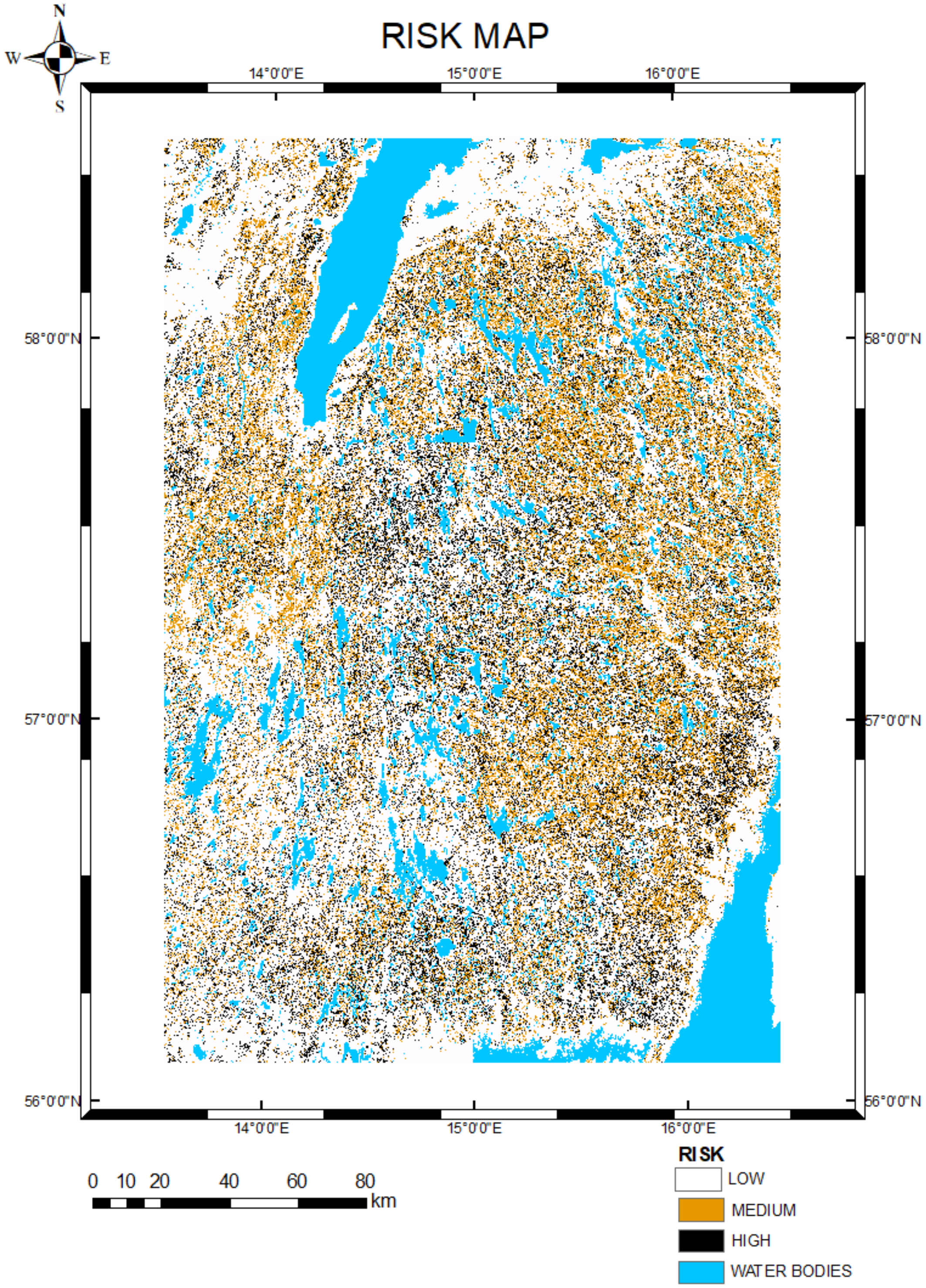


Figure 13 Risk map of bark beetle attacks in Southeastern Sweden

For a more detailed study, individual tile analysis of this map could yield important findings (Figure 14). Based on the density of risk classes medium risk seems the most dominant class. By examining Figure 14 high risk locations are concentrated in the W2, E2. Some high-risk regions exist in W3 and E3 as well. In the other tiles high risk regions appear more dispersed.

