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Occurrences of insect outbreaks in Sweden in relation to climatic parameters since 1850

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Master thesis, 30 credits, in *Physical Geography and Ecosystem Analysis*

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Table of contents

Abstract

This study was carried out in order to identify the main insect species responsible for forest damages (pests) in Sweden, and to explore the relationships between insect outbreaks and environmental variables (temperature, precipitation, and availability of insect host trees, including storm damaged trees). Special attention was given to changes in management practices through time, and their consequences for pest outbreaks. The occurrences of insect outbreaks were analyzed for the southern, central and northern Sweden during two periods, 1850-1950 and 1961-2014. A Principal Component Analysis was conducted for each of the three regions in order to assess which insect families and insect species caused the main forest damage. The ratio between broadleaved and coniferous trees was calculated to highlight the type of forests mostly attacked by insect pests. A Variation Partitioning Analysis was carried out to study the influence of the climatic variables (temperature and precipitation) and the volume of storm felled trees on the occurrences of insect species responsible for outbreaks. During the first period, insect outbreaks increased markedly after 1911, and remained at a high level throughout the period. The Variation Partitioning Analysis showed that this trend might have been strongly influenced by climate and storm events. However, for the second period of time an association between these variables and the insect species responsible for the main forest damage could not be distinguished, and a clear decrease in the occurrences of insect outbreaks could be noticed in comparison with the first period. Other studies clearly showed a relation between outbreaks and climate also for the second period. The inconsistency in this study between the two time periods is attributed to the different datasets used and to other processes, such as changes in forest management practice, the use of insecticides and other countermeasures.

Key-words: insect species, pests, temperature, precipitation, storm damages, Sweden

1. Introduction

Insects are one of the world's most varied class of organisms. They are ubiquitous disturbance organisms with a key role in long-term dynamics of forest ecosystems. Most of the forest insect species maintain a low density level and are rarely noticed, but a few species can cause massive and severe defoliation, dieback or mortality of their host trees (Liebhold and Bentz 2011). Insects can be serious threats to trees health by attacking trees and killing or weakening them so they become more vulnerable to other insect attacks or diseases. These insects are being considered pests (North Carolina Forest Service 2013). Invasive species are widely recognized as among the greatest threats to biodiversity and ecosystem stability worldwide, imposing serious economic and social costs (Simberloff 2000; Pimentel et al. 2001).

Over the past 100 years, Swedish forestry has undergone extensive changes, which are reflected in forestry legislation (Ekelund and Hamilton 2001). Intensive use of forests led to demands for artificial reforestation (i.e. planting) in the early 1900s, and during the first part of the 1900s, the pressure on forests remained high, partly due to use of wood as resources during the wars. Clear felling practices became common during the second half of the 1900s, and when agriculture was rationalized it was common that abandoned arable land was planted with spruce, while naturally regenerated birch and other brushwood were seen as weeds and combated with chemicals (Ekelund and Hamilton 2001).

Climate can affect directly or indirectly the forest insect population dynamics (Figure 1). Temperature has a direct effect on the insect population dynamics through adjustments of developmental rates, reproduction and mortality. With alteration of the abundance, distribution and physiology of host trees, temperature has also an indirect effect on the insect population dynamics. Different indirect effects can occur at higher levels of the food web; i.e. the impact of temperature on the development and abundance of predators, pathogens and associated microorganisms (Liebhold and Bentz 2011).

Future changes in climate are anticipated to significantly alter the dynamics of the outbreaks of some forest insect species, due to the fact that forest insect populations are influenced by environmental conditions. This can have different consequences, leading either to the occurrence of larger and more frequent insect outbreaks or to the disruption and reduction of recurring outbreaks. Fluctuations in temperature (affecting insects directly) as well as the influence of shifts in precipitation (affecting the resistance of host trees) can contribute to the growth of forest insect population. Otherwise, in the case of a disruption of local adaptation to climate, a localized population extinction could occur (Liebhold and Bentz 2011). Studies for southern Sweden have indicated that under the ongoing climate change the population dynamics of species such as *Ips typographus* will undergo significant changes, e.g. regarding a second generation that will be produced in the same year, which may lead to more severe damages (Jönsson 2007).

As stated before, insect species are influenced both directly and indirectly by weather and climate conditions. Insect pests have a direct impact on host trees, causing severe damage and in some cases even mortality. The aims of this study are to identify the main insect species responsible for forest damage, and to explore the relationships between insect outbreaks and environmental variables (climate factors and availability of insect host trees). Special attention has been attributed to the management practices, and their consequences in the main trends of pest outbreaks through time. This study has been designed around the research question: Are climate factors (i.e. temperature, precipitation and forests damages caused by storms) related to the occurrences of insect outbreaks during 1850 to 2014?

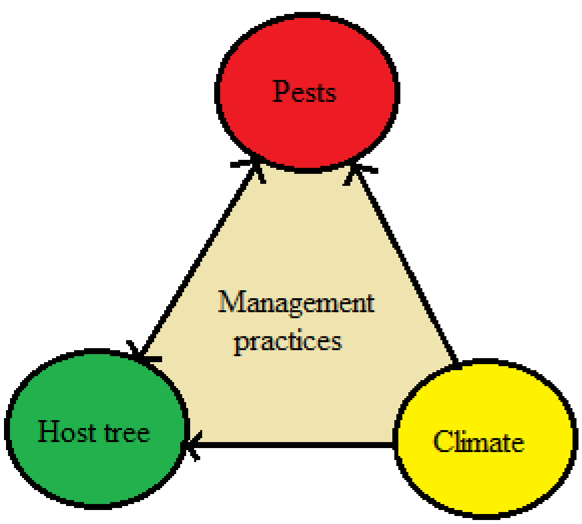

Figure 1 – Relation between pests and climate (which affects pests directly or indirectly – by affecting the host trees) that can lead to pest outbreaks. In order to counteract those outbreaks management practices can be adopted.

2. Background

<u>2.1. Study area</u>

The area chosen for this study is Sweden. Sweden is a Scandinavian country located in the Northern Europe. It is a country dominated by forests. Forestry occupy an important role in the national economy and most of the Swedes directly relate to forests and forestry pursuits. Although Sweden possesses just below 1% of the world's commercial forest area, it supplies 10% of the world's sawn timber, pulp and also paper (Barklund 2009).

This study was conducted with respect to the three divisions of Sweden, i.e. southern, central and northern. Division in these three parts was formulated considering these three following lands of Sweden: Norrland, the northern part and the largest of the three parts, covering ca. 60 percent of the total Swedish territory, Svealand, the central part and the smallest of the three parts, and Götaland, the southern, most densely populated part (Figure 2) (Högman 2014).

Figure 2 – Map of Sweden with division in Norrland, Svealand and Götaland

2.2. Why Sweden is important to explore insect outbreaks

Forestry represents an important sector and an important part of the national economy in Sweden, (Barklund 2009). Forests cover approximately 70% of the country, with 28 million hectares (Swedish Forest Agency 2014). Sweden is, after Russia, the largest afforested area in Europe. The predominant species are spruce and pine, which account for more than 80% of the timber stock. Pine is most common in Northern Sweden, whereas spruce, together with birch are dominant species in the south (Swedish National Forest Inventory 2013). Total standing volume on productive forest land is represented by Norway spruce (42%), Scots pine (39%) and birch (12%). The other deciduous trees cover together about 7.4% (Figure 3) (Swedish National Forest Inventory 2013; Swedish Statistical Yearbook of Forestry 2014).

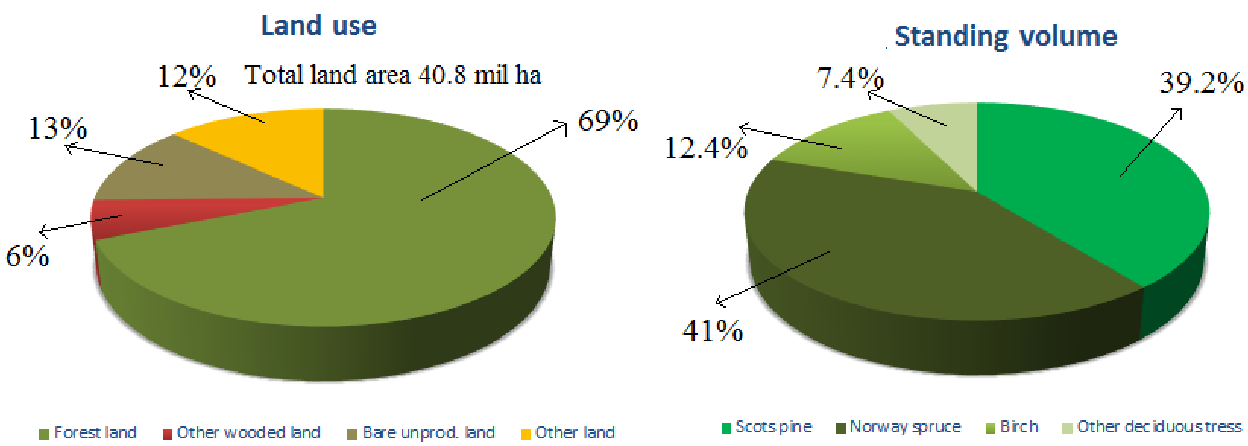

Figure 3 - Land area divided into land use classes according to the Swedish Forestry Act and Standing volume for different tree species by diameter class (excluding dead or wind thrown trees). 2009-2013 (data source: Swedish National Forest Inventory)

The different types of forest (see above) are depending on the climatic conditions; conifers in the northern part, defined as boreal forests, and hemiboreal forests in the southern part, composed of both coniferous and broadleaved deciduous trees (e.g. oak and beech are considered to be typical species). Moreover, in the northern part and along the Scandinavian mountain range large areas of forests are predominant with birches. Overall, the major part of the Scandinavia forests consist of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) (Swedish Statistical Yearbook of Forestry 2014).

As previously specified, forests occupy a large area of the country and have important roles in economy. Measures for improving and adapting forestry practices are undertaken by public and private forest managers (the largest part of forest lands in Sweden is owned by private individuals) (Swedish Forest Industries Federation 2012). Outbreaks of pests cause serious damages to forests, and hence affect the economy. Being a country with large areas covered with forests, Sweden faces insect outbreaks to a large extent, and experiences important economic losses (Lekander 1950; Lekander 1954).

2.3. Vegetation and climate in Sweden

I have specified in the previous section that forest in Sweden is the major ecosystem and is important for Swedish economy and ecosystem services. I will go more into details hereafter describing the current pattern of vegetation as well as the evolution of vegetation through time to better understand the present day vegetation.

2.3.1 Present day vegetation and climate

We distinguish eight vegetation zones, from Northern to Southern Sweden: Arctic Alpine, Alpine (both in the north-western part of the country), North Boreal, North-South Boreal, Boreal, South Boreal (all these zones cover most of northern Sweden and also a large area of central Sweden), Boreo-Nemoral (covering a large area in central and most of the southern part) and Nemoral (in the southern part of the country, a small zone of mainly deciduous forests) (Sjörs 1965; Jongman et al. 2005; Metzger et al. 2005). The Boreal zone and its sub-zones cover the majority of the land area and are consisting of coniferous dominated forests. Climate of Sweden is mainly influenced by the northerly location of the country. The climate is temperate with four distinct seasons. Most parts of Sweden receive between 500 and 800 mm of precipitation each year, much drier than the global average, which is 1123 mm (Legates and Willmott 1990; Gunawardhana and Al-Rawas 2014). Notable quantities of precipitation are observed in the southwestern part of the country, between 1000 and 1200 mm. The mountain areas in the northern part can receive up to 2000 mm. Snowfall mainly occurs from December to March in southern Sweden, from November to April in central Sweden, and from October to May in northern Sweden (World Weather and Climate Information 2015). The averages of the July temperatures in Sweden are from 13 to 17°C. February is usually Sweden's coldest month, with temperatures varying from - 22 to -3°C. In northern Sweden, winter temperatures can often drop to -30°C, sometimes even lower (Weather Online 2015).

The landscape, mainly consisting of forests, lakes, shallow water, wetland areas and nutrient-deficient soils, was strongly influenced by the end of the last glacial periods that ended at ca. 11700 years ago. The land was having a low productive capacity, with a majority of coniferous forests and relatively slow vegetation growth (Barklund 2009). Although Sweden's forests are among the most northerly in the world, due to the warming effect of the Gulf Stream forest growth takes place at latitudes characterized in other parts of the world by treeless tundra (Lundin 2006).

2.3.2 Past vegetation and climate

After the last glacial period, climate became more favorable (more wet and warm) for growth of plants, in particular trees. One of the consequences was that many vascular plants and deciduous trees migrated from the south to north of Sweden. The northern parts of the country were dominated by birch and pine whereas forests in the southern parts were consisting of hazel, elm, oak and somewhat later lime and ash (Lundin 2006). Bradshaw and Sykes (2014) showed, based on pollen diagrams from Fennonscandia, that about 4000 years ago pine-dominated boreal forests were having a large coverage in the northern parts of Sweden. Mixed boreal forests were also found, but in a small extent. The southern part was mainly consisting of broadleaved forests. Some areas with mixed deciduous forests were found in the central part. At about 4000-3000 years ago humans started to make their presence to be felt (Behre 1988; Berglund et al. 2008; Marquer et al. 2014). The influence of humans strongly affected vegetation by deforestation, in order to develop cultivations and pasturages (Björkman 1997; Giesecke et al. 2006).

The vegetation changed dramatically about 2000 years ago. Spruce-dominated forests entered Sweden from Finland (Kullman 2001; Giesecke and Bennett 2004) (they were present in Finland about 4000 years ago), and covered the central part and half of the northern part. The northerly parts of Sweden were still dominated by pine forests. Mixed boreal forests were found in a small extent in south-east and in central. The mixed deciduous forests that were found around 4000 years ago in central moved towards south due to colder and drier climate (Renssen et al. 2009). Broadleaved forests were also found in the southern part, but to a somewhat smaller degree than around 4000 years ago (Bradshaw and Sykes 2014).

Close to present day the spruce dominated forests (plantation of coniferous trees for wood production became important at large scales during the last century) gained a larger coverage in Sweden. Pine dominated boreal forests and mixed boreal forests are found in the northern part of the country. In the southern part, in addition to the spruce forests, there are also present mixed deciduous forests, small areas with broadleaved forests as well as mixed boreal forests (Bradshaw and Sykes 2014).

The climate in Sweden has been relatively warm over the last century, particularly in the 1930s and since 1987. From the end of the 19th century, the temperature rose considerably, until the 1930s (Figure 15). The winter temperature in northern Sweden experienced a particularly large rise of around 2.5°C. Starting with 1930s till 1980s, the average annual temperature decreased by a round 0.8°C in the north and half as much in southern Sweden (Swedish Government Official Reports 2007).

2.4 Insect outbreaks

2.4.1 Definition

Although insects are a natural part of the forest's ecosystem by being a source of food for birds and other animals or breaking down and helping in the recycling of litter from the forest floor, certain insects can pose as a serious threat from a tree's health point of view. Insects can attack valuable trees, weaken them and make them subject to other insect attacks or diseases, or even kill them. These insect are called pests (North Carolina Forest Service 2013).

From an ecological point of view an outbreak is defined as a sudden and hazardous increase in the abundance of a particular species, occurring mostly over a relatively short period of time. It can be defined as an increase in an organism's population, with a harmful influence on the survival and well-being of different ecosystems (Hill 1983).

Pests and their disturbances are ubiquitous across forest ecosystems, affecting their structure, composition and especially their species composition. Pests and different pathogens disturbances can cause diffuse mortality of trees (Flower and Gonzalez 2015).

2.4.2 Types of insect outbreaks

Depending on the nature of the pests attacking the trees, different parts of the host trees can be damaged. Some insects, like defoliators, feed on the foliage (leaves and needles) of trees, by removing the chlorophyll containing tissues responsible for photosynthesis. In some cases trees can survive this process, if the defoliation is minor or infrequent. Defoliation can also stress trees and make them more susceptible to attacks from other insects and diseases, and repeated defoliation can lead to killing of trees. Defoliators are mainly represented by the moth species, but the caterpillar (the larval stage) is in most of the cases responsible for severe defoliation. Defoliators comprise pine sawflies, the gypsy moths, the pine webworm and the forest tent caterpillars (Douce et al. 2002; Glavendekić and Medarević 2010; North Carolina Forest Service 2013).

Some other insects, like the bark borers, bore into the bark of trees to feed or reproduce. They cause damages to trees, by destroying the phloem (a thin layer of cells just beneath the surface of the tree bark that transports carbohydrates and nutrients throughout the tree). If this insect destroys the phloem all the way around the stem, the tree can be killed. Bark boring beetles are among the most damaging pests. Healthy trees are capable to prevent the bark beetles from entering the bark. If, however, the beetle population becomes very large in outbreak years, even the healthy trees succumb to attacks (Douce et al. 2002; North Carolina Forest Service 2013). The mainly families of boring insects include *Cerambycidae* beetles, *Buprestidae* beetles, *Scolytidae* beetles, clear-winged moths and sawflies. Most of the bark beetles attack and kill the trees by spreading a blue-stain fungi. The resistance of the trees to beetles and fungal pathogens may be reduced if the tree's resources are consumed by this blue-stain fungi, instead of using them in order to defend against the beetle (Lahr and Krokene 2013).

Other insects attack only seedlings or the young succulent tissues of small twigs, shoots and buds. This is the case for many of the forest insect pests. This can cause the killing of seedling or even the disfiguration of larger trees. However, it is very difficult to identify this kind of infestations accomplished by these type of insects described above, and also the symptoms can be confused with those of other insects or diseases. Examples are the pales weevils, tip moths, white pine weevil (Douce et al. 2002; North Carolina Forest Service 2013).

Some other insects harm the trees by piercing the surface of the soft plant tissues and feeding on nutrient-rich sap. In abundant numbers, piercing/sucking insects can cause the starvation of a tree by depleting it of the carbohydrates produced from photosynthesis. This can lead to the killing of the tree if the infestation lasts several years. On top of that, many of the piercing/sucking insects can carry pathogens that can also cause the death or decline of the trees. Several of this piercing/sucking species are among the most destructive forest pests. This category gathers species like the aphids, scales, hemlock wooly adelgid and balsam wooly adelgid (Douce et al. 2002; North Carolina Forest Service 2013).