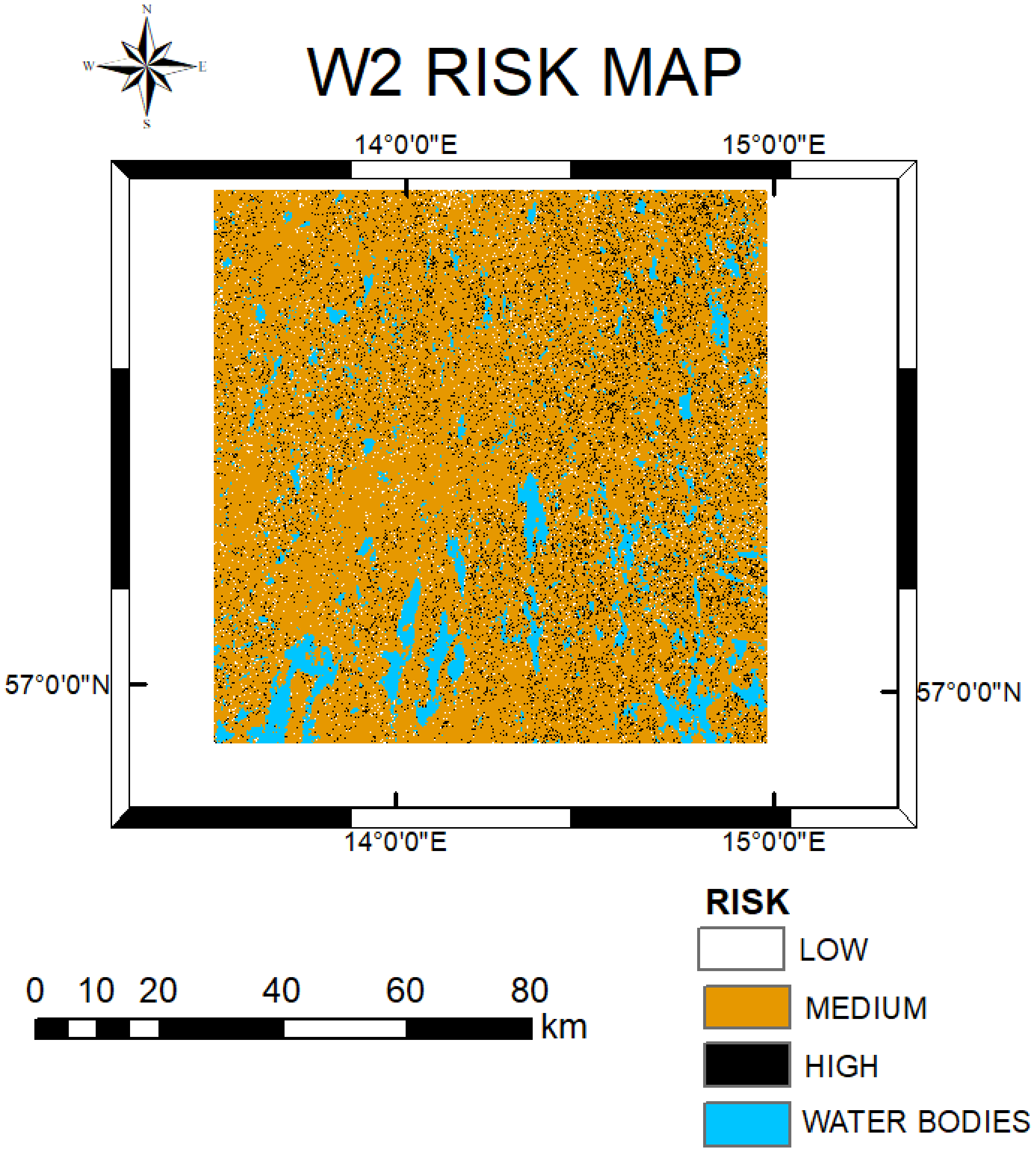


Figure 14 W2 bark beetle risk map (region with elevated risk)

5. Discussion

In this section we will delve deeper into the findings of the analysis section. The main goal of this part is to extend and evaluate the results of the tools and the methodology that were adopted. Furthermore, benefits and drawbacks of the specific approach will be debated. Finally, the risk factors and thesis workflow will be questioned. It is important to clarify that the risk factors that were studied are about a drought-triggered outbreak and could differ in a storm-triggered outbreak.