2.4.3 Causes and consequences of insect outbreaks

Insects, through their attacks have caused serious damages in Swedish forests. Most of the insects attack coniferous trees (Lekander 1950; Lekander 1954), which occupy most of the forest area (Figure 3). Insect species can be in some cases considered as invasive species. Invasive species are widely recognized as among the greatest threats to biodiversity and ecosystem stability worldwide, as they can impose serious ecologic damages and social costs (Simberloff 2000; Pimentel 2001). Insect species destroy or damage large areas of commercially valuable forest. The infestation can also lead to killing of trees, implying socioeconomic losses. The economic impact of insects is measured not only by the market value of products they destroy and by the cost of damage they inflict. It also implies the money and resources expended on prevention and control of pest outbreaks (Meyer 2007).

Many insect species compete with us for food. Human activities encouraged most of them by planting of monocultures crops, but then insects become a problem as they thrive on the crops, and that's when we start to call them pests. Humans have caused some insect species to be moved from one part of the world to another - deliberately or by accident which can become a real problem if the introduced insect species has no natural enemies in their new home (The Amateur Entomologists' Society 2015).

Pests influence negative the resilience of forests to future climate as well as to new outbreaks, by reducing their structural and functional redundancy. Therefore, pests can be considered as biotic forcing agents that can cause consequences of similar magnitude as climate forcing factors. They can act as biological forcing agents of changes in ecosystems, by causing fast and diffuse mortality of functional groups or species. Pest can also have a strong impact on forest productivity and can alter the exchange of energy and carbon between forests and atmosphere (Flower and Gonzalez 2015).

Climate exerts powerful effects on the distribution and abundance of the earth's insect species. The warming of the climate is expected to generate changes for many insect populations and also for the ecosystems they inhabit. The distribution, abundance and ecology of all insect species will be profound influenced by the changes in climate (Andrew et al. 2013; Nooten et al. 2014). The frequency and intensity of forest pest outbreaks may become more severe in a warming climate. This can have important consequences. Unfortunately, the potential impact of these consequences to the climate system at the local and global levels are unknown (Flower and Gonzalez 2015).

Interactions between insects and human use of pesticides have had a major impact on the occurrence of insects. An increasing public and political opinion against the use of pesticides led to an adjustment in agreement with legislative support of their use. In Sweden forestry between 1987 and 1990 it was banned the use of all insecticides, except permethrine (Harding et al. 1998). Interactions between the plants and pesticides can lead to complications in the control of the pests. Allelochemicals that induce production of enzymes in insects can increase tolerance to pesticides (Brewer et al. 1995). Some other studies have demonstrated that plant's developmental stage can affect the insect's resistance to pesticide (Attah and van Emden 1993). Eliminating chemical pesticides from forest management in Sweden has been a long and challenging process that still persist nowadays (Giurca and von Stedingk 2014).

Investigation of outbreaks is necessary for a good understanding and ultimately taking control measures and preventing the spread of insects. By understanding the behavior, and studying the patterns followed by the insect species, the collected information can be used to identify sources of the outbreaks and undertake control measures for stopping their spread.

2.4.4 What do we know regarding past and present insect outbreaks

Insect occurrences in southern and central Sweden through millennia to centuries

Southern Sweden

Depending on the climate and the surrounding landscape, different types of insects characterized an area. A study at a site in SW Sweden (Halland) of about ninety-eight insect taxa conducted by Lemdahl and Gustavsson (1997) showed interesting results, with assemblages being dominated by beetles. Another study conducted on insect records by Olsson and Lemdahl (2009) on a site situated in southern Sweden showed similar results. Results of their studies are presented in Table 1.

Year	Type of environment	Type of insects	Some examples of insect species
2.400 BC-1.200 BC	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, deciduous trees seem to have dominated	species confined to deciduous trees dominate but also open-ground species	*Trechus quadristriatus, Trechus rivularis, Hypnoidus spp.*
1.200 BC-AD 1.400	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, deciduous trees seem to have dominated	dung beetles, species confined to heather-dominated heathland, species dependent on or favoured by fire, species confined to wood and also leaf litter species	*Cymindis humeralis, Trechus quadristriatus, Strophosoma capitatum, Cryptocephalus bipunctatus, Phyllopertha horticola, Calathus piceus, Agonum bogemanni, Elater ferrugineus, Ampedus praeustus, Ampedus nigrinus, Denticollis linearis, Dorcatoma serra, Lochmaea capraea, Chalcoides and Dorytomus weevils, Blastophagus minor, Dalopius marginatus, Agriotes aterrimus, Athous subfuscus*
AD 1.400-1.850	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, deciduous trees seem to have dominated	beetles favoured by fire are recorded, species confined to coniferous trees dominate the wood-dwelling assemblages, beetles that live in dung are still present	*Loricera pilicornis, Cassida flaveola, Lochmaea capraea, Ampedus nigrinus, Rhizophagus bipustulatus, Paromalus flavicornis and Agathidium atrum, Hylastes opacus, Blastophagus minor, Pityogenes quadridens and Pityogenes bidentatus, Pityogenes chalcographus, Hylobius abietis, Rhagonycha testacea*
AD 1.850 - present	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, deciduous trees seem to have dominated	wood-dwelling beetles are species confined to coniferous trees	*Rhagonycha testacea, Pityogenes chalcographus and P. bidentatus, Pterostichus diligens, Acidota crenata, Lathrobium spp., Quedius spp., Bryaxis sp. and Cytilus auricomus, Notiophilus biguttatus*

Table 1 – Results from two different studies (Lemdahl and Gustavsson 1997; Olsson and Lemdahl 2009) from different locations in southern Sweden. The table indicates the period and the specific environment for that period, as well as the types of insect species that were confined to that environment. Some examples of insect species are also given.

During the late Holocene (2400 BC to the present) the woodlands were opened up and beetles which indicated the formation of heather-dominated heathlands were making an appearance at around 800 BC. From 1200 BC till AD 1400 it was an increase in the number of species that are confined to wood, and also a growing in the population of leaf litter species. Before AD 1850 a marked decline could be observed in the number of species correlated with wood and leaf litter, after which no pyrophilic beetles were recorded (Olsson and Lemdahl 2009). Extensive grazing is indicated between 1400 BC and 1850 AD by the presence of coprophilous and coprophagous beetles. The dominate species for this period were the ones confined to wood-dwelling assemblages. Dung beetles were also present. From AD 1850 till present few insect remains were recorded. They found few wood-dwelling beetles confined to coniferous trees, but there were not records of species favored by fire (Olsson and Lemdahl 2009).

Species found in the assemblages, such as *Ochtebius auriculatus* is a species rare throughout Scandinavia today and in Sweden it has been recorded only from a few localities. Some species (*Calosoma sycophanta*) present in the fossil assemblages were not recorded so far in the province of Halland and in some cases in the whole area of southern Sweden. *Pterostichus anthracinus* is rare today in southern Sweden, with the exception on the islands of Oland and Gotland. Other species that have not previously been recorded from the province of Halland are *Cartodere constricta* and *Cordicomus instabilis* (Lemdahl and Gustavsson 1997). Most of the beetles found in the samples are also found today to have a part of their geographical distribution in southern Sweden. However, species such as *Bembidion normannum, B. iricolor, Badister dorsiger* and *Galerucella grisescens* are some exceptions. Their closest occurrence is in Finland or Denmark, not Sweden (Lemdahl and Gustavsson 1997).

Central Sweden

A study conducted by Hellqvist and Lemdahl in 1996 on insect remains from a mediaeval settlement in the town of Uppsala, central Sweden indicated the domination of beetles for the whole period (12^{th} to the 15^{th} century). Only few remains of other insects such as butterflies, true flies and a bumble bee were found. The climate during the above specified period in southern Sweden was similar to the climate of the period when the research was conducted (i.e. 1996), with slightly higher summer temperatures. A number of species that in present days are considered rare species were also recorded (Hellqvist and Lemdahl 1996).

Between 1100 and 1200 AD the landscape was consisting of moist habitats, open areas and cultivated fields. Species such as *Cercyon unipunctatus* was especially found around farm buildings. The mould beetle, *Enicmus brevicornis* is today a rare species in Scandinavia, recorded only from a few localities in southern Sweden. Today, the furniture beetle, found in the samples, *Hardrobregmus pertinax*, is found indoor in Scandinavia, where it attacks mostly coniferous timber, damped and softened by fungi. The weevil *Stereocorynes truncorum* is a rare species today in most of southern Sweden. It was found on beech, hornbeam and oak (Hellqvist and Lemdahl 1996).

During late 13th and early 14th century there were only indicated remains of Coleoptera order. During the first part of the 15th century (ca. 1400 AD) several beetles were recorded. Today, species such as the bark beetle *Xyleborus monographus* is found extremely rarely in northern Europe, mostly in southern Scandinavia, in unbarked wood of old oaks and sometimes even beech.

The presence of the beetles *Enicmus brevicornis*, *Stereocorynes truncorum*, *Xyleborus monographus* (all three confined to deciduous trees), and *Aphodius subterraneus* is only in a smaller extent in Sweden today. Their appearance in the record from Uppsala could suggest that they were more common during the Middle Ages (Hellqvist and Lemdahl 1996).

Occurrences of insects responsible for outbreaks since 1850

Studying the insect outbreaks is a critical problem in Sweden. No study regarding insect outbreaks have been carried out so far at millennia and century scales. Available for Sweden are only studies referring to the occurrence of different insect species throughout millennia (see previous section). The only studies available about insect outbreaks through millennia are known in North America (e.g. Bhiry and Filion 1996; Simard et al. 2006; Lavoie et al. 2009; Morris et al. 2014). It is important to follow and observe the past occurrences of insects, and starting with this, to try to understand the present occurrences of insect outbreaks. Data related to insect outbreaks in Sweden are only available for the last century. The information over the last 165 years (from AD 1850 to 2015) presented below will be used as the primary data for conducting this thesis.

After collecting the data from different sources (Lekander 1950; Lekander 1954; Christiansen 1970; Ehnström et al. 1974; Löyttyniemi et al. 1979; Austarå et al. 1983; Ehnström et al. 1998; Harding et al. 1998; Skogskada 2015) (Table 3), it resulted that the southern part of Sweden gathered for the first period, 1850-1950, a total of 112 different insects responsible for outbreaks, and for the second period, 1961-2014, 67 different insects responsible for outbreaks. The central part of Sweden comprised a lower number of different insect types: 79 occurred in the first period and 55 in the second one. The lowest number of insects is in the northern part of the country. It comprises 64 different insects in the first period and only 26 in the second period.

Some examples of records of occurrences of insect outbreaks are given below (Table 2). Starting with 1859, species such as *Diprion sertifer* were observed having a mass behavior for the first time in Sweden. Ravages caused by the green oak moth, *Tortrix viridana* were so strong, that resulted in the most extensive devastation that occurred in the state's forests. *Ernobius abietis* and *Vanessa polychloros* appeared in great abundance and caused significant damage. *Diprion* sp. caused intense and severe damages. In 1898 the black arches, *Lymantria monacha*, suddenly began to make itself noticeable in Södermanland County. In 1898 it was observed for the first time a great spread of the gypsy moth, *Lymantria dispar*. In 1901 the winter moth, *Operophthera brumata*, occurred in enormous quantities in the southern and central parts of the country. Species like the northern winter moth, *Operophthera fagata*, continued its raids. In 1908 occurred attacks largely on pine cones from Gotland by *Pissodes validirostris*. Between 1911 and 1950 occasional attacks of some species like *Abraxas sylvata* and *Acantholyda hieroglyphica* led to damages to elms and pines. The European June beetle, *Amphimallon solstitialis*, continued its swarming throughout this period. Species like *Blastophagus piniperda* and *Blastophagus minor* continued with their severe, and even in a bigger number, attacks. In 1916 it was observed strong swarming by *Bupalus piniarius*. Species like *Cephaleia arvensis, Coleophora fuscedinella*, *Coleophora laricella*, continued to cause damages. Species like *Cryptorrhynchus lapathi*, appeared for the first time in 1950 in Halland. Sporadic attacks by species like *Emphytus serotinus* (1931), *Epinotia diniana* (1916), *Epinotia nanana* (1933), *Eriophyes tiliae* (1917), *Eriophyes betulae* (1921) *Prays curtisellus* (1934) and more were reported. Attacks of *Rhynchaenus* sp. also occurred. The pine shoot moth, *Evetria buoliana*, started to occur widely in different parts of the south. *Hylobius abietis* was an important pest, causing major injuries, along with *Ips typographus*. Ravages of *Panolis flammea* before 1947 have been extremely rare.

Starting with 1961 new species like *Anthonomus phyllocola* and *Aradus cinnamomeus* emerged. *Chrysomela populi* caused heavily defoliation of *Populus* sp. Sporadic occurrences of *Cinara pini* were reported. The western larch case-bearer, *Coleophora laricella*, continued to cause severe damages on *Larix* sp. Attacks on beech occurred by *Cryptococcus* sp. and the lymantrid moth, *Dasychira pudibunda*. Mass occurrence of *Diprion Pini* was reported. Species like *Lymantria monacha* occurred in mass outbreaks, and species like *Microdiprion pallipes* started to occur, but to a smaller extent. *Neodiprion sertifer* attacked Scotch pine forests. During 1991-2014 some of the most important species that caused significant damages were *Dendroctonus micans*, *Erannis defoliaria*, *Ips typographus*, *Neodiprion sertifer* and *Strophosoma capitatum*.

Year (AD)	Environment	Type of insects	Some examples of insect species
1850 - 1910	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, coniferous trees dominate	wood-dwelling beetles are species confined to coniferous trees	*Bupalus piniarius, Blastophagus piniperda and B. minor, Amphimallon solstitialis, Diprion spp., Erannis defoliaria, Evetria buoliana, Hylobius abietis, Ips typographus, Tortrix viridana, Laspeyresia strobilella, Lymantria monacha, L. dispar, Melolontha melolontha and M. hippocastani, Operophthera fagata and O. brumata, Vanessa polychloros*
1911 - 1950	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, coniferous trees dominate	wood-dwelling beetles are species confined to coniferous trees	*Bupalus piniarius, Blastophagus piniperda and B. minor, Amphimallon solstitialis, Diprion spp., Erannis defoliaria, Evetria buoliana, Hylobius abietis, Ips typographus, Tortrix viridana, Laspeyresia strobilella, Lymantria monacha, L. dispar, Melolontha melolontha and M. hippocastani, Operophthera fagata and O. brumata, Vanessa polychloros*
1961 - 1990	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, coniferous trees dominate	wood-dwelling beetles are species confined to coniferous trees	*Acantholyda hieroglyphica, Andricus testaceipes, Anthonomus phyllocola, Aphrastasia pectinatae, Aradus cinnamomeus, Argyresthia goedartella, Chrysomela populi, Dendroctonus micans, Erannis defoliaria, Ips typographus, Neodiprion sertifer, Strophosoma capitatum, Cameraria ohridella, Bupalus piniarius, Cryptorrhynchus lapathi, Hylobius abietis, Lymantria monacha, Dasyneura marginemtorquens, Diprion pini*
1991 - 2014	woodland gradually became more openthrough increasingly extensive land use and in wooded areas, coniferous trees dominate	wood-dwelling beetles are species confined to coniferous trees	*Dendroctonus micans, Erannis defoliaria, Ips typographus, Neodiprion sertifer, Strophosoma capitatum, Cameraria ohridella, Bupalus piniarius, Cryptorrhynchus lapathi, Hylobius abietis, Lymantria monacha*

Table 2 – Results from the datasets used to procure the primary data for this thesis (Lekander 1950; Lekander 1954; Christiansen 1970; Ehnström et al. 1974; Löyttyniemi et al. 1979; Austarå et al. 1983, Ehnström et al. 1998; Harding et al. 1998; Skogskada 2015) for southern Sweden. The table indicates the period and the specific environment for that period, as well as the types of insect species that were confined to that environment. Some examples of insect species are also given.

3. Materials and Methods

The main steps followed in order to complete this study are displayed in figure 4:

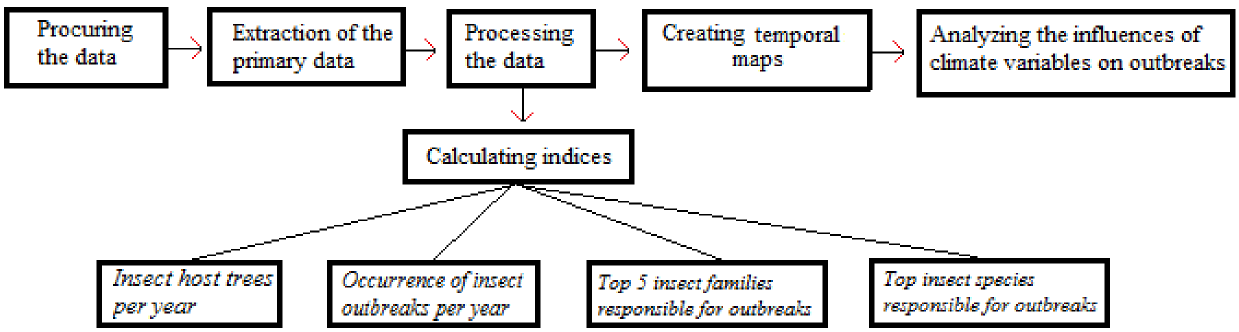

Figure 4 – The main steps that were followed to conduct this study.

3.1. Datasets

For the purpose of this thesis, the following sources were identified as containing relevant information (Table 3).

Period	Type of source	Reference
1850-1945	S	Lekander (1950)
1946-1950	S	Lekander (1954)
1961-1966	R	Christiansen et al. (1970)
1967-1971	R	Ehnström et al. (1974)
1972-1976	R	Löyttyniemi et al. (1979)
1977-1981	R	Austarå et al. (1983).
1982-1986	R	Ehnström et al. (1998)
1987-1990	R	Harding et al. (1998)
1991-2014	W	Skogskada (2015)

Table 3 – Datasets used to procure the primary data, where S stands for scientific article, R for published report and W for website. It is also specified the periods of time for which data were available.