5.1 Methods discussion

The first strategic decision that was made revolved around the methodological framework. This framework was shaped by the research questions that were stated in the earliest stage. The research questions drove the data selection. As mentioned above the workflow for this thesis comprised of three stages. The first stage was the clearing process and the creating of the bark beetle attacks dataset. The methodological framework was formed based on this layer. The main process was to perform overlay operations between the bark beetle attacks dataset and the various risk factors. Later the results were grouped according to predefined criteria. Various calculations were performed. Comparing the results would drive us to answer the questions. This was the second stage. The final stage was about the creation of the risk map of the study area. Each one of this risk factors is evaluated in the rest of this section.

5.2 Landcover discussion

Landcover category was clearly observed to in some cases increases the risk of bark beetle attacks. Spruce forest was preferred by the bark beetles in both cases that data were available (2018 and 2020). As it was shown this was the most dominant category among the damaged areas. The portion that was attributed to this class was extremely high (almost 50%). This metric indicated that spruce forest is favored by bark beetle and should be managed accordingly which agrees with Hart et al. (2013). Pine forest, according to the landcover data, was also attacked in a systematic fraction of the damaged areas. Coniferous was the third most vulnerable class in both cases. These three categories were repeatedly coincided with bark beetle attack incidents. A clear pattern was revealed and should be further investigated. One key observation is that the accuracy of the land cover affects the analysis and the results, it is e.g. likely that the pine forest should have been classified as mixed coniferous forests i.e. including also spruce trees since only spruce trees are attacked by European spruce bark beetles. Trees collected by harvester machines exceed the cell size of the dataset. Furthermore, some trees were also considered attacked and were removed as a precautionary action. This could result in cells classified as a different landcover category from the actual one. It is hard to quantify but it is an uncertainty in the results. One of the key measures to prevent future damage is to plant pine trees – not spruce trees – on dry forest soils. For many years spruce trees were planted on dry soil, to avoid heavy browsing by moose in pine plantations (Felton et al. 2020). Another important factor that was not considered is distance to previous year's attack.

This is mainly for 2020 since there was an ongoing outbreak then with large numbers of attacked trees the year before. Spatial outbreak progression between years is influenced by previous attacks. For 2018 the bark beetle populations were much lower.

Forests that are mostly covered by these three classes, should be managed by targeted policies to avoid negative effects. Forests are important contributors in the fight against climate crisis. Climate variability and deforestation is a self-feeding process as it was discussed in the background section. Deforestation deteriorates the effects of climate change which creates favorable conditions for pest outbreaks. The contribution of forest ecosystems to the carbon cycle is of the utmost importance. The ability of forests to alleviate the climate consequences should not be disturbed. The balance that forest ecosystems provide to the carbon cycle should not be shifted.

As pointed out landcover is an important risk factor. Specific forest types have a higher probability of being attacked. Holistic management policies and actions should be determined. Based on the results efficient management strategies should be implemented. There are many management options to restrain pest outbreaks. One solution could be to create safety zones inside forest with some buffer areas between high-risk category trees (spruce trees). This paper focused on environmental parameters and risk factors. A sustainable management should incorporate social and economic perspectives of bark beetle attacks.

5.3 Soil wetness and Drought insights

Another parameter that was included was soil moisture. It was observed by the analysis that attacked locations displayed lower values of soil moisture than healthy ones. Similar mean values of soil moisture were preferred by bark beetles which is also an indicator of a pattern. Soil moisture values were also observed on a landcover category level. The results enhanced the deductions about the high risk landcover categories. These three susceptible classes displayed mean moisture values like the ones that were observed for attacked locations. The specific results of soil moisture values reinforced the existence of high risk landcover categories. Another key notice was that some landcover classes could be potentially vulnerable in the future based on the moisture values. Mixed forest class and deciduous forest category could face high risk of bark beetle attacks in the coming years. Based on the findings of the analysis adaptive policies could be structured. This result could lead to the construction of appropriate management guidelines.

Drought was a variable that had to be measured. The impact of drought on the importance of the risk factors was quantified indirectly. Data were provided for two distinct years 2018 and 2020. The former was considered a drought year. The latter was studied as a “normal” meteorological year. All the risk factors were examined and compared under this prism. The impact of drought on the risk factors was not illustrated in the results. Landcover classes that were preferred by bark beetles were similar for the two seasons. Furthermore, portions of damaged areas were close. Soil moistures values were not majorly differentiated between the two years of study. Attacked and healthy locations were attributed almost identical values. Bark beetle populations were higher in 2020-ongoing outbreak- and that is factor to consider when comparing 2018 and 2020 but it was not possible how to quantify. Based on the provided data and the methodology no strong impact of drought on the relative importance was depicted in the results. The lack of recognition does not necessarily mean lack of existence.

To summarize, we can conclude that lower soil moisture values were much more susceptible to bark beetle attacks. Since areas with low soil moisture is at higher risk drought is a risk factor which agrees with Robbins et al. (2022) and Netherer et al. (2019). Drier areas are always at risk, even in more “normal” conditions from a weather perspective.

5.4 Topography discussion

The next research question evaluated the impact of topography on bark beetle attacks. Topography was included in the equation by examining the effect of slope and aspect on bark beetle outbreaks. Slope of the study area was divided into 7 categories. Class 2 (2.5 -8.4 %) displayed the highest percent of attacked regions. Class 3(8.5-16.0 %) and Class 4(16.0-25.2 %) were also linked to a high possibility of pest disturbances. This fact clearly indicates that slope is related the bark beetle hazard. The specific findings should be incorporated to an adjusted management framework. Forests that are found in the specific slope intervals should be supervised accordingly. A focused policy based on the necessities of each case should be implemented for maximum efficiency.

Another parameter that was examined was aspect. Aspect was divided into 10 categories. Based on the results some specific directions accumulated higher percentages of attacks. East facing slopes were found to be the most vulnerable. East slopes comprised of 3 individual categories:

- Northeast
- East
- Southeast

The most susceptible class was observed to be category 4 (East 67.5-112.5). This category contained 16.7% and 16.5% of the damaged areas for the corresponding years of study. Aspect was also recognized to be an important factor that should be implemented in a sustainability strategy.

Slope was considered to be an important risk factor. The results that were reached in the two temporal occasions were similar. The same slope interval (category 2) was responsible for the bigger portion of attacked locations. The results do not manifest any diversification. The specific category received more attacks in terms of percentage for the year 2020. Another perspective about the importance of slope is the possible correlation with soil wetness. In general, flat areas (low slopes) will have a higher soil wetness value than areas with higher slopes. A possible explanation is that water flows down to the lower slopes. On the other hand, there are flat areas on higher parts of mountains/hills with low slope that also have low soil wetness. A possible negative correlation may appear in the results between slope and soil wetness. It was hard to quantify this possible correlation and a correlation test was not performed.

Aspect was also recognized to favor the bark beetle attacks. Locations in the eastern facing slopes were observed to be the most vulnerable. The result did not display any major variance for the years of this study. Drought effect was not emphasized in the results. Attacked regions were related in both cases.

To summarize, slope and aspect proliferate the ability of bark beetles to infest and breed which matches with Kaminska et al. (2021). This means that the topography of a region should always be incorporated in any attempt to tackle pest disturbances. This fact also proves that each management policy should be tailored to the needs and the characteristics of the specific location. A one size fits all approach should be replaced. This was the dominant methodology in the past. As it was pointed out in the introduction and it was observed with the abovementioned results, a “fit for purpose” framework will yield greater profits and revenues.