- Datasets for the time interval 1850-1950

The first dataset used was Marianne Lekander's paper (1950) in Swedish "Skogsinsekternas uppträdande i Sverige under tiden 1741-1945" (in English "Forest insects' behavior in Sweden during the period 1741-1945"). This paper is a compilation of available data on insect damages in Sweden forests from 1741 till 1945. It is based on forestry data and entomological literature, insect reports from Domain Authority, Forestry Board annual reports and Forest Research Institute written communications. The second compilation, “Skogsinsekternas uppträdande i Sverige under tiden 1946-1950” (in English “Forest insects' behavior in Sweden during the period 1946-1950”) by Bertil Lekander (1954) was a direct continuation of Marianne Lekander’s paper before mentioned. The main data were obtained from the Domain Administration insect reports, foresters’ annual reports and the State Forestry Research Institute incoming reports, inquiries and samples.

- Datasets for the time interval 1961-1990

The information that covered the period 1961-1990 was extracted from a length of five year reports published on a bulletin within the Nordic group of forest entomologists. The first report “Insect Pests in Forests of the Nordic Countries 1961-1966” by Erik Christiansen (1970) was a survey consisting of outbreaks of the most important pests in deciduous and coniferous forests, whereas other outbreaks were presented in a tabular form. The second report covered the 1967-1971 period and was conducted by Ehnström et al. (1974). In the report it was described briefly the prevailing conditions in forestry in the Nordic Countries. The occurrence of insect pests in the Nordic Countries between 1972 and 1976 has been studied by Löyttyniemi et al. (1979) and published as the next five-year report. In the first reports there were short introductory notes on the tree species composition, different changes in logging and transportation methods, and also notes about the continuous process of legislative appraisal and adjustment regarding the insecticides. All these factors have contributed to the pest status of the insects and have also determined, to some extent, the research problems to be encountered. The report covering the period 1977-1981 has been conducted by Austarå et al. (1983). This latter report had been performed by Ehnström et al. (1998). Major attention during this period has been attributed to the association between forest damage and air pollution. On the last report of the Nordic Forest Entomologists’, the research group covered only four years, from 1987 till 1990 and was supervised by Harding et al. (1998).

- Datasets for the time interval 1991-2014

Between 1991 and 2014 data were extracted from the official website of Forest Damages in Sweden (http://www.slu.se/sv/centrumbildningar-och-projekt/skogsskada/). “Skogskada” is a tool to identify and report on forest damages online. The information was available (at the time I extracted the data – i.e. 25 April 2015) from 1990 and it was based on reports of various injuries caused by different types of insects.

Note that information is missing for the time interval 1950-1960 due to the absence of publications regarding this issue. Additionally, the use of several sources resulted in differences of the data (i.e. the quality of the information and the quantity of data can differ from one dataset to other), which is taken into account through this study. In particular, I divided the datasets into two sub periods. The first sub period covers the first 100 years, from 1850 till 1950. It includes the first two described datasets, due to the similarity between them; these datasets are well detailed and offer great quantity and quality of data.

The second sub period covers the period from 1961 till 2014. For this sub period data were acquired from the above described reports of the Nordic Forest Entomologists' research group and from the official website of Forest Damages in Sweden. The information for this second sub period was not as detailed as the first one; the location of the insect outbreaks was not clearly specified (e.g. it was only indicated the country of the insect outbreaks, not the location in southern, central or northern Sweden). From this second sub period I therefore excluded ca. 10% of the data due to the fact that the information from this datasets couldn't be compared with the other datasets that I used, as the location in northern, central neither southern Sweden was not specified.

3.2. Extraction of data

The information from all the above datasets was extracted in a tabular form in a *.xlsx file. The data were structured in a table including the following columns: Year of the attack, Insect order (taxonomic range), Insect Family, Insect Species, Location Sweden: North-Central-South (division in these three regions was made in correlation with the three lands of Sweden: Norrland, Svealand and Götaland, as described in Background), Location in Southern Sweden (location was specified through the different counties), Information related to the host trees, Information related to damages, Other information and References.

The Excel tables were then modified to include only the name of different insect species displayed on columns and the years on rows. The table used to calculate Top insect species appears as a binary form, represented by “1” when outbreaks of insects have been recorded in a year within southern, central or northern Sweden (i.e. defined and used within this study as “occurrence of insect outbreaks”) and by “0” when outbreaks have not been recorded. In order to determine Top insect species (i.e. insect species causing important damages and occurring most frequently in the records of forest damages during a period of time) two different tables corresponding to the two sub periods were carried out for southern, central and northern Sweden. To determine the Top insect families, again, two different tables (for both sub periods) were also carried out. The tables didn’t have a binary form since the same class of family is composed from different insect species, and therefore their occurrence was bigger than one (i.e. it was done a sum of the occurrences of species that were noted before with “1” or “0”). The same, if the family of insects did not occur within a year “0” was introduced in the table.

3.3. Evaluate the major trends of insect outbreaks

For this purpose, I have calculated several indices for southern, central and northern Sweden using the modified Excel tables (see above):

Insect host trees per year: broadleaved trees versus coniferous. The datasets used did not include information of the host trees for each insect species. In order to procure this information several new sources were used (Byers 2004; Byers 2006). In some cases there were more than one type of trees that hosted the same insect, and it was taken into account for each type of insects. The insect species were grouped in relation to their host trees (conifers or broadleaved) and after, a sum of the host trees was conducted. These two groups were chosen as the same insect species can have different host trees within broadleaved trees or coniferous. It was also taken into account that in some years the same species attacked both broadleaved and coniferous trees, these species being accounted for both groups.

Occurrences of insect outbreaks per year based on the sum of the occurrences of insect outbreaks (sum of the number “1” for species that have been defined in the binary table above).

Top insect species and families responsible for outbreaks (separately for the two sub datasets). The terms *Top insect species* and *Top families responsible for outbreaks* refer to the insect species and families that explain the most of the variation within my dataset of insect outbreaks; i.e. the insect that are the most responsible for outbreaks. For describing the behavior of the species and their families, the different tables realized previously in Excel were used.

In order to determine the Top insects species and families a statistical program was applied. The program chosen for this study was Canoco 5 for Windows, a program for multivariate statistical analysis using ordination methods (Šmilauer and Lepš 2014). The first step was to identify the families that are the most responsible for insect outbreaks, i.e. Top Families. Dataset with the primary data was imported within the program from Excel (.XLSX format). The column within the table referring to Years is now correlated as samples. Each sample comprises values for multiple species (i.e. Insect Families). The matrix represents compositional data with empty cells considered as zeros (i.e. no occurrence of insect outbreaks). Based on the matrix, I used two unconstrained methods, Detrended correspondence analysis (DCA) and Principal Component Analysis (PCA), in order to achieve the best results through several runs and tests. For the DCA (non-linear method), a statistical technique widely used to find the main factors or gradients in large datasets (Šmilauer and Lepš 2014), the results, unfortunately, were unsatisfactory, as the output figures were not clear. PCA (linear method), a statistical procedure to view a large dataset objectively through the major principal component axis (representation of each axis has an eigenvalue that indicates its importance) (Šmilauer and Lepš 2014) was applied. This transformation is defined in such a way that the first axis has the largest possible explanation of the compositional matrix. The importance of axis decreases in the same order as the decreasing eigenvalue (Šmilauer and Lepš 2014).

Results from PCA were satisfactory to select the top families for each of the two sub periods for southern, central and northern Sweden. For each one of the three divisions of Sweden, as well as for the two sub periods I selected the Top five insect families, which included the most important five families of insect species (considering that each family is represented through a vector using PCA, I therefore selected the five vectors that were the longest – i.e. having the highest impact on the variation of my dataset).

After choosing these Top Families, the next step was selecting Top Species. For the first period, the variation explained by PCA-axis (axis 1 and 2 together) are: Southern Sweden 42%; Central Sweden 41%; Northern Sweden 57%. To increase the significance of my results I did a second run for the PCA to take into account only the species corresponding to the Top Families selected just before. The variation explained by PCA-axis (axis 1 and 2 together) are higher than previously: Southern Sweden 58%; Central Sweden 56%; Northern Sweden 80%. For the second period all species were taken into account because lower numbers of species are recorded in the dataset. The variation explained by PCA-axis (axis 1 and 2 together) are: Southern Sweden 46%; Central Sweden 45%; Northern Sweden 58%. PCA results are generally displayed as a biplot (Jolicoeur and Mosimann 1960) with the axes corresponding to a new coordinate system and both samples (years) and species (insect species) represented. The samples are represented as circles and species as vectors (as will be seen in the Results section). The direction of a species arrow indicates the lure to different years, whereas its length may be related to the importance of a pest throughout the years of outbreaks.

It was easy to select the top families using PCA graphs, but to identify the top species was harder because so many species were recorded and a visual selection of the largest vectors would not have been objective. I therefore used a new program, Adobe Illustrator CS. Using this program I have drawn a circle (the size of the circle was arbitrary chosen) over the vectors representing the insect species. The size of the circle was chosen to identify the species that influence the most the variation of the datasets; circles have constant sizes from one graph to other (i.e. circle with the same size was used for each southern, central and northern, and for the two sub periods in order to have comparable results between the two different sub periods and regions).

The summary tables of the PCA analysis for Top Insect Families as well as for Top Insect Species are displayed in the Appendices section (Tables 13-24).

3.4. Creating temporal maps

The next step in this research was to map the occurrence of insects (all species together). The program used was ArcGIS 10.3 for Desktop, an application used for mapping and spatial data analysis (between the interrelated component programs of ArcGIS the applied ones were ArcCatalog and ArcMap). ArcMap was used primarily to view, edit, create, and analyze geospatial data. ArcCatalog was applied to create a New Shape File, with polygon as a feature type, the polygons representing the Southern, Central and Northern Sweden. Likewise, a special attention was been paid to the appropriate Spatial Reference system. By using as a background a base map provided by the software (Imagery with Labels), the chosen Coordinate System for the Shape File was WGS 1984 Web Mercator (Auxiliary Sphere).

For mapping it was taken into account the sum of occurrences of insect outbreaks (all species together). The first period, 1850-1950, was divided into two sub periods: 1850-1910 and 1911-1950, the first sub period with a continuous and similar trend of insect outbreaks and the second sub period with an increase in the number of outbreaks. For the second period, 1961-2014, the division was made in correlation with the two different datasets employed to procure the primary data for this thesis, i.e. 1961-1990 and 1991-2014. For each sub period an average of the occurrences of insect outbreaks per years of outbreaks had been calculated. This was applied for each southern, central and northern Sweden (Figure 8).

3.5. Analyzing the influence of climate on the occurrences of insect outbreaks through time

In order to explore the part of the occurrences of insect outbreaks explained by climate variables I used three independent climate variables: temperature, precipitation and storm damages.

Information concerning climate data was extracted from the website DataGURU, which works as a tool for the acquisition, re-scaling, re-gridding and conversion of environmental and climate data. The required data were selected as CRU TS3.20. The CRU TS series of data sets (CRU TS = Climatic Research Unit Time series) includes month-by-month time series of variations in precipitation, daily maximum and minimum temperatures, cloud cover, and other variables covering Earth's land areas for 1901-2011, on 0.5x0.5 degree resolution grids (Jones and Harris 2013; National Center for Atmospheric Research Staff 2014). The output format contained information about temperature and precipitation for different locations in Sweden. Location was indicated by its Latitude and Longitude (Decimal Degrees). The value for Daily Mean Temperature was in degrees Celsius and for Precipitation in mm/month. In order to have better results it was used the average temperature and precipitation for each county (again, for each county it was made an average between all the locations from the output file; locations close to the sea were intentionally not taken into account as the sea may influence the values for the nearby locations.

The gathered information was divided in three periods for temperature (A-M-J - average value of the mean temperatures in April, May and June, J-A-S - average between mean temperatures in July, August and September and Winter - average between mean temperatures in December, January and February) and two periods for precipitation (A-M-J - sum of the monthly precipitation in April, May and June and J-A-S - sum of monthly precipitation in July, August and September). These combinations of months were chosen as these are more relevant from a tree phenological point of view. To handle the correlation with the Top Species dataset an average between all counties for southern, central and northern Sweden was applied. Information, as stated before was available from 1901 till 2011.

The values for the storm damages were presented for each county in cubic meters per hectare of forest land, and refered to the extent of fallen trees due to storms. Information was available from 1902 till 2007 (Nilsson 2008). Sums of the damages for southern, central and northern Sweden were calculated (sums between damages within each counties).

To illustrate the dependence of insect outbreaks against climate parameters and storm damages the software Canoco 5 for Windows was used again. The analysis applied in this case was Variation Partitioning Analysis with two groups, first group: climate parameters, i.e. temperature (average between A-M-J and J-A-S) and precipitation (sum between A-M-J and J-A-S), and the second group: storm damages; – simple effects testes. The method used was the constrained linear Redundancy Analysis (RDA). Redundancy analysis (RDA) is a direct gradient analysis techniques that shows in a linear form the relationship between components of response variables that are redundant with (i.e. "explained" by) a set of explanatory variables (Buttigieg and Ramette 2014).

Variation Partitioning Analysis displayed as results the compared groups represented by circles as in the following diagram, where “a” stands for the effect of the first group – Temperature (°C) + Precipitation (mm), “b” – Storm damages (m^3/ha) and “c” is the combined effect of both the two groups (Figure 5). For each one of “a”, “b” and “c” it was specified the percent of explained variation (percent of the individually influence of each factor), and the percent of all variation explained by these groups (how much of the behavior of species is explained by these factors). The unexplained variation have also been calculated.

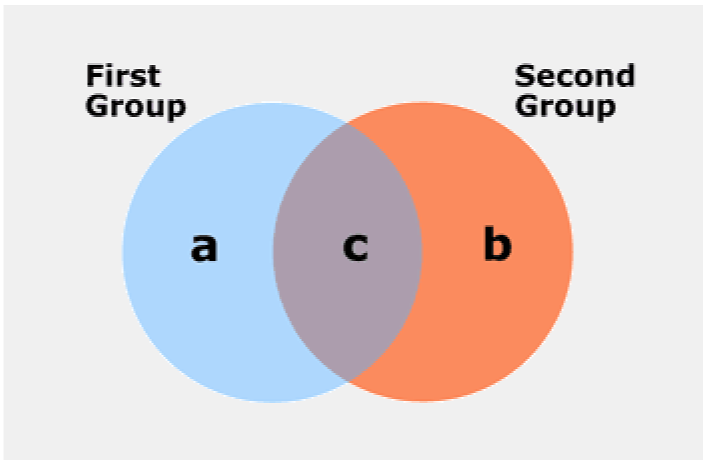

Figure 5 – Results of Variation Partitioning Analysis where “a” stands for the effect of the first group – Temperature (°C) + Precipitation (mm), “b” – Storm damages (m^3/ha) and “c” is the combined effect of both the two groups.

The summary tables of the Variation Partitioning Analysis (Tables 25-30) and Redundancy Analysis (Tables 31-36) are displayed in the Appendices section.

4. Results

4.1. Insect host trees per year: attacked broadleaved trees versus attacked coniferous trees

1850-1950

Large differences between the three regions are observed (Figure 6). An increase in the occurrences of insect outbreaks is noticeable around 1911, before that the extent of those occurrences was more or less the same through the years. Taking into account the correlation between host trees and insect outbreak occurrences, the southern part has the biggest number of insect outbreak occurrences, due to the fact that more insect outbreaks occurred here than in the other parts of Sweden. Insects confined to coniferous trees are more abundant than insects preferring broadleaved trees. This is more noticeable in the northern part, where broadleaved trees are attacked only in a small extent, due to the fact that conifers are the dominant species in this region. In the southern part insects attacking broadleaved trees occurred closely to the extent of the insects confined to coniferous trees (Figure 6).

1961-2014

The degree of attacked coniferous trees is still larger than the attacked broadleaved trees as we observed over the previous period. From 1961 till 1990 there are some fluctuations in the host trees, but not with a clear and great decrease, and the trend follows the same pattern throughout the whole period (1961-1990). Slightly more attacked host trees are located in the southern part, in comparison with the other two regions. The lowest extent of attacked host trees is for the northern part of the country, whereas the other two regions have more or less the same values (Figure 6).

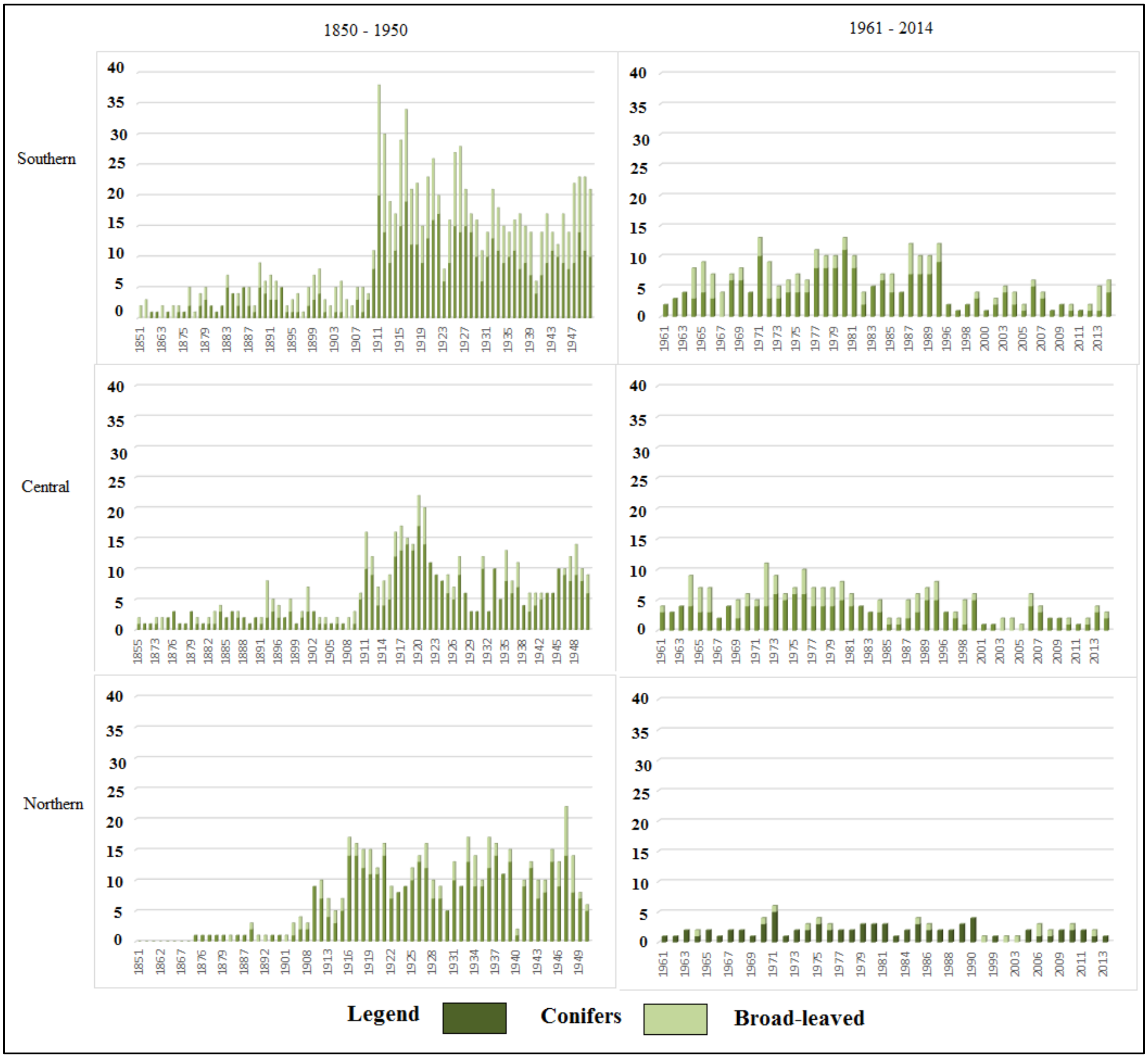

Figure 6 – Attacked host trees and insect outbreak occurrences considering all insects for each southern, central and northern Sweden and also for the two periods, 1850-1950 (left) and 1961-2014 (right). Figure shows the attacked host trees grouped within coniferous and broadleaved trees.

4.2. Occurrences of insect outbreaks

Division of the whole period 1850-2014 was made considering the same two periods used before, 1850-1950 and 1961-2014. Likewise, these two periods were divided each into two sub periods. First period into: 1850-1910 - with a continuous and similar trend of insect occurrences, and 1911-1950 – with an evident increase in the number of insect occurrences (see Figure 7). The second period was divided into: 1961-1990 and 1991-2014, as to show the two different datasets used to procure the primary data for this thesis.

Figure 7 – Occurrences of insect outbreaks in Sweden considering all insect species, divided into two periods: 1850-1950 and 1961-2014, and in three regions: Southern, Central and Northern Sweden. For the first period (left), the red line is used to delineate two sub periods, 1850-1910 and 1911-1950, the first sub period with a continuous and similar trend of insect outbreak occurrences and the second sub period with an evident increase in the number of outbreak occurrences. For the second period (right) the red line is used to show the two different datasets used to procure the primary data for this thesis, 1961-1990 and 1991-2014.

It is important to note that the numbers used to show the averages for the occurrences of insect outbreaks should be taken into consideration only within each period, and used only for a comparison of all the three regions (northern, central and southern), and not to make comparisons of the occurrences of insect outbreaks between the two periods described before. It is important to state this, as there are dissimilarities between the different datasets used to procure the primary data (as mentioned in Materials and Methods). Each period corresponds to a different dataset, and therefore a comparison between them might be biases.

1850-1910

The occurrence of insect outbreaks follows the same pattern throughout the period, 1850 till 1910, in central Sweden, with no important differences regarding fluctuations of outbreaks. For the southern region a small increase in the occurrence of outbreaks can be visible from the beginning of the period. In the southern part outbreaks reached a peak (for this period) around 1890, followed by a decrease till the same extent as before. In north the trend of outbreaks follows a continuously growing pattern after 1988. The occurrences of insects differ between the three regions, varying from 4 in central and north till 10 (when the outbreaks reached a peak) in the south (Figure 7). The average of insect outbreak occurrences per each year is comprised between 1-2 occurrences per year in central and north and 3 to 5 in south (Figure 8).

1911-1950

Starting with 1911 a large increase in the number of outbreak occurrences occurred in all three regions. In north, even if some fluctuations appeared, the increase in the occurrences maintained on the same trend throughout the whole period (1911-1950). The occurrence of insects responsible for outbreaks varied between 8 and 15, reaching the lowest range of 2 occurrences in 1940. In the central area, after a peak (19 different occurrences of outbreaks) around 1920, a continuously decreasing pattern occurred within the next period, not exceeding however more than 12 for the rest of the years. In the southern region, this increase in the 1911 was followed in the subsequent years by a decrease. The occurrences of insect outbreaks expanded, varying between 26 - when it reached its peak in 1916, and 6 - when it reached the lowest value for this period, in 1940 (Figure 7). During 1911-1950 the average of occurrences per year reached approximately 6-9 in the central region, 10-11 in the northern region and a maximum of 15 in the southern region (Figure 8).

1961-1990

From 1961 till 1990 no important fluctuations in the occurrences of insects responsible for outbreaks are observed. The occurrences of insects responsible for the attacks does not exceed 11 for the southern region, 8 and 5 for the central and respectively the northern one. The lowest value reached during 1961-1990 is of one occurrence, for all three regions (Figure 7). The average for this period is of about 1-2 occurrences per year in north, 3-5 in central and 6-9 in south (Figure 8).

1991-2014

The next analyzed period, i.e. 1991-2014, shows a low occurrence of outbreaks. There is a great decrease in recorded insect damage to forests after 1996, followed in 2007 by an abrupt increase in central Sweden. In the southern region, the occurrences are more or less consistent, showing an increasing trend, reaching up to 6 occurrences of outbreaks in 2006. The northern part doesn't show big differences in the occurrences of insects involved in outbreaks (Figure 7). The average reaches 3-5 occurrences of outbreaks per year in both southern and central regions. In the northern one the trend of insect outbreaks does not shows big fluctuations, with an average of 1-2 per year (Figure 8).

Figure 8 below comprises a map of the average values for each period and for all the three regions analyzed, as well as for the entire Sweden.

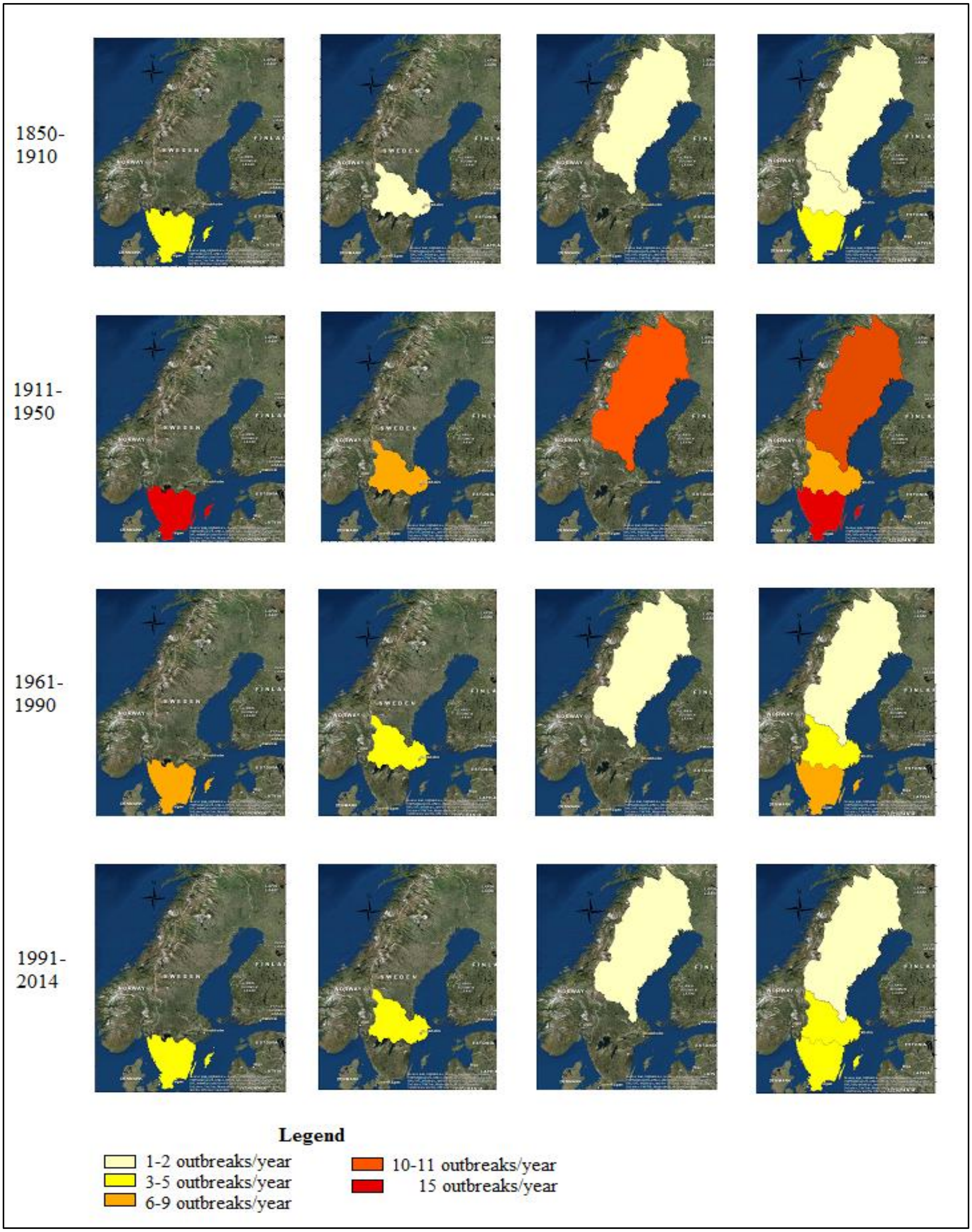

Figure 8 – Mapping using ArcGIS the average of insect outbreak occurrences per year of outbreaks covering all four sub periods (as chosen and described in Materials and Methods section): 1850-1910, 1911-1950, 1961-1990 and 1991-2014, for all southern, central, northern and the whole Sweden.

4.3. Top five families responsible for outbreak occurrences

4.3.1. Southern Sweden

The families of insects responsible for outbreaks in Southern Sweden for the periods 1850-1950 (left) and 1961-2014 (right) are displayed below (Figure 9). In the figure it is only mentioned the name of the most important families, each represented by a different vector. The names of the other vectors (families) and years were intentionally removed for a better perspective and overview. Top five families (Table 4) refers to the longest five vectors (as mentioned in Section 3.3).

Southern Sweden	
Top 5 families (1850-1950)	**Top 5 families (1961-2014)**
Curculionidae	Geometridae
Tortricidae	Curculionidae
Geometridae	Tephritidae
Diprionidae	Cecidomyiidae
Scarabeidae	Noctuidae

Table 4 – Top 5 families of insect species for Southern Sweden, ordered after their importance (i.e. the length of the vectors), for the two periods, 1850-1950 and 1961-2014

1850-1950

For the first period the longest vector and representing the family with the most significant impact is *Curculionidae* – snout beetles and true weevils, gathering 32 different insect species responsible for outbreaks in Southern Sweden. This family had an important impact in 1912, 1918 and 1926. It is closely followed by *Tortricidae* – tortrix moths or leafroller moths, which includes 9 different insect species, and causes significant damages in 1911 and 1921. After these two most dominant families, a significant impact have the following three families: *Geometridae* – moths, *Diprionidae* – conifer sawflies, which causes damages in 1911, 1921 and 1945, and *Scarabeidae* – scarab beetles, having an impact in 1916, 1925 and 1932-1933. These last three species comprise 16 different insect species altogether (Figure 9).

1961-2014

Between 1961 and 2014 the distribution of the most important five families has significantly changed, hence only two families from the first period managing to be indicated again as important families. The family with the most substantial impact is now *Geometridae*, which includes 4 types of insect species. It produced significant damages from 1964 till 1967. *Curculionidae* stands now on the second position, with 11 different insect species and causing damages around 1971. The last three places are assigned to *Tephritidae* - fruit flies, *Cecidomyiidae* - gall midges or gall gnats, and *Noctuidae* - owlet moths. These families are being responsible for damaging mostly from 1987 to 1990 (Figure 9).

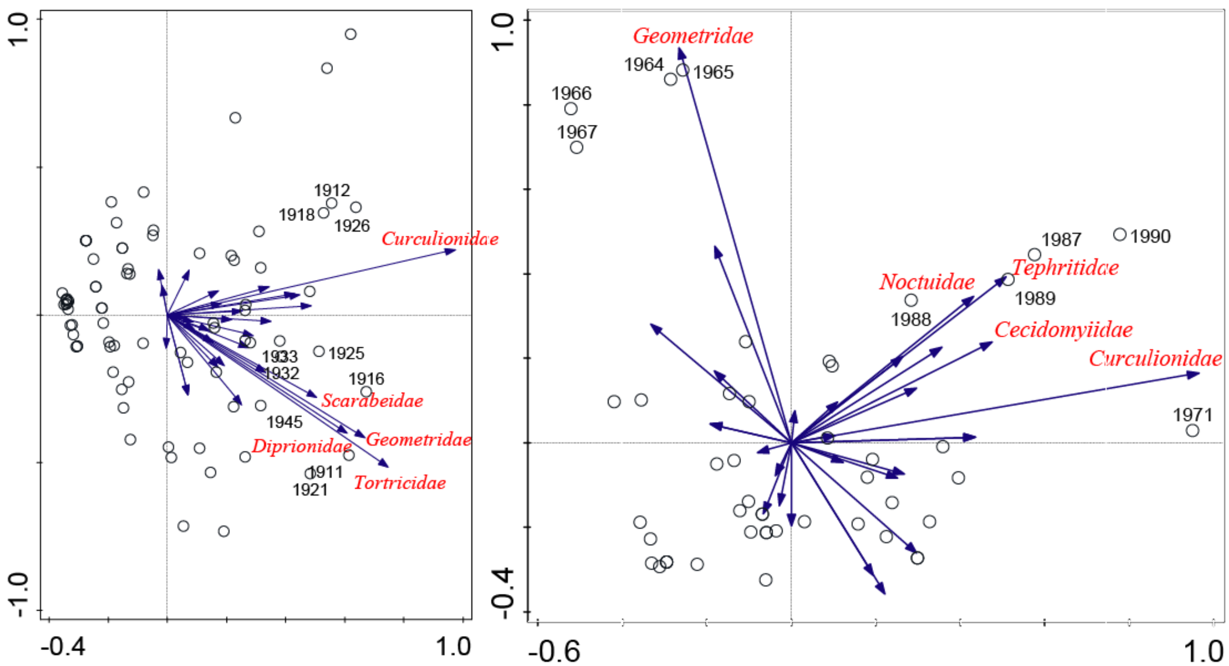

Figure 9 – Biplots of Principal component analysis showing the families of insect species responsible for outbreaks (represented by vectors) and the years of outbreaks (represented by circles) for Southern Sweden. 1850-1950 (left) and 1961-2014 (right). It is only displayed the name of the top five most important insect families for a better perspective. Top five families refers to the longest vectors. The names of the less important families and years had been intentionally removed

4.3.2. Central Sweden

Central Sweden	
Top 5 families (1850-1950)	**Top 5 families (1961-2014)**
Curculionidae	Curculionidae
Geometridae	Geometridae
Tortricidae	Diprionidae
Pampiliidae	Chrysomelidae
Pyralidae	Adelgidae

Table 5 - Top 5 families of insect species for Central Sweden, ordered after their importance (i.e. the length of the vectors), for the two periods, 1850-1950 and 1961-2014

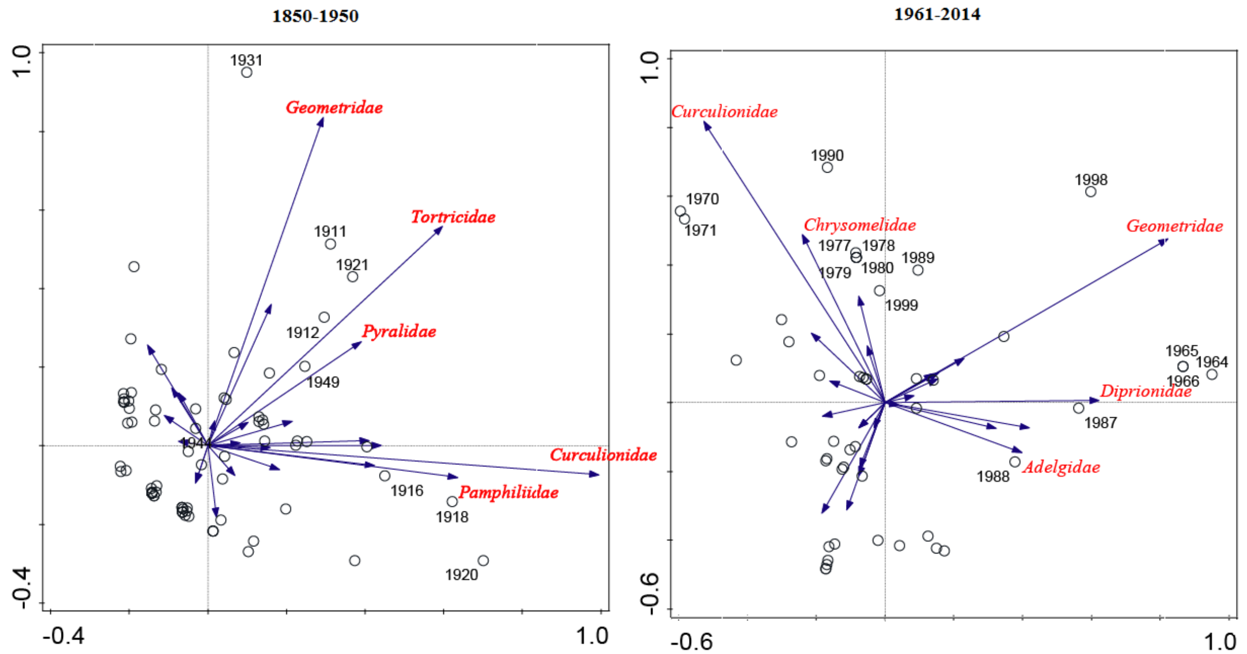

Figure 10 – Biplots of Principal component analysis showing the families of insect species responsible for outbreaks (represented by vectors) and the years of outbreaks (represented by circles) for Central Sweden. 1850-1950 (left) and 1961-2014 (right). It is only displayed the name of the top five most important insect families for a better perspective. Top five families refers to the longest vectors. The names of the less important families and years had been intentionally removed.