5.5 Risk map discussion

The final stage of the workflow was the creation of a risk map of the study area. All risk factors were considered of equal weight. The risk zones were generated based on the findings of the analysis. Highest risk regions appear in the central tiles of the study area and specifically E2 and W2. Actions should be focused to these tiles to reduce the potential risk. Creating maps of gradual risk of outbreaks can be very useful and preventive. These maps could be offering a critical help during specific periods when disturbances reach historical high rates. Including more variables and accurate data will return more precise locations that could be found on greater hazards of attacks. Identifying potential hotspots will shape a sustainable and effective management strategy. This can be achieved by adopting an impact-driven policy which will incorporate deteriorating climate conditions.

6. Conclusions

This thesis had to two main goals. The first one was to evaluate which type of forest is more susceptible to bark beetle outbreaks. The second one was to evaluate the effect of soil moisture and topography to the bark beetle risk. The results of the analysis pointed out that landcover, soil moisture and physical landscape could intensify the bark beetle spread. Bark beetle risk was higher in spruce forest. Furthermore, locations with lower soil moisture values had higher percent of bark beetle attacks. In addition, slope class 2(2.5 - 8.4%),3(8.4 - 16.0%) and 4 (16.0 - 25.2%) manifested higher bark beetle attack risk. Similarly, aspect class 3(22.5-67.5°) and class 4(67.5-112.5°) favored the bark beetle risk. The final stage of the analysis included the creation of a risk map for the study area. This map displayed zones of gradual bark beetle risk over the entire study area. This map can be used by policy makers to structure targeted guidelines in the locations which demonstrated the highest risk. It is important to state that the abovementioned results were not supported by statistical tests.

To summarize, deteriorating climate effects are challenging forest ecosystems and their services. Various natural disturbances including bark beetle are expected to intensify in the coming years. Incorporating environmental social and economic criteria could quantify the risk of these disturbances and drive a more sustainable and focused management policy.

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Appendix

Table 11 Total number of attacked and healthy cells for each soil wetness value in 2018

2018 SOIL MOISTURE VALUE	HEALTHY CELLS	ATTACKED CELLS
0	28915	2709
1	31214	2611
2	18037	1311
3	12224	809
4	9617	556
5	7736	458
6	6485	381
7	5736	315
8	4878	282
9	4490	227
10	4063	223
11	3696	168
12	3417	170
13	3138	142
14	2914	142
15	2801	141
16	2654	133
17	2521	122
18	2395	101
19	2308	102
20	2176	100
21	2129	87
22	1967	91
23	1901	80
24	1895	76
25	1835	76
26	1834	88
27	1723	81
28	1643	102
29	1611	80
30	1644	61
31	1573	74
32	1563	70
33	1533	72
34	1453	76
35	1505	68
36	1420	69
37	1402	52
38	1366	48
39	1361	49

40	1306	41
41	1321	61
42	1246	49
43	1241	51
44	1265	57
45	1228	36
46	1182	57
47	1162	60
48	1197	44
49	1148	40
50	1170	37
51	1182	50
52	1155	50
53	1190	43
54	1138	35
55	1196	51
56	1213	54
57	1220	35
58	1168	42
59	1200	44
60	1155	46
61	1156	37
62	1142	37
63	1162	52
64	1147	53
65	1149	43
66	1131	50
67	1206	50
68	1155	35
69	1152	46
70	1127	35
71	1173	43
72	1198	38
73	1180	34
74	1197	46
75	1135	35
76	1214	46
77	1192	52
78	1226	37
79	1203	43
80	1213	30
81	1207	45
82	1209	49
83	1281	30
84	1168	30
85	1279	32

86	1207	32
87	1204	24
88	1216	26
89	1151	23
90	1124	31
91	1043	18
92	927	15
93	861	19
94	904	20
95	791	16
96	837	9
97	818	6
98	1032	5
99	1440	4
100	269	0
101	97	0

Table 12 Total number of attacked and healthy cells for each soil wetness value 2020

2020 SOIL MOISTURE VALUE	HEALTHY CELLS	ATTACKED CELLS
0	145764	7631
1	161984	7638
2	98084	4435
3	67904	3002
4	52573	2232
5	43207	1837
6	36795	1532
7	31983	1196
8	28372	1039
9	25439	954
10	23312	855
11	21144	782
12	19585	687
13	18041	614
14	16573	605
15	15543	516
16	14607	517
17	14114	489
18	13323	475
19	12998	417
20	12391	395
21	11744	381
22	11177	360
23	10646	375

24	10541	356
25	10203	327
26	9915	318
27	9717	298
28	9267	276
29	9094	303
30	8955	294
31	8712	276
32	8415	250
33	8355	255
34	8057	276
35	8015	259
36	7936	223
37	7724	244
38	7538	220
39	7463	208
40	7330	220
41	7217	227
42	7049	182
43	7018	192
44	6973	155
45	6824	190
46	6642	196
47	6703	172
48	6570	169
49	6384	160
50	6380	185
51	6280	169
52	6417	152
53	6299	138
54	6493	143
55	6398	120
56	6220	137
57	6150	118
58	6090	150
59	6022	139
60	6179	129
61	6026	107
62	6026	131
63	6200	133
64	6066	110
65	5938	126
66	6141	123
67	6080	133
68	6100	114
69	6207	92

70	6226	101
71	6253	104
72	6236	102
73	6222	116
74	6477	139
75	6368	119
76	6554	108
77	6661	110
78	6561	109
79	6642	117
80	6820	113
81	6775	93
82	6852	126
83	6945	103
84	6933	133
85	6904	105
86	6836	93
87	6893	99
88	6647	109
89	6529	87
90	6402	79
91	5958	87
92	5387	71
93	5076	57
94	4711	35
95	4492	23
96	4457	27
97	4994	15
98	6472	23
99	6618	34
100	831	1
101	516	1

Table 13 Portions of attacked and healthy locations for each slope interval for the east and west tiles of the study area (2018 and 2020 respectively)

W1	SLOPE (PERCENT)	HEALTHY (%)	ATTACKED (%)	W2	SLOPE (PERCEN)	HEALTHY (%)	ATTACKED (%)	W3	SLOPE (PERCENT)	HEALTHY (%)	ATTACKED (%)
1	0 - 2.5	4.8	6.0	1	0 - 3.2	10.4	11.8	1	0 - 2.2	4.9	12.3
2	2.5 - 8.4	7.7	8.7	2	3.2 - 8.5	9.9	9.8	2	2.2 - 6.6	4.3	7.3
3	8.4 - 16.0	9.4	8.5	3	8.5 - 14.8	9.8	10.9	3	6.6 - 13.2	3.7	7.3
4	16.0 - 25.2	8.8	7.5	4	14.8 - 22.3	10.1	11.2	4	13.2 - 20.9	3.0	4.9
5	25.2 - 38.7	7.3	6.2	5	22.3 - 32.9	12.5	9.8	5	20.9 - 30.8	1.5	2.6
6	38.7 - 62.2	5.5	6.2	6	32.9 - 49.8	12.7	12.3	6	30.8 - 49.6	0.8	1.5
7	62.2-214.3	1.3	0.0	7	49.8 - 270.3	14.3	100.0	7	49.6 - 280.9	0.0	0.0

1	0 - 2.5	6.8	6.2	1	0 - 3.2	7.5	4.3	1	0 - 2.2	12.0	4.6
2	2.5 - 8.4	10.0	8.7	2	3.2 - 8.5	6.8	2.4	2	2.2 - 6.6	15.0	5.0
3	8.4 - 16.0	9.7	10.5	3	8.5 - 14.8	7.3	2.2	3	6.6 - 13.2	21.0	8.4
4	16.0 - 25.2	8.0	8.1	4	14.8 - 22.3	7.1	2.5	4	13.2 - 20.9	21.8	9.3
5	25.2 - 38.7	7.9	4.4	5	22.3 - 32.9	7.2	4.4	5	20.9 - 30.8	22.5	8.0
6	38.7 - 62.2	7.6	2.7	6	32.9 - 49.8	7.0	4.9	6	30.8 - 49.6	22.0	8.2
7	62.2 - 214.3	6.6	0.0	7	49.8 - 270.3	8.7	0.0	7	49.6 - 280.9	6.9	0.0

E1	SLOPE (PERCENT)	HEALTHY (%)	ATTACKED (%)	E2	SLOPE (PERCENT)	HEALTHY (%)	ATTACKED (%)	E3	SLOPE (PERCENT)	HEALTHY (%)	ATTACKED (%)
1	0 - 3.9	12.9	5.0	1	0 - 2.9	21.8	25.8	1	0 - 2.3	45.1	39.2