1850-1950

Top five important families for Central Sweden (Table 5) between 1850 and 1950 includes the following: *Curculionidae*, with 22 different insect species, *Geometridae*, gathering 7 different insect species, and causing damages in 1931, *Tortricidae*, with an important impact in 1911-1912 and 1921 and containing 7 types of insects, *Pyralidae* – snout moths, with 4 different insect species and having an impact in 1921 and 1949, and *Pampiliidae* – butterflies, which includes 3 types of insects and which has caused damages around 1916-1920 (Figure 10).

1961-2014

From 1961 till 2014 the first two families as in the previous period remain the two most important pests (Table 5). *Curculionidae* proves to be an important family which constantly causes significant losses in 1970-1971 and 1990. It is followed by *Geometridae*, being an important pest in 1998, and *Diprionidae,* with the last one having a strongly impact around 1964-1966. Two families newly entered in the Top five are *Adelgidae* – aphids, plant lice, and

Chrysomelidae – leaf beetles. The first one caused important damages in 1988, while the latter impacted from 1977 till 1980, 1990 and 1999 (Figure 10).

4.3.3. Northern Sweden

The top families for the northern part of the country are displayed in the following table (Table 6).

Northern Sweden	
Top 5 families (1850-1950)	**Top 5 families (1961-2014)**
Curculionidae	Curculionidae
Tortricidae	Diprionidae
Diprionidae	Adelgidae
Cerambycidae	Cecidomyiidae
Adelgidae	Tenthredinidae

Table 6 - Top 5 families of insect species for Northern Sweden, ordered after their importance (i.e. the length of the vectors), for the two periods, 1850-1950 and 1961-2014

1850-1950

The most important family which caused most of the damages and occurred from 1850 till 1950 is *Curculionidae*, which gathers 24 different types of insects and has a strong impact around 1926 and 1927. It is closely followed by *Tortricidae*, covering 6 different insect species and causing damage from 1921 till 1936, and *Diprionidae* with one important insect species but still causing damage in 1939. Less important in comparison with the three above mentioned dominant families during this period, but still very important considering the other families, are the last two families from Top five, *Cerambycidae*, with 2 types of different insects, and acting as important pests in 1937 and *Adelgidae*, which causes damages throughout the whole periods, from 1911 till 1947 (Figure 11).

1961-2014

For the last period the dominant family remains *Curculionidae*, causing major damage in 1988 and 2012. *Diprionidae* still continues to be a notable family, causing valuable damage in 1967. *Adelgidae* is found on the third position in Top five families with attacks in 1983-1984 and 1999-2003, being very closely followed by *Cecidomyiidae*, which determined strong damages between

1976 and 1981, and 1987 - 1990, and *Tenthredinidae* - sawflies, between 1972 and 1974, in 1988 – 1989, as well as in 2013 (Figure 11).

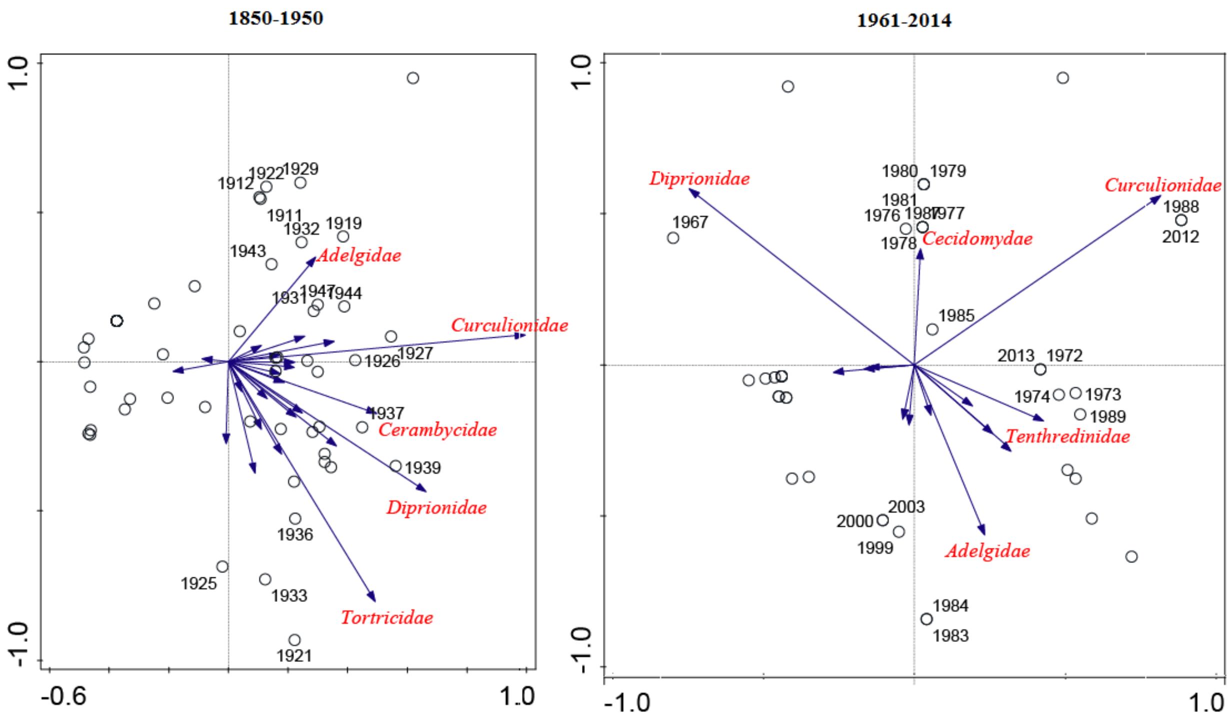

Figure 11 – Biplots of Principal component analysis showing the families of insect species responsible for outbreaks (represented by vectors) and the years of outbreaks (represented by circles) for Northern Sweden. 1850-1950 (left) and 1961-2014 (right). It is only displayed the name of the top five most important insect families for a better perspective. Top five families refers to the longest vectors. The names of the less important families and years had been intentionally removed.

4.4. Top species responsible for outbreak occurrences

4.4.1. Southern Sweden

The species representing Top species were selected relaying on their importance (were chosen the vectors corresponding to the most important species that were outside the circle, as described in Section 3.3) (Table 7).

1850-1950

Ips typographus (Family: *Curculionidae*, Host trees: coniferous) was an important pest between 1933 and 1937, *Blastophagus piniperda and B. minor* (Family: *Curculionidae*, Host trees: coniferous) caused damage in 1918-1925 and 1932, and *Laspeyresia strobilella* (Family: *Tortricidae*, Host trees: coniferous) had an important impact in 1918. *Hylobius abietis* (Family:

Curculionidae, Host trees: coniferous) caused significant damages in 1920-1921 and in 1945, *Melolontha melolontha* (Family: *Scarabeidae*, Host trees: coniferous and broadleaved) in 1948-1950 and 1969, and *Melolontha hippocastani* (Family: *Scarabeidae,* Host trees: coniferous and broadleaved) in 1915 (Figure 12).

1961-2014

For the second period new species turned out to be the most important pests, such as *Microdiprion pallipes* (Family: *Diprionidae,* Host trees: coniferous), *Chrysomela populi* (Family: *Chrysomelidae,* Host trees: broadleaved), *Strophosoma capitatum* (Family: *Curculionidae*, Host trees: coniferous), *Aradus cinnamomeus* (Family: *Aradidae,* Host trees: coniferous) and *Neodiprion sertifer* (Family: *Diprionidae,* Host trees: coniferous), while *Ips typographus* remained the only insect species from the first period still present to a large scale. It caused damages around 1972-1974. Species like *Microdiprion pallipes* and *Chrysomela populi* became important pests between 1977 and 1981 and *Thecodiplosis brachyntera* (Family: *Cecidomyiidae,* Host trees: coniferous) caused damages in 1987 (Figure 12).

Southern Sweden	
Top insect species	
1850 - 1950	**1961 - 2014**
Pissodes pini	*Ips typographus*
Ips typographus	*Microdiprion pallipes*
Laspeyresia strobilella	*Chrysomela populi*
Hylobius abietis	*Strophosoma capitatum*
Melolontha melolontha	*Aradus cinnamomeus*
Melolontha hippocastani	*Neodiprion sertifer*
Blastophagus piniperda and B. minor	*Thecodiplosis brachyntera*

Table 7 - Top insect species for Southern Sweden, ordered after their importance (i.e. the length of the vectors outside the circle), for the two periods, 1850-1950 and 1961-2014

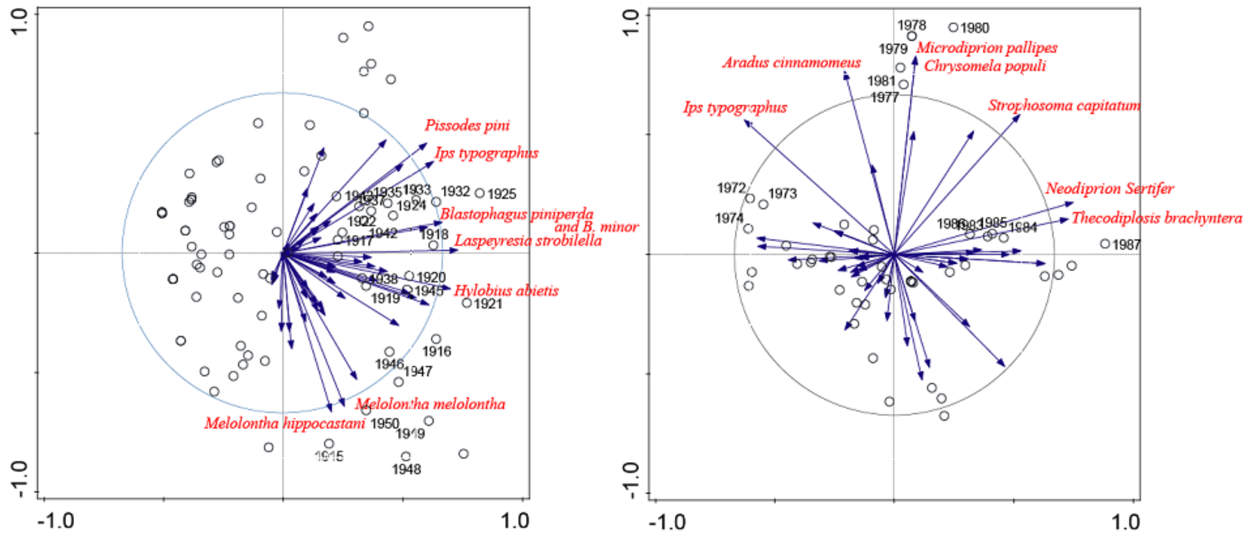

Figure 12 – Biplots of Principal component analysis showing the insect species responsible for outbreaks (represented by vectors) and the years of outbreaks (represented by circles) for Southern Sweden. 1850-1950 (left) and 1961-2014 (right). It is only displayed the name of the most important insect species for a better perspective. The names of the less important species and years had been intentionally removed. The circle is used to differentiate the species with the most impact.

4.4.2. Central Sweden

The species chosen as Top species were selected by their importance (species corresponding to the vectors that were outside the circle) (Table 8).

Central Sweden	
Top insect species	
1850 - 1950	**1961 - 2014**
Bupalus piniarius	*Neodiprion sertifer*
Ips typographus	*Ips typographus*
Blastophagus piniperda and B. minor	*Microdiprion pallipes*
Pityogenes chalcographus	*Erannis aurantiaria*
Dendroctonus micans	*Erannis defoliaria*
	Tortrix viridana

Table 8 – Top insect species for Central Sweden, ordered after their importance (i.e. the length of the vectors outside the circle), for the two periods, 1850-1950 and 1961-2014

1850-1950

Top species responsible for important outbreaks for Central Sweden between 1850 and 1950 shows some big differences in comparison with southern Sweden, with new species making an appearance and having a big influence in causing damage. *Ips typographus* and *Blastophagus* *piniperda and B. minor* remain some of the most important species. *Ips typographus* caused substantial damage in 1920–1927 and 1935–1937, *Blastophagus piniperda and B. minor* around 1918 and 1919 and *Pityogenes chalcographus* (Family: *Curculionidae*, Host trees: coniferous) in 1916–1921. *Bupalus piniarius* (Family: *Geometridae*, Host trees: coniferous) manifested as a pest in 1911–1912 (Figure 13) and *Dendroctonus micans* (Family: *Curculionidae*, Host trees: coniferous) in 1918.

1961-2014

From 1961 to 2014 new species emerged, species that didn't show importance as main pests from 1850 till 1950. In comparison with the Top species in the southern part of Sweden for this period (Table 7), Top species in central shows some resemblances, containing same species as *Microdiprion pallipes, Neodiprion sertifer* and *Ips typographus.* The latter has caused significant damage from 1972 till 1981. *Neodiprion sertifer* causes damage around 1990. *Microdiprion pallipes and Erannis aurantiaria* (Family: *Geometridae*, Host trees: broadleaved) have a strong impact between 1964 and 1966, *Erannis defoliaria* (Family: *Geometridae*, Host trees: broadleaved) and *Tortrix viridana* (Family: *Tortricidae* Host trees: broadleaved) in 1986-1987 (Figure 13).

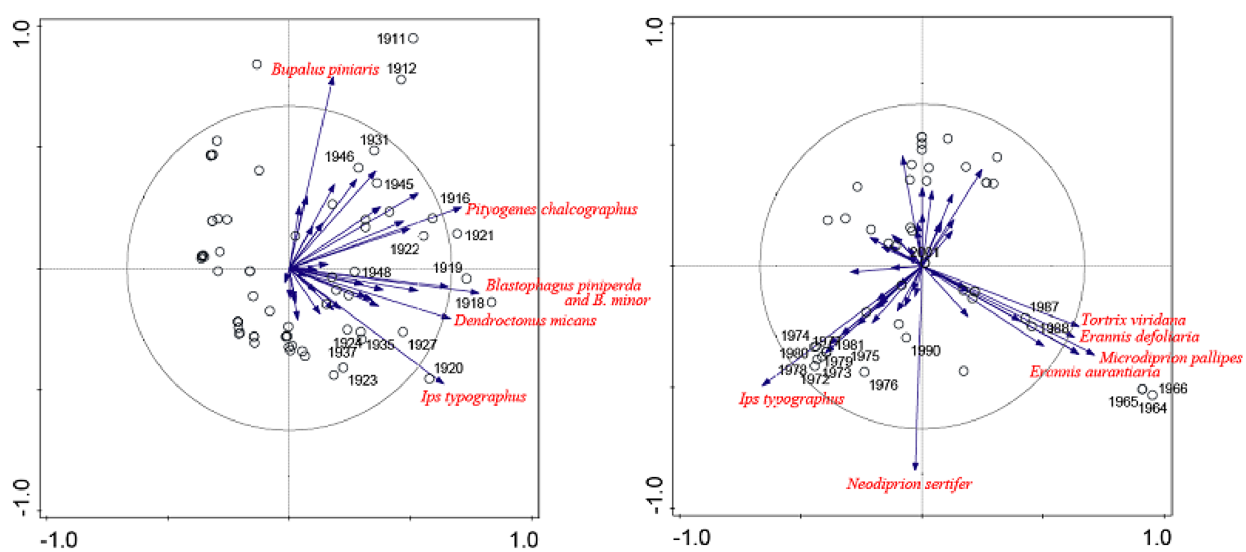

Figure 13 – Biplots of Principal component analysis showing the insect species responsible for outbreaks (represented by vectors) and the years of outbreaks (represented by circles) for Central Sweden. 1850-1950 (left) and 1961-2014 (right). It is only displayed the name of the most important insect species for a better perspective. The names of the less important species and years had been intentionally removed. The circle is used to differentiate the species with the most impact.

4.4.3. Northern Sweden

The species chosen as Top species were selected by their importance (species corresponding to the vectors that were outside the circle) (Table 9).

Northern Sweden	
Top insect species	
1850 - 1950	**1961 - 2014**
Hylobius abietis	*Microdiprion pallipes*
Blastophagus piniperda and B. minor	*Ips typographus*
Monochamus sutor	*Diprion butovitschi*
Ips acuminatus	*Thecodiplosis brachyntera*
Diprion sertifer	*Oporinia autumnata*
Ips typographus	
Pityogenes chalcographus	
Ips sexdentatus	
Laspeyresia strobilella	

Table 9 – Top insect species for Northern Sweden, ordered after their importance (i.e. the length of the vectors outside the circles), for the two periods, 1850-1950 and 1961-2014

1850-1950

The northern part of Sweden shows a larger diversity of insect species causing damage in comparison with the other two parts of Sweden for the first period, i.e. 1850-1950, with no less than 9 different species manifesting as important pests. *Ips sexdentatus* (Family: *Curculionidae*, Host trees: coniferous) and *Pityogenes chalcographus* are pests which had an important impact between 1935 and 1941. *Ips acuminatus* (Family: *Curculionidae*, Host trees: coniferous) caused damage in 1918-1920. *Ips typographus* and *Blastophagus piniperda and B. minor* occurred to a large extent in 1946 and 1947, while *Laspeyresia strobilella* and *Diprion sertifer* (Family: *Diprionidae*, Host trees: coniferous) performed in 1916-1917. *Hylobius abietis* made itself notable around 1927 and 1942 and *Monochamus sutor* (Family: *Cerambycidae*, Host trees: coniferous) still caused damage between 1921 and 1926 and also in 1932 (Figure 14).

1961-2014

Between 1991 and 2014 only *Ips typographus* continued to cause significant damages, as new species emerged. For this period other four different species caused damage. *Microdiprion pallipes* caused serious damages in 1985 and 1986, followed by *Oporinia autumnata* (Family:

Geometridae, Host trees: broadleaved), an insect species which has a big occurrence in 1967 and *Thecodiplosis brachyntera* (Family: *Cecidomyiidae,* Host trees: coniferous), which produced significant damages from 1977 till 1981. *Diprion butovitschi* (Family: *Diprionidae,* Host trees: coniferous) occurred around 1974 (Figure 14).

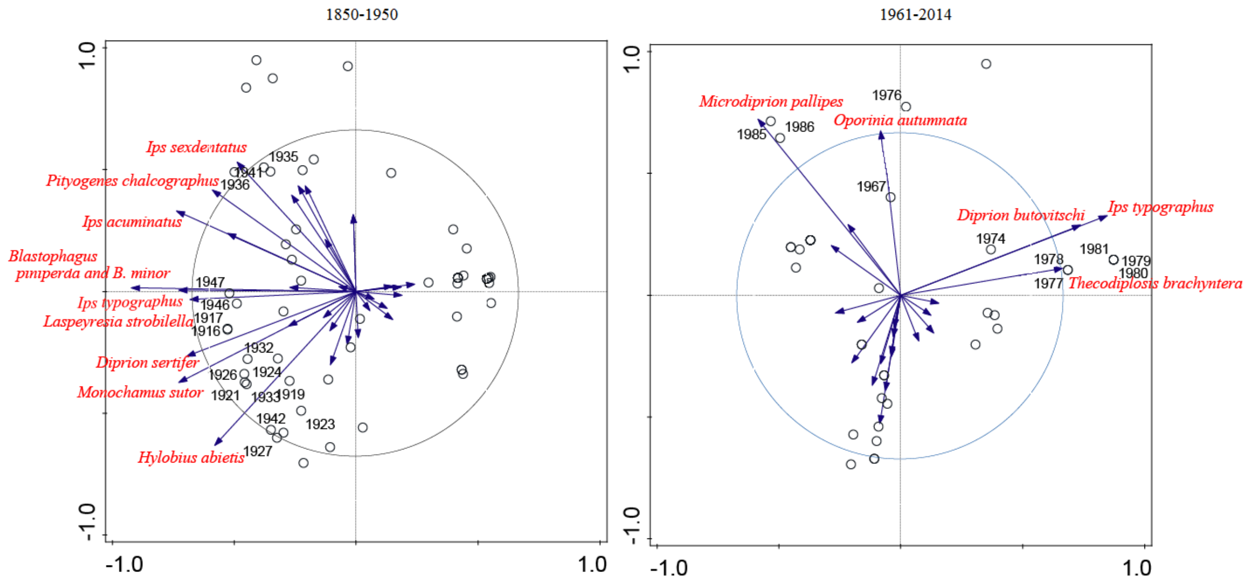

Figure 14 – Biplots of Principal component analysis showing the insect species responsible for outbreaks (represented by vectors) and the years of outbreaks (represented by circles) for Northern Sweden. 1850-1950 (left) and 1961-2014 (right). It is only displayed the name of the most important insect species for a better perspective. The names of the less important species and years had been intentionally removed. The circle is used to differentiate the species with the most impact.

<u>4.5. Climate influence on the occurrences of insect outbreaks</u>

In order to further analyze the influence of climate variables on the occurrence of insect outbreaks I used the variation partitioning method. The climate parameters used are temperature (°C) and precipitation (mm). Average mean temperature for J-A-S in the southern region reaches even up to 17°C, a difference of almost 3°C from the northern and 1°C from the central regions. Average mean temperature for A-M-J, J-A-S and winter follows a continuous trend over the years, and it is observed an increase starting with 1990. In the southern part, the winter mean temperatures do not exceed -6°C, in central they begin to decrease, reaching -10°C, while in the northern part they go as far as -19°C. Precipitation shows a more discontinuous trend in comparison with the average temperatures, with large fluctuations in the mean, J-A-S reaching a peak of about 360 mm in the northern region around the year 2000, and a lowest value of about

65 mm in central around 1900. A-M-J precipitation do not show major discrepancies between all the above three regions, illustrating values between 50 mm and up to 200 mm (Figure 15).

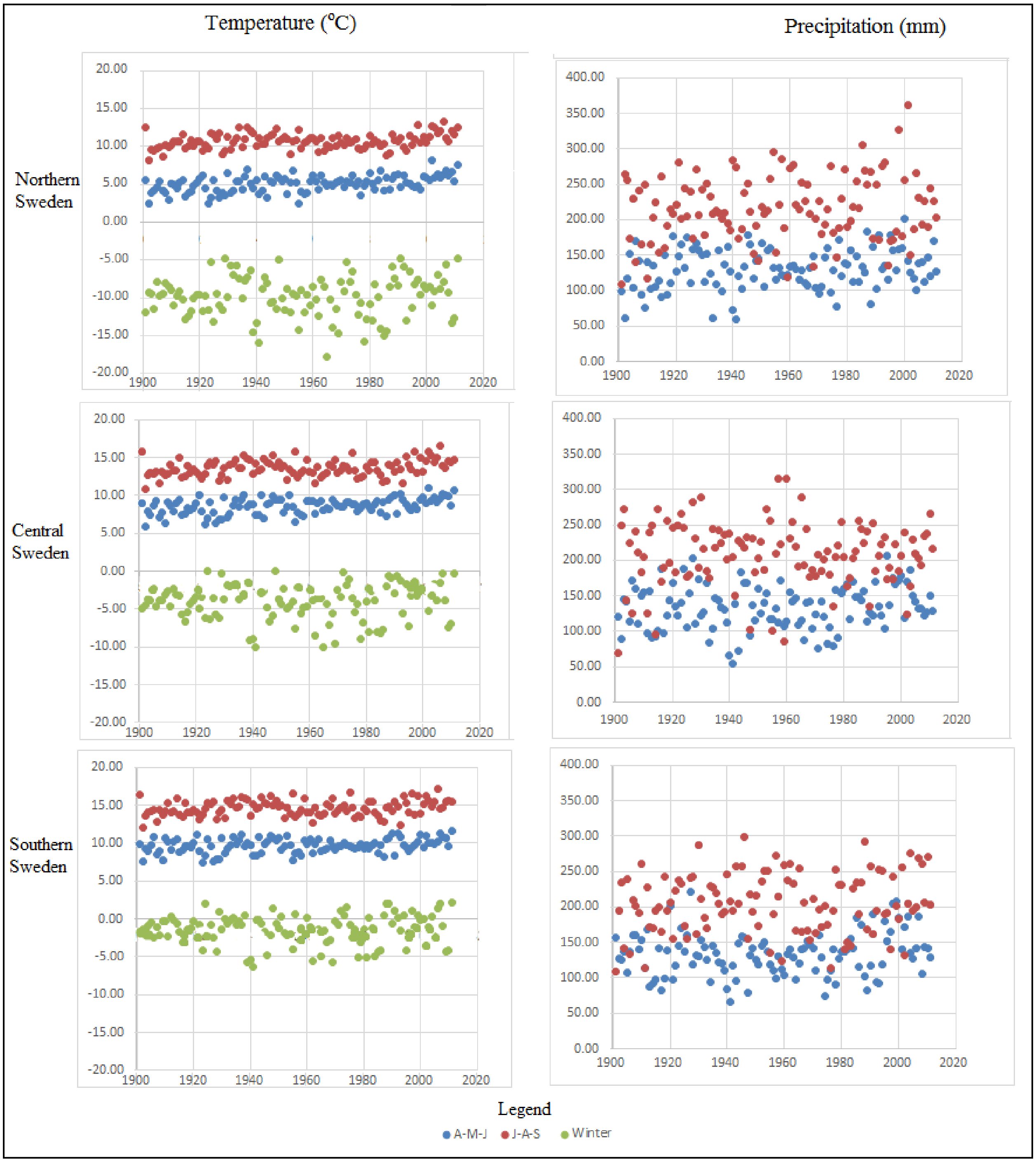

Figure 15 – Changes in average mean temperature (°C) and precipitation (in mm) from 1901 till 2011 in all three regions of Sweden (southern, central and northern). For temperature (left) A-M-J represent the average between mean temperatures of April, May and June, J-A-S the average mean temperature between July, August and September, and Winter the average between December, January and February. For precipitation A-M-J represents the sum of monthly precipitation between August, May and June, and J-A-S the sum for July, August and September. These combinations of months were chosen as these are more relevant from a tree phenological point of view.

4.5.1. Southern Sweden

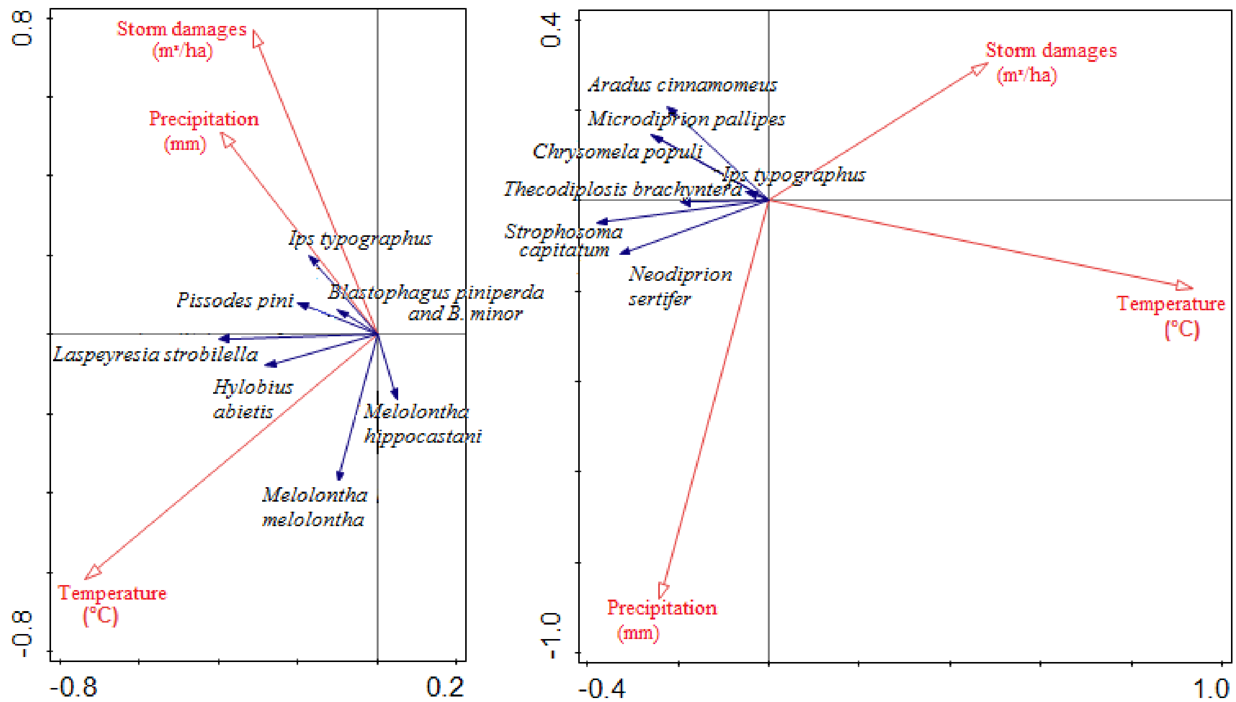

Figure 16 – Biplots of Redundancy analysis (RDA) showing the behavior of Top species in Southern Sweden, indicated by blue vectors, correlated to climate parameters (Temperature - °C and Precipitation - mm) and Storm damages - m³/ha, indicated by red vectors for 1850-1950 (left) and 1961-2014 (right).

1850-1950

The correlation between environmental factors like temperature, precipitation and storm damages and the most harmful insect species occurs more visibly in the first period, 1850-1950 than in the latter period, 1961-2014. Species respond different to environmental parameters, some being more affected by temperature or precipitation while others experience a big influence caused by the storm damages (Figure 16). Among the species which react to temperature changes we note *Hylobius abietis*, and to a smaller extent species like *Melolontha melolontha* and *Laspeyresia strobilella*. Resonating more with fluctuations in precipitation are species like *Pissodes pini, Blastophagus piniperda and B. minor* and *Ips typographus*. The latter shows strongly correlation with the changes in the mean precipitation. The behavior of *Melolontha hippocastani* does not seem to be related to fluctuations in these factors whatsoever (Figure 16).

Table 10 indicates the proportion in which temperature and precipitation ("a") and storm damages ("b") influence the behavior of insect species for the first period. The effect of temperature and precipitation has the strongest impact, with 70.4%. Damages caused by storms only affect species in a small extent that is 26.8%. However, these three factors only explain 8.6% of the whole behavior of species. The rest of 91.4% is subject to other factors or processes.

		Fraction	% of Explained	% of All	
South	1850-1950	a	70.4	Explained	Unexplained
		b	26.8	8.6	91.4
		c	2.8		
		Total	100		

Table 10 - Variation Partitioning Analysis for Southern Sweden, where "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" for the second group – Storm damages (m^3/ha) and "c" is the combined effect of both two groups. For each one of "a", "b" and "c" it is specified the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation explained by these groups (how much of the behavior of species is explained by these factors).

1961-2014

The situation dramatically changed for the second period (Figure 16). None of the species which caused the most significant damages throughout this period show the tendency to relate to the environmental factors. This can be a result of the different datasets used for this study, or their behavior in this case can be explained by different processes.

4.5.2. Central Sweden

1850-1950

Among the species influenced in a large scale by temperature are species like *Pityogenes chalcographus* and, to a smaller extent, *Ips typographus* as well. *Dendroctonus micans* is affected in an important amount by fluctuations in precipitation. The species *Bupalus piniarius* and *Blastophagus piniperda and B. minor* show less correlation with the above mentioned factors, their comportment depending on other processes (Figure 17).

Table 11 indicates the proportion in which temperature and precipitation ("a") and storm damages ("b") influence the comportment of insect species for the first period. The first two variables (temperature and precipitation) have an important and substantial influence, with 80.5%, while storm damages only influence in a proportion of 16.4%. Still, these three factors only explain 10.7% of the whole behavior of species. The rest of 89.3% is subject to other factors (Table 11).

1961-2014

For the second period, 1961-2014, the situation encountered in southern Sweden seems to repeat, with no association between the behavior of the most important species that caused serious outbreaks and factors such as temperature, precipitation or storm damages. This can be a result of the different datasets used for this study, or the behavior of species in this case can be explained by other processes (Figure 17).

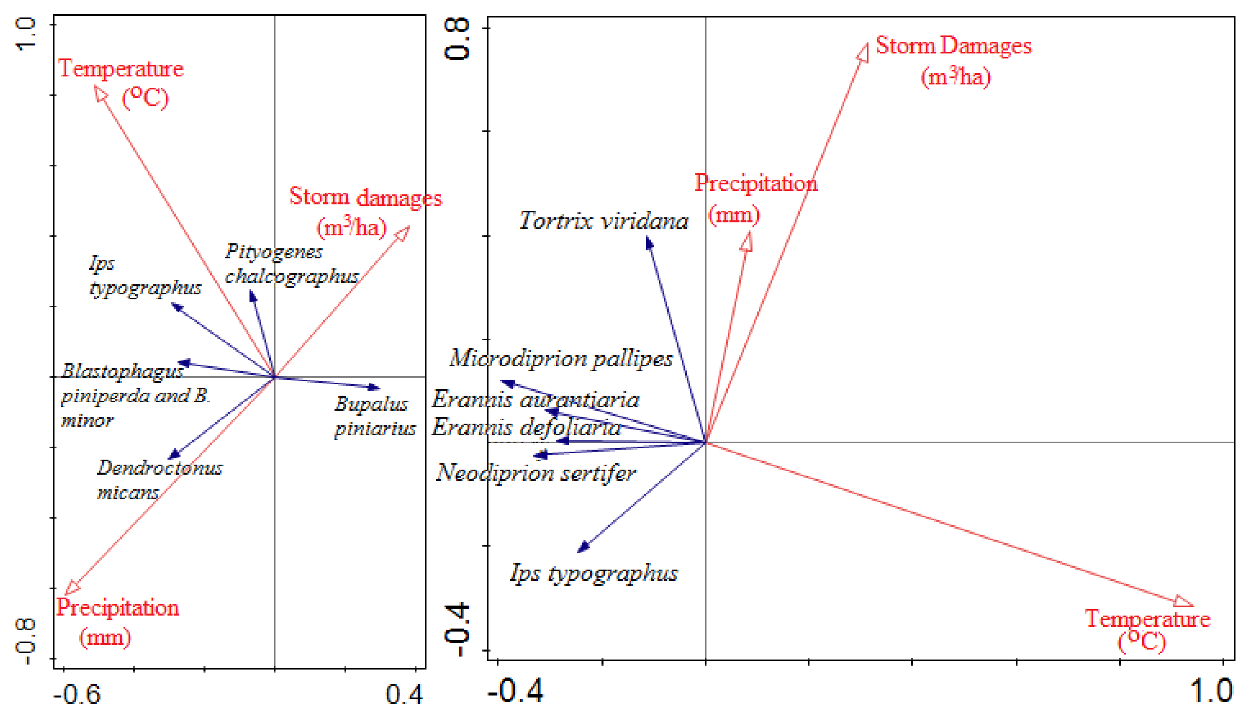

Figure 17 – Biplots of Redundancy analysis (RDA) showing the behavior of Top species in Central Sweden, indicated by blue vectors, correlated to climate parameters (Temperature - °C and Precipitation - mm) and Storm damages - m^3/ha, indicated by red vectors for 1850-1950 (left) and 1961-2014 (right).

		Fraction	% of Explained	% of All	
Central	1850-1950	a	80.5	Explained	Unexplained
		b	16.4	10.7	89.3
		c	3.2		
		Total	100		

Table 11 – Variation Partitioning Analysis for Central Sweden, where "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" for the second group – Storm damages (m³/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it is specified the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation explained by these groups (how much of the behavior of species is explained by these factors).

4.5.3. Northern Sweden

1850-1950

Between 1850 and 1950 damages caused by storms are having an important effect on *Pityogenes chalcographus* and *Ips sexdentatus.* Fluctuations in the average values of temperature and precipitation seem to influence only in a small degree species like *Ips typographus, Ips acuminatus, Blastophagus piniperda and B. minor* and *Laspeyresia strobilella. Diprion sertifer, Monochamus sutor* and *Hylobius abietis* are species which appeared to relate more to variations in precipitation (Figure 18).

Table 12 illustrates the proportion in which Temperature and Precipitation ("a") and Storm damages ("b") influence the comportment of insect species for the first period. While the first two had an influence in a proportion of 73.4%, the latter had only of 17.2%. A big proportion is explained by the combination of all the above three factors, 10.4%. Again, only 13.8% of the entire behavior of species is explained by these factors. The rest of 86.2% is subject to other factors (Table 12).

1961-2014

The circumstances for the species behavior slightly changed for the second period, 1961-2014, in comparison with southern and central Sweden. Although the species *Microdiprion pallipes, Ips typographus, Diprion butovitschi* and *Oporinia autumnata* showed no tendency to be influenced by temperature, precipitation and storm damages, *Thecodiplosis brachyntera* seems however, to a small extent, to be affected by variations in precipitation, but this species is not showing a clear influence of the precipitation (Figure 18).

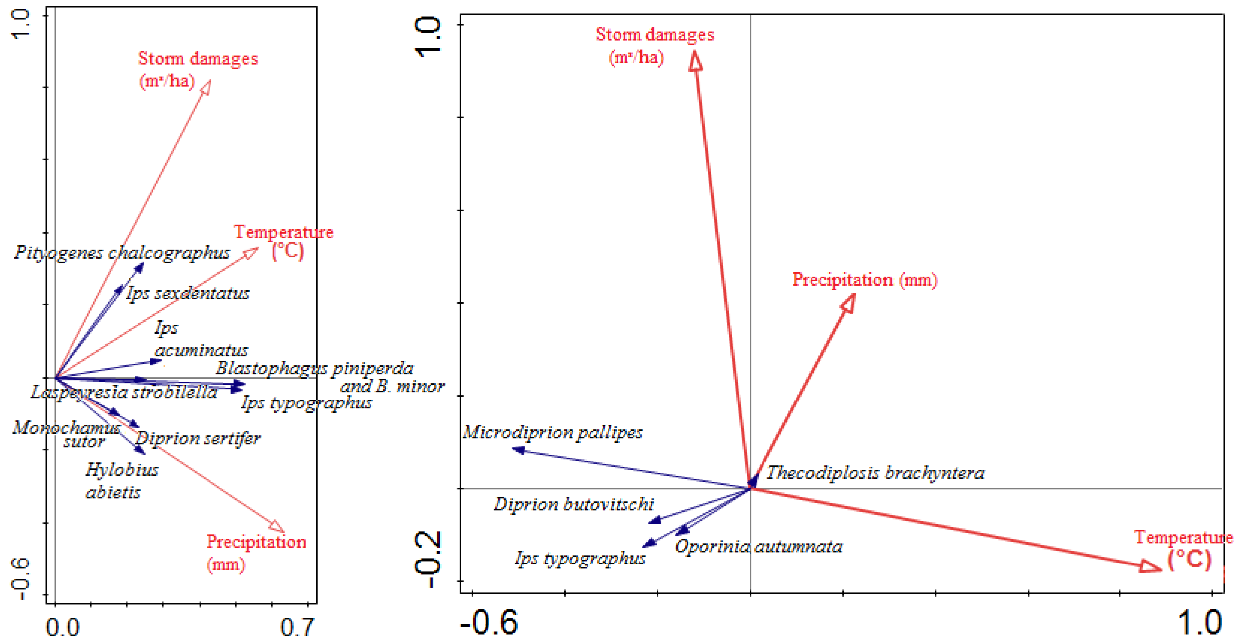

Figure 18 – Biplots of Redundancy analysis (RDA) showing the behavior of Top species in Northern Sweden, indicated by blue vectors, correlated to climate parameters (Temperature - °C and Precipitation - mm) and Storm damages - m³/ha, indicated by red vectors for 1850-1950 (left) and 1961-2014 (right).

		Fraction	% of Explained	% of All	
				Explained	Unexplained
North	1850-1950	a	72.4		
		b	17.2	13.8	86.2
		c	10.4		
		Total	100		

Table 12 – Variation Partitioning Analysis for Northern Sweden, where "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" stands for the effect of the second group – Storm damages (m³/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation explained by these groups (how much of the behavior of species is explained by these factors).

5. Discussion

This study was conducted for all of Sweden in accordance with the division in the three large regions (southern, central and northern) and for two time periods (1850-1950 and 1961-2014). This study revealed that some of the species responsible for outbreaks at those times caused greater forest damages than other, i.e. “Top insect species” (Figure 12, 13, 14). Relationships between climatic variables (temperature and precipitation) or storm damages (volume of storm felled trees) and changes in insect outbreak occurrences showed interesting results (Figure 16, 17, 18). For the first period (i.e. 1850-1950), the top insect species showed the tendency to be influenced by the above factors, whereas for the second period (i.e. 1961-2014) the situation dramatically changed so that none of the insects from the top insect species tended to relate to these factors. *Thecodiplosis brachyntera*, in the northern region, was the only species to show a tendency to climate variables, but it was only in a small extent, and a clear influence of the climate on this species could not be observed. This discrepancy between the two periods can be due to many factors which will be further discussed.

5.1. Occurrences of insects responsible for outbreaks during 1850-1950 under climate influence

5.1.1. Southern Sweden

For this period and region, among 112 different insects responsible for outbreaks that were recorded, the most important ones and composing the Top insect species were: *Pissodes pini, Ips typographus, Laspeyresia strobilella, Hylobius abietis, Melolontha melolontha, Melolontha hippocastani, Blastophagus piniperda* and *B. minor* (ordered after their importance – i.e. the longest vectors in PCA graphs) (Table 7). These particular insects responded differently to temperature, precipitation and storm damages (Figure 16). In this study, *Pissodes pini*, the species with the biggest influence in causing forest damages appeared to be mostly influenced by precipitation. *P. pini* was an important species throughout this whole period of time in attacking pine trees. Damages caused by *P. pini* were reported from 1917 till 1939 (Lekander 1950).

The analysis showed that the second species from Top species list is *Ips typographus* (Table 7) and caused important damages between 1933 and 1937 (Figure 12). After the big storm in January and February 1932 in southern Sweden (0.578 m^3/ha forest land was affected, Nilsson

2008), *Ips typographus* caused significant damages to spruce trees for several years (Lekander 1950). Damages caused by this species have been reported from 1873 till 1950 (Lekander 1950, Lekander 1954). Outbreaks of *I. typographus* have killed millions of Norway spruce trees (*Picea abies*), and therefore reduced the quality of the wood used as resource for timber or pulp (Kärvemo and Schroeder 2010). My analysis showed that *Ips typographus* is influenced to a large extent by the precipitation during J-A-S and A-M-J and to a small extent by storm damages (Figure 16). From other studies it is known that important outbreaks of these particular species are initiated by storm fellings, which provided large amount of wind-thrown trees as breeding material (Lekander 1950; Lekander 1954; Grégoire and Evans 2004). Storms recorded in southern Sweden occurred in 1873, 1915, 1918, 1932 and 1945, and were followed in the subsequent years by outbreaks of *Ips typographus* (Trägårdh and Butovitsch 1935; Lekander 1950; Lekander 1954). It is also indicated from those studies that attacks were additionally triggered in warm summers. For example, in 1925 due to the dry and hot summer these species appeared with two generations, out of which especially the second one caused more serious problems and triggered spruce mortality (Lekander 1950). As these pests usually swarm from April to June, a second generation will swarm from July till October (Smith et al. 1997), hence causing more damages. In the same year, attacks occurred in older spruce forests, as the tree viability probably had been weakened by the unusual high precipitation over the last two years (Lekander 1950). This was also indicated in my analysis, which showed that mean precipitation for A-M-J in that period reached a high value, i.e. 225 mm. The precipitation for J-A-S was even higher, i.e. 250 mm (Figure 15). Control measures against this pest were taken such as stamping trees for logging, cutting and chopping the damaged trees, removing the fallen trees after storms or debarking the recent felled trees (Lekander 1950; Lekander 1954).

Laspeyresia strobilella is the third most important species according to this study, having an important impact around 1918 (Figure 12). This year this species developed plentiful and caused damage to spruce cones (Lekander 1950). Regarding the factors that could influence its behavior, my analysis indicated that these species can be influenced by both temperature and precipitation (Figure 16). Average temperatures in 1918 for A-M-J and J-A-S were high, i.e. 10°C, respectively 15°C for the latter. Precipitation was up to 250 mm in J-A-S (Figure 15), leading to strong attacks during that year.

The next most important species is *Hylobius abietis,* which caused significant damages in 1920-1921 and 1945 (Figure 12). Major injuries to spruce trees occurred during 1920-1921 in southern Sweden. Damages in southern Sweden were reported from 1879 till 1950 (Lekander 1950; Lekander 1954). The results of my study have revealed that these species are influenced by temperature (Figure 16). During 1920-1921 values of temperature for southern Sweden were 10°C, respectively 15°C for A-M-J and J-A-S (Figure 15), which may have influenced their behavior.

Melolontha melolontha and *Melolontha hippocastani* are the next insects from the Top species (Table 7). *Melolontha melolontha* had an important impact in 1919 and 1948-1950, and *Melolontha hippocastani* in 1915 (Figure 12). In 1915 there was a mass occurrence of both species attacking different deciduous tree species (Lekander 1950). The results of my analysis have shown that broadleaved trees were attacked in a large extent in southern Sweden around 1915, (Figure 6), almost to the same extent than the outbreaks affecting coniferous trees (see attacks related in the paragraphs above). These two species have had a major impact in achievement of the increase in the broadleaved trees, considering that before this period the extent of attacked broadleaved trees was smaller in comparison with attacked coniferous trees. In 1948-1950 *Melolontha melolontha* caused significant damage to oak trees in different parts of the southern region (Lekander 1954). My analysis supports the fact that broadleaved trees were attacked to a large extent during these years (Figure 6). Broadleaved trees were reported as being attacked by this species from 1851 (Lekander 1950). My study has illustrated that both of *Melolontha melolontha* and *Melolontha hippocastani* are influenced mainly by changes in mean temperature (Figure 16). During 1948-1950 the averages for A-M-J and J-A-S were high; i.e. 12°C and 15°C (Figure 15) and contributed to the attacks. Studies have indicated that these two species occurred mostly where natural conditions were suitable for their developments. For example, conditions for these species were favorable in Halland County (SW of Sweden) in 1890, where the hills around arable fields was being dense with coniferous trees, preferred as food by these insect species during the mating season. The lack of appropriate food for these species during the mating season constitutes a major obstacle to stronger propagation, such as it has been evidenced in Skåne County where conifers are planted on the highest slopes therein, and insects could not reach to the trees, and so the forests didn't presented outbreaks of these two insect species (Lekander 1950).

The analysis indicated that the last species from Top insect species responsible for outbreaks are *Blastophagus piniperda* and *B. minor* (Table 7) and that these two species caused damage in 1918-1925 and 1932 (Figure 12). During 1918-1925 these pests attacked pine trees (the extent of attacked coniferous trees is large during these years according to my results – Figure 6). Throughout the years (1850-1950) these insects attacked the middle-aged pine stocks and in some cases standalone pines, especially in the vicinity of saws and timber storage sites. To counteract the damages, the most heavily infested trees, which were almost killed, were harvested and debarked. Countermeasures were taken, such as laying catch trees and debarking all the winter felled pine timber (Lekander 1950). The results of my study show that these species are mainly influenced by precipitation and storm damages. This is in accordance with other studies that have shown that most of the attacks occurred in the felled trees left in the forests after storms (Lekander 1950; Lekander 1954).

5.1.2. Central Sweden

The Top insect species found for this region are (they are classified following their importance): *Bupalus piniarius, Ips typographus, Blastophagus piniperda* and *B. minor, Pityogenes chalcographus* and *Dendroctonus micans* (Table 8). Results of this study have shown that *Bupalus piniarius* acted as important pests in 1911 and 1912 (Figure 13). During these two years the species attacked pine trees so heavily, that most of the trees were strongly damaged (Lekander 1050). My analysis indicated that between 1911 and 1912 a large increase in the number of insects responsible for outbreaks was also noticed (Figure 7), as well as an increase in the number of attacked coniferous trees (Figure 6), this species contributing to the increase.

Like in southern Sweden, *Ips typographus* is still an important pest (Table 8) that caused substantial damages, in particular in 1920–1927 and 1935–1937 (Figure 13). My results have shown that these species are more influenced by temperature (Figure 17). This is a big change towards southern Sweden, where the main factors were precipitation and storm damages. This could be due to the fact that more severe storms occurred in the southern part. In 1920 from

Uppsala, in the late summer, could be noticed that the bark beetle increased considerably in number (Lekander 1950). Standing trees were infested, and in 1921 and 1925 the conditions were favorable for the pest to develop two generations, hence causing serious damage. Again in 1926 the spruce bark beetle caused considerable damage after the summer, probably by a numerous second generation (Lekander 1950). Temperature in J-A-S was reaching up to 15°C in this period (i.e. 1920-1927), constantly growing towards the previous years (Figure 15). As soon as the attacks were observed chopping of the infested wood was performed. Catch trees had been placed and infested trees had been felled and debarked (Lekander 1950). Damages in 1935-1937 occurred after the big storms in 1931-1932 (Butovitsch 1941; Lekander 1950).

Blastophagus piniperda and B. minor are the next most important species responsible for outbreaks (Table 8), in particular in 1918-1919 (Figure 13). The results have showed that these pests respond less to fluctuations in the analyzed factors, but only in a small extent to temperature (Figure 15). For that period (i.e. 1918-1919) and region, temperature was high in comparison with the whole period analyzed (i.e. 1901-2011), such as 9°C, respectively 14°C for A-M-J and J-A-S (Figure 15), which contributed to the attacks. Records of attacks by these species began from 1870 and were constant through the whole period (1870-1950). These pests attacked pine trees (Lekander 1950; Lekander 1954).

Pityogenes chalcographus and *Dendroctonus micans* are the last species from this Top insect species, the first species causing damages in 1916 and 1921, and the latter in 1918 (Figure 13). According to my results *Pityogenes chalcographus* is mostly influenced by temperature (Figure 17). Average temperature for that period was reaching up to 15°C for J-A-S and 10°C for A-M-J (Figure 15). Attacks of this pest were recorded in central Sweden on coniferous forests from 1911 (Lekander 1950). This period coincides with the great increase in the occurrences of outbreaks (Figure 7), and also with the increase in the attacked coniferous host trees (Figure 6).

Dendroctonus micans manifested as an important pest around 1918 (Figure 13). From my study it is demonstrated that this particular species reacts to shifts in precipitation (Figure 17). Precipitation for that year (i.e. 1918) reached high values, i.e. 260 mm for J-A-S and 200 mm for

A-M-J (Figure 15), influencing the attacks. Attacks of this species were recorded from 1916, preferring through years trees with external injuries, such as decayed trees (Lekander 1950).

5.1.3. Northern Sweden

The Top insect species in this region comprises a greater variety of species in comparison with the other regions (gathering species that have not shown a big importance as pests in southern or central). The Top insect species correspond to *Hylobius abietis, Blastophagus piniperda* and *B. minor, Monochamus sutor, Ips acuminatus, Diprion sertifer, Ips typographus, Pityogenes chalcographus, Ips sexdentatus* and *Laspeyresia strobilella* (Table 9).

Hylobius abietis is the species of major importance. Outbreaks from this species occurred in 1927 and 1942 (Figure 14); attacks were reported specifically on pine trees (Lekander 1950). Outbreaks from this species started to be recorded in 1877, and continued to cause damages throughout the whole period (i.e. 1877-1950) (Lekander 1950; Lekander 1954). My results showed that this pest is strongly influenced by fluctuations in precipitation (Figure 18). In both the two years with important attacks (i.e. 1927 and 1942) the values for precipitation reached important values, i.e. 270 mm (J-A-S) and 160 mm (A-M-J) for the first year, respectively 275 mm (J-A-S) and only 120 mm (A-M-J) for the latter year (Figure 15). Control measures were taken, such as placing catch bark on the field, with good results to avoid significant damages on pine seedlings (Lekander 1954).

Blastophagus piniperda and *B. minor* continue to manifest as important pests also in the northern part of the country, occurring to a large extent in 1946 and 1947 (Figure 14). Furthermore, my results showed that these pests are influenced to a small extent by both temperature and precipitation (Figure 18). During the above years the pests occurred abundantly in pine stamps, forests being subject to infestation especially after extensive harvesting (Lekander 1954). Attacks of these pests in the northern parts were registered from 1912 (Lekander 1950), coinciding with the increase in the occurrences of insects responsible for outbreaks (Figure 7), and also with the increase in attacked coniferous trees (Figure 6). In 1939 heavy attacks of these pests have been not only at round timber storages, but also on the accumulation of debarked firewood. Most likely this was due to the wet spring and early summer (Lekander 1950). My study indicated that temperature for that period was of about 6°C in A-M-J and 13°C in J-A-S (Figure 15).

Monochamus sutor and *Ips acuminatus* are the next two most important species (Table 9), with the latter causing damages in 1918-1920 and seemed to be influenced by shifts in temperature. The damages caused during this years is also evident from other study (Lekander 1950). *Monochamus sutor* caused damages between 1921 and 1926, and also 1932 (Figure 14). During this period, 1921-1926, *M. sutor* appeared in great abundance and caused serious damages (Lekander 1950). Records of the outbreaks of this species start in 1916 and continue throughout the whole period, 1916-1950 (Lekander 1950; Lekander 1954). My results demonstrated that this pest is influenced by precipitation (Figure 18). Precipitation for the period of mass occurrence of *Monochamus sutor* (i.e. 1921-1932) reached a high value (270 mm during J-A-S), for that period and contributed to the attacks. Throughout the whole period of outbreaks (i.e. 1916-1950) these pests occurred generally on burned forest clearings, causing damages to coniferous trees (Lekander 1950; Lekander 1954). *Ips acuminatus* is mainly influenced by changes in temperature (Figure 18). This is also recorded from other studies (Lekander 1950; Lekander 1954).

The above species are followed by *Diprion sertifer*, also an important pest which performed in 1916-1917 (Figure 14). My results also show that this particular species is strongly influenced by variations in precipitation (Figure 18). Precipitation values for the two years were of 260 mm during J-A-S and 150 mm during A-M-J (Figure 15). From other studies this pest is also recorded as an important pest that caused significant damages (Lekander 1950; Lekander 1954).

Ips typographus is indicated as the seventh insect species from the top list (Table 9), and occurred to a large extent during 1946 and 1947 (Figure 14). During these two years the spruce bark beetle, *I. typographus*, only appeared on fallen timber. The infested trees were chopped (Lekander 1954). Large amounts of trees were felled after the storm in autumn 1945, but due to a lack of manpower the trees were left lying in the forest. This was an important factor that contributed to severe attacks in the following years (Lekander 1954). First attack of this species was recorded in 1875 and throughout the whole period (1875-1950) attacked *Picea abies* (Lekander 1950; Lekander 1954).