2	3.9 - 10.8	18.2	8.0	2	2.9 - 8.0	26.0	35.9	2	2.3 - 5.8	33.9	30.3
3	10.8 - 18.7	21.9	8.8	3	8.0 - 13.8	25.0	34.1	3	5.8 - 10.4	30.3	30.4
4	18.7-28.6	23.7	11.3	4	13.8 - 21.0	28.6	35.8	4	10.4 - 16.2	25.8	29.3
5	28.6 - 41.4	27.6	14.0	5	21.0-30.4	31.6	39.5	5	16.2 - 23.8	19.5	27.9
6	41.4 - 63.0	26.1	29.2	6	30.4-46.4	42.6	35.4	6	23.8 - 36.5	12.3	15.4
7	63.0-251.2	17.7	0.0	7	46.4 - 184.7	58.9	0.0	7	36.5-147.8	7.7	0.0

1	0 - 3.9	14.7	9.9	1	0 - 2.9	37.0	47.3	1	0 - 2.3	22.0	27.7
2	3.9 - 10.8	17.4	14.1	2	2.9 - 8.0	34.2	47.1	2	2.3 - 5.8	16.5	22.7
3	10.8 - 18.7	21.7	17.2	3	8.0 - 13.8	25.8	35.7	3	5.8 - 10.4	14.5	25.9
4	18.7-28.6	26.7	18.7	4	13.8 - 21.0	25.4	32.4	4	10.4 - 16.2	11.0	29.1
5	28.6 - 41.4	27.7	16.3	5	21.0-30.4	25.8	33.8	5	16.2 - 23.8	8.8	33.1
6	41.4 - 63.0	26.8	18.6	6	30.4-46.4	27.7	20.2	6	23.8 - 36.5	8.9	45.4
7	63.0-251.2	30.0	36.4	7	46.4 - 184.7	38.1	9.1	7	36.5-147.8	9.7	54.5

Table 14 Number of healthy and attacked cells for the west tiles of the study area for each aspect interval for 2018 and 2020

WEST1	ASPECT	HEALTHY	ATTACKED	WEST2	ASPECT	HEALTHY	ATTACKED	WEST3	ASPECT	HEALTHY	ATTACKED	2018
1	Flat (-1)	0	0	1	Flat (-1)	0	0	1	Flat (-1)	0	0	
2	North (0-22.5)	1061	67	2	North (0-22.5)	1481	82	2	North (0-22.5)	602	63	
3	Northeast (22.5-67.5)	2463	135	3	Northeast (22	3308	304	3	Northeast (22.5-67.5)	1234	194	
4	East (67.5-112.5)	3073	196	4	East (67.5-112	4364	392	4	East (67.5-112.5)	1493	160	
5	Southeast (112.5-157.5)	2364	156	5	Southeast (11	2435	180	5	Southeast (112.5-157.5)	1442	132	
6	South (157.5-202.5)	2052	138	6	South (157.5-	1886	128	6	South (157.5-202.5)	1455	112	
7	Southwest (202.5-247.5)	2427	137	7	Southwest (2	2981	161	7	Southwest (202.5-247.5)	1230	136	
8	West (247.5-292.5)	2530	134	8	West (247.5-2	5177	145	8	West (247.5-292.5)	1418	193	
9	Northwest (292.5-337.5)	2217	118	9	Northwest (2	3567	126	9	Northwest (292.5-337.5)	1243	142	
10	North (337.5-360)	1004	83	10	North (337.5-	1508	66	10	North (337.5-360)	604	53	
WEST1	ASPECT	HEALTHY	ATTACKED	WEST2	ASPECT	HEALTHY	ATTACKED	WEST3	ASPECT	HEALTHY	ATTACKED	2020
1	Flat (-1)	0	0	1	Flat (-1)	0	0	1	Flat (-1)	0	0	
2	North (0-22.5)	6368	203	2	North (0-22.5)	4598	49	2	North (0-22.5)	4598	49	
3	Northeast (22.5-67.5)	13061	544	3	Northeast (22	12947	170	3	Northeast (22.5-67.5)	12947	170	
4	East (67.5-112.5)	17734	717	4	East (67.5-112	18784	267	4	East (67.5-112.5)	18784	267	
5	Southeast (112.5-157.5)	16854	509	5	Southeast (11	12098	186	5	Southeast (112.5-157.5)	12098	186	
6	South (157.5-202.5)	12586	377	6	South (157.5-	7985	180	6	South (157.5-202.5)	7985	180	
7	Southwest (202.5-247.5)	13065	445	7	Southwest (2	11589	209	7	Southwest (202.5-247.5)	11589	209	
8	West (247.5-292.5)	20638	669	8	West (247.5-2	17717	219	8	West (247.5-292.5)	17717	219	
9	Northwest (292.5-337.5)	17931	521	9	Northwest (2	11940	129	9	Northwest (292.5-337.5)	11940	129	
10	North (337.5-360)	6565	206	10	North (337.5-	4359	50	10	North (337.5-360)	4359	50	