Pityogenes chalcographus, the next top species, has an important impact as a pest (Table 9) and his behavior is influenced by damages caused by storms (Figure 18). This results are supported by studies which show that this species caused damages mostly around areas with wind thrown trees, and in alliance with the spruce bark beetle (Lekander 1950; Lekander 1954).

The last two species, *Ips sexdentatus* and *Laspeyresia strobilella,* are acting as important pests in 1935-1941, respectively 1946-1947 (Figure 14). This analysis revealed that, while *Ips sexdentatus* resonates more with the damages caused by storms, the latter species, *Laspeyresia strobilella,* is influenced in a lesser extent by both temperature and precipitation (Figure 18). This results are also highlighted by studies, which showed that *Ips sexdentatus* occurred mostly after damages caused by storms (Lekander 1950). During the period *Ips sexdentatus* proved to have the largest impact (i.e. 1935-1941), strong winds created large quantities of fallen trees; i.e. in 1937 and 1938 storms occurred and the combined damages were of 0.6211 m^3/ha of forest land (Nilsson 2008). These large areas with fallen trees in 1937 and 1938 have contributed to severe attacks in the subsequent years.

5.2. Occurrences of insects responsible for outbreaks during 1961 – 2014

5.2.1. Top insect species and climate variables

During this period (i.e. 1961-2014) the Top insect species is in all the three regions different in comparison with the previous one (i.e. 1850-1950). Only few species remain in the Top insect species while other new species emerged (Tables 7, 8 and 9). Climate for this second period is continuously changing, with temperature and precipitation reaching values never encountered before, as indicated in Figure 15. According to IPCC (2013) the last three decades had been continually warmer than the other previous decades since 1850. IPCC stated with medium confidence that for the Northern Hemisphere the period 1983-2012 was likely the warmest 30-year period of the last 1400 years. Also changes in many extreme weather and climate events occurred and have been observed from 1950 (IPCC 2013). My results though indicated that none of the insects from Top insect species showed a correlation with the climatic parameters (temperature and precipitation) or with the damages caused by storms. From other studies it has been demonstrated that the pests are influenced by the above parameters. For example, *Ips typographus* is strongly influenced by the amount of trees felled after strong storms or by the summer temperatures which generate suitable conditions for the pests to develop a second generation. Moreover, *Tortrix viridana* attacks are also depending on temperature while *Microdiprion pallipes* caused severe defoliation and high tree mortality in stands exposed to severe climatic conditions (Lekander 1950; Lekander 1954; Grégoire and Evans 2004). Another example is that from 1987 to 1990 Sweden was climatically characterized by unusual temperatures, setting climatic records, as can also be seen in Figure 15. Due to the mild winters and with the addition of early springs some species such as aphids (plant lice) increased in population and in the subsequent years presented an abnormally dense population and attacked woody plants (Harding 1998).

My results, however, show that the total amount of variation explained by these parameters stated above, registers low values (i.e. only 8.7% for the southern part, 14.7% and 11.5% for the central and northern regions – illustrated in the Appendices section – Tables 26, 28 and 30), the unexplained variation being very high. Other factors or variables could be the major explanation for the rest of unexplained variation. These new factors could be the uncertainties of the primary data used for this study, the management of forests and land use or other environmental variables.

5.2.2. Uncertainties due to the primary data

The primary data for this study were obtained from different sources (Table 3), and for each period of time (i.e. 1850-1950 and 1961-2014) different datasets were utilized. For the first period the two papers used contained a detailed description of the occurrences of outbreaks, showing detailed information about the recorded outbreaks. For the second period, the reports used were not as detailed as the first two datasets, the number and occurrences of outbreaks only being mentioned for the whole country, and not for the exact location (i.e. southern, central or northern Sweden), and about 10% of the data had to be excluded from the analysis (Section 3.2). From 1991-2014 the dataset from Skogskada was quite precise, having more detailed information. This was, however, based on people' reports of the outbreaks, and in some cases the outbreaks were reported few years after the actual occurrence. We can't know for sure if the decrease in the occurrences of insect outbreaks observed in Figure 7 from 1961 is real or mainly due to the different datasets. This decrease can be partly right, as before 1950 humans were not concerned about the conditions of the forests and leaving them to be more susceptible to insect attacks; i.e. more insect outbreaks than the recent times. Over time forests status gained more importance, and people started to take care of the forests and hence decreasing the number of outbreaks (Ekelund and Hamilton 2001). I will discuss hereafter this potential influence of forest management on insect outbreaks.

5.2.3. Forest management influence

Starting with 1960, due to the great quantities of timber left in the forests an increase in the population of pests was noticed, even if the timber was treated with insecticides. For that period, the living conditions of the insect species were radically improved by introduction of new clear-cutting systems in forestry. The size of the cutting areas had increased, contributing to the increase of the insects. Another contributory cause was that cutting often took place within the same areas for successive years (Christiansen et al. 1970; Ehnström et al. 1974). Starting with 1967 changes in the forest management were made, especially regarding the methods used for cutting and transporting timber. Within this period, 1967-1971, an increase of the population of different insects was sustained by modern forestry practices. Other reasons for the increase is that in 1970 the use of DDT was prohibited in Sweden and the climate was mainly characterized by dry weather in the early summer, especially from 1969 till 1970 (Ehnström et al. 1974). The number of insect species in deciduous forests had also increased due to the introduction of short rotation forestry in Sweden (Löyttyniemi et al. 1979). My analysis has indicated that for this period (1972-1976), the number of attacked coniferous trees had suffered a small increase, as well as the broadleaved trees (Figure 6). The climate for this period (i.e. 1972-1976) was warmer and drier than usual (Löyttyniemi et al. 1979). This can also be seen from my results, temperatures in J-A-S reaching up to 17°C, 16°C and 12°C for the southern, central and respectively northern part (Figure 15), but this values are still low in comparison with the temperatures in recent years. Figure 15 shows an increase of the temperature towards the last decades. This increase is also evident from the IPCC reports (IPCC 2013). From 1977 to 1981 the Forestry Authorities had encourage a rapid extraction campaign of attacked and killed trees, before the emergence of the new brood, reducing thereby the density of the insect population in the forests (Austarå et al. 1983). For this period (i.e. 1961-2014) my analysis indicated a decrease in the number of insect outbreaks. Probably due to the changes in forest management described above, insect affected larger areas than before, but as in my analysis insect outbreaks were recorded only as a binary form, the real importance and damages caused by insect are therefore not taken into account. Furthermore, during the second period (i.e. 1961-2014) the spruce bark beetle was the insect that caused the most problems, and the areas affected by their outbreaks have expanded (Christiansen et al. 1970; Ehnström et al. 1974; Löyttyniemi et al. 1979; Austarå et al. 1983; Ehnström et al. 1998; Harding et al. 1998). With an increase in the population of spruce bark beetles, new practices were taken, such as salvage and sanitary cuttings. The removal of dead wood from the forests to reduce the risk of insect pest outbreaks can have negative consequences for forest biodiversity in general, and for insects living in dead wood in particular (Lindgren and Raffa 2013).

As stated before, for this period insects from my analysis show no correlation with the climatic variables. A reason to sustain this can be that the above described management techniques, which favored the insect species, have contributed to an increase in their population. However, my analysis has also indicated a decrease in the occurrences of insect outbreaks for the second period. It could be that the fewer insect responsible for outbreaks recorded in this period were responsible for larger scale outbreaks (as it is the case for *Ips typographus*), whereas for the first period, due to the greater variety of different species, insect species were causing damages to a lesser spatial extent. If, however the analysis is real, and climate is not influencing these pests, a question to be asked is if other processes interact and influence more with the dynamic of insect outbreaks rather than climate, and if climate, with all the changes in temperature and precipitation within the last years, and also with an increase in extreme events is not the mainly influence for the occurrences of insect outbreaks.

Considering that climate will continue to change in the following years, reaching even more extreme temperatures (IPCC 2013) and expected to continue in the far future, and considering that humans can do very little to asses this change, maybe with improvements of the managing techniques insect outbreaks can be further strongly reduced. New improved management techniques (immediate removing of the trees felled, debarking the recently felled trees and a better monitoring and reporting of the outbreaks) can improve the decrease in pest attacks.

5.3. Future implication

This study has demonstrated that climate is an important factor that has to be taken into account in association with the occurrences of insect outbreaks. From other papers regarding insect occurrences in Sweden it is shown that changes in the past occurrences of insects were caused by changes in climate, as well as changes in the surrounding landscape (Lemdahl and Gustavsson 1997; Olsson and Lemdahl 2009). My analysis has shown that the most important species responsible for outbreaks for the first period (i.e. 1850-1950) are influenced by climate parameters (temperature and precipitation) and by the availability of storm felled trees. Although my analysis showed no connection between the above mentioned parameters and the most important species responsible for outbreaks for the second period (i.e. 1961-2014), it was indicated from other studies, based on local and large-scale comparisons, that in reality there is a relation between them (Christiansen et al. 1970; Ehnström et al. 1974; Löyttyniemi et al. 1979; Austarå et al. 1983; Ehnström et al. 1998; Harding et al. 1998; Grégoire and Evans 2004). A further change in climate and in the risks from extreme events related to climate change (i.e. extreme precipitation, heat waves) will increase further at higher temperatures (IPCC 2014), hence strongly influence the behavior of the pests. The risks of climate change in Swedish forests can be reduced through large-scale adaptation of forest management (Jönsson et al. 2013).

A small reduction in the predisposition to storm damages by an increased fraction of broadleaved forest could be observed from different studies (Valinger and Fridman 2011; Jönsson et al. 2013). An example of a measure of adaptation against insect outbreaks can be planting of mixed forests instead of monocultures. Most of the sustainable forestry plans grant more and more importance to mixed forests and hence highlight the necessity to increase the proportion of deciduous trees in Swedish forests (Swedish Forest Industries Federation 2012; PEFC 2013). In harvested forests conservation agreements with landowners can be established and led to a strategy of adapted forestry management (AF), which includes active measures such as the conversion of conifer-dominated stands to deciduous-dominated stands, in removing directly coniferous trees (Jong and Lonnstad, 2002). Different measures are conducted concerning this issue. For example areas covered with mature deciduous forest are being set aside, and protected by the legislation of natural reserves, for instance (Swedish Forest Industries Federation 2012). Most of the insect species that can cause outbreaks have preferences for the tree species and also for the age of the forests. By having a mixed forest it will be more difficult for insects to find their host tree.

A method to reduce the losses of valuable timber due to insect outbreaks could be the implementing of short-term practices, such as improving the harvest scheduling, careful salvage logging, and also controlling the use of insecticide. Furthermore, it is also important to implement a long-term strategy concerning the host trees, by managing the tree species diversity and forest age structure at stand and landscape scales. This strategy can promote more resistant forests. It is therefore important to try and achieve a balance between short and long-term goals (Doblas-Miranda et al. 2009).

It is important to know how insects acted in the past. By appreciating how insects behaved in the past, and identifying the factors that triggered the outbreaks, assumptions about future insect outbreaks can be made. A good measure that can be taken against insect outbreaks could be a better monitoring and also reporting of the outbreaks. As mentioned before in some cases the outbreaks were reported many years after the actual occurrence. By improving technologies and also the long-term research, the remaining uncertainties about insect outbreaks could be seriously reduced.

6. Conclusions

The occurrence of insects responsible for outbreaks shows great changes regarding the most important species and families responsible for outbreaks over the two periods of time 1850-1950 and 1961-2014. While for the first period, the composing species of the Top insects responsible for outbreaks displayed some resemblances among southern, central and northern Sweden (some species remained as important pests within all three regions), for the second period the situation changes noticeably, such as one or two species only were the same as for the first period, and new species emerged and became top species responsible for outbreaks. This study has demonstrated that important factors contributing to insect outbreaks for the first period were climate variables (temperature and precipitation) and damages caused by storms, with each species responding differently to these variables. Different control measures were taken against these pests, from laying catch trees, to stamping trees for logging and chopping them and debarking of newly felled trees. For the second period my analysis presented different results. The insect species responsible for outbreaks seemed not to be influenced by the above mentioned variables. Other factors such as the impact of forest management, insecticides or different human activities could have gained more importance regarding these changes, although the different datasets used to procure the primary data probably played a role in the results of this study and made difficult a direct comparison between the two time periods.

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Appendices

<u>Top five families of insect species responsible for outbreaks</u>

The summary tables of the PCA analysis are as follows:

Southern Sweden:

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 1220.524				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.5992	0.0889	0.0741	0.0437
Explained variation (cumulative)	59.92	68.82	76.23	80.6

Table 13- Summary of results for Top Families using Principal Component Analysis for Southern Sweden. 1850-1950

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 244.45833				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.2864	0.1651	0.1184	0.0977
Explained variation (cumulative)	28.64	45.15	56.99	66.75

Table 14 - Summary of results for Top Families using Principal Component Analysis for Southern Sweden. 1961-2014

Central Sweden:

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 703.60256				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.6583	0.0799	0.0638	0.0467
Explained variation (cumulative)	65.83	73.82	80.2	84.87

Table 15- Summary of results for Top Families using Principal Component Analysis for Central Sweden. 1850-1950

Analysis 'Unconstrained'				
Method: PCA				
Total variation is 192.10417				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.2923	0.2032	0.1202	0.0962
Explained variation (cumulative)	29.23	49.55	61.57	71.19

Table 16 - Summary of results for Top Families using Principal Component Analysis for Central Sweden. 1961-2014

Northern Sweden:

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 613.82456				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.6801	0.0837	0.0491	0.0347
Explained variation (cumulative)	68.01	76.39	81.29	84.76

Table 17 - Summary of results for Top Families using Principal Component Analysis for Northern Sweden. 1850-1950

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 62.52500				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.3102	0.2011	0.1094	0.0974
Explained variation (cumulative)	31.02	51.13	62.07	71.81

Table 18 - Summary of results for Top Families using Principal Component Analysis for Northern Sweden. 1961-2014

Top insect species responsible for outbreaks

The summary tables of the PCA analysis for Top Species were as follows:

Southern Sweden:

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 364.89286				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.2368	0.1004	0.0736	0.0558
Explained variation (cumulative)	23.68	33.73	41.09	46.67

Table 19- Summary of results for Top Species using Principal Component Analysis for Southern Sweden. 1850-1950

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 201.04167				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.1639	0.1344	0.0985	0.0743
Explained variation (cumulative)	16.39	29.82	39.68	47.1

Table 20 - Summary of results for Top Species using Principal Component Analysis for Southern Sweden. 1961-2014

Central Sweden:

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 208.19231				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.2292	0.0951	0.0889	0.076
Explained variation (cumulative)	22.92	32.43	41.32	48.92

Table 21 - Summary of results for Top Species using Principal Component Analysis for Central Sweden. 1850-1950

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 147.50000				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.1559	0.1396	0.0838	0.0776
Explained variation (cumulative)	15.59	29.55	37.93	45.7

Table 22 - Summary of results for Top Species using Principal Component Analysis for Central Sweden. 1961-2014

Northern Sweden:

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 183.01754				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.3446	0.1032	0.0765	0.0631
Explained variation (cumulative)	34.46	44.78	52.42	58.73

Table 23 - Summary of results for Top Species using Principal Component Analysis for Northern Sweden. 1850-1950

Analysis 'Unconstrained-2'				
Method: PCA				
Total variation is 68.40000				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.2094	0.1559	0.0992	0.0918
Explained variation (cumulative)	20.94	36.53	46.45	55.63

Table 24 - Summary of results for Top Species using Principal Component Analysis for Northern Sweden. 1961-2014

Analysis of the occurrences of insect outbreaks in relation to climate parameters

Southern Sweden:

Variation Partitioning Results for Two Groups in Analysis 'Var-part-2groups-Simple-effects-tested'					
Explained variation					
Fraction	Variation	% of Explained	% of All	DF	Mean Square
a	0.06089	70.4	6.1	2	0.03044
b	0.02321	26.8	2.3	1	0.02321
c	0.00238	2.8	0.2	--	--
Total Explained	0.08648	100	8.6	3	0.02883
All Variation	1	--	100	49	--
Significance tests					
Tested Fraction	F	P			
a+b+c	1.5	0.116			
a+c	1.6	0.1			
b+c	1.3	0.25			

Table 25 – Summary of results for the behavior of insect species in correlation with additional parameters, like Temperature, Precipitation and Storm damages, using Variation Partitioning Analysis for Southern Sweden. 1850-1950. "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" – Storm damages (m^3/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified (yellow) the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation (pink) explained by these groups (how much of the behavior of species is explained by these factors).

Variation Partitioning Results for Two Groups in Analysis 'Var-part-2groups-Simple-effects-tested'					
Explained variation					
Fraction	Variation	% of Explained	% of All	DF	Mean Square
a	0.06619	75.8	6.6	2	0.03309
b	0.01381	15.8	1.4	1	0.01381
c	0.00728	8.3	0.7	--	--
Total Explained	0.08728	100	8.7	3	0.02909
All Variation	1	--	100	49	--
Significance tests					
Tested Fraction	F	P			
a+b+c	1.5	0.152			
a+c	1.9	0.079			
b+c	1	0.313			

Table 26 – Summary of results for the behavior of insect species in correlation with additional parameters, like Temperature, Precipitation and Storm damages, using Variation Partitioning Analysis for Southern Sweden. 1961-2014. "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" – Storm damages (m^3/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified (yellow) the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation (pink) explained by these groups (how much of the behavior of species is explained by these factors).

Central Sweden:

Variation Partitioning Results for Two Groups in Analysis 'Var-part-2groups-Simple-effects-tested'					
Explained variation					
Fraction	Variation	% of Explained	% of All	DF	Mean Square
a	0.08619	80.5	8.6	2	0.04309
b	0.01751	16.4	1.8	1	0.01751
c	0.00337	3.2	0.3	--	--
Total Explained	0.10707	100	10.7	3	0.03569
All Variation	1	--	100	42	--
Significance tests					
Tested Fraction	F	P			
a+b+c	1.6	0.112			
a+c	2	0.058			
b+c	0.9	0.504			

Table 27 – Summary of results for the behavior of insect species in correlation with additional parameters, like Temperature, Precipitation and Storm damages