Table 15 Number of healthy and attacked cells for the east tiles of the study area for each aspect interval for 2018 and 2020

EAST1	ASPECT	HEALTHY	ATTACKED	EAST2	ASPECT	HEALTHY	ATTACKED	EAST3	ASPECT	HEALTHY	ATTACKED	2018
1	Flat (-1)	0	0	1	Flat (-1)	0	0	1	Flat (-1)	0	0	
2	North (0-22.5)	3621	63	2	North (0-22.5	5757	285	2	North (0-22.5)	5870	242	
3	Northeast (22.5-67.5)	8368	206	3	Northeast (22	12962	896	3	Northeast (22.5-67.	12060	608	
4	East (67.5-112.5)	6168	163	4	East (67.5-112	8595	802	4	East (67.5-112.5)	12595	768	
5	Southeast (112.5-157.5)	4739	119	5	Southeast (11	5905	564	5	Southeast (112.5-15	12123	695	
6	South (157.5-202.5)	4894	101	6	South (157.5-	6165	555	6	South (157.5-202.5)	11230	644	
7	Southwest (202.5-247.5)	5800	159	7	Southwest (2	7230	506	7	Southwest (202.5-24	10531	549	
8	West (247.5-292.5)	6128	199	8	West (247.5-2	7474	505	8	West (247.5-292.5)	10324	516	
9	Northwest (292.5-337.5)	5986	130	9	Northwest (2	7656	529	9	Northwest (292.5-33	10319	493	
10	North (337.5-360)	3003	73	10	North (337.5-	4843	313	10	North (337.5-360)	5489	244	
EAST1	ASPECT	HEALTHY	ATTACKED	EAST2	ASPECT	HEALTHY	ATTACKED	EAST3	ASPECT	HEALTHY	ATTACKED	2020
1	Flat (-1)	0	0	1	Flat (-1)	0	0	1	Flat (-1)	0	0	
2	North (0-22.5)	20684	427	2	North (0-22.5	33811	1427	2	North (0-22.5)	14570	780	
3	Northeast (22.5-67.5)	46890	1209	3	Northeast (22	81493	3505	3	Northeast (22.5-67.	33744	1940	
4	East (67.5-112.5)	37253	1125	4	East (67.5-112	63710	3520	4	East (67.5-112.5)	39140	2175	
5	Southeast (112.5-157.5)	24590	868	5	Southeast (11	44891	2783	5	Southeast (112.5-15	34181	2029	
6	South (157.5-202.5)	22363	711	6	South (157.5-	45652	2631	6	South (157.5-202.5)	30224	1666	
7	Southwest (202.5-247.5)	28616	817	7	Southwest (2	54619	2697	7	Southwest (202.5-24	27064	1410	
8	West (247.5-292.5)	34825	869	8	West (247.5-2	50119	1958	8	West (247.5-292.5)	23835	1135	
9	Northwest (292.5-337.5)	36212	724	9	Northwest (2	53546	2064	9	Northwest (292.5-33	23099	1181	
10	North (337.5-360)	18359	399	10	North (337.5-	30383	1133	10	North (337.5-360)	12953	586	

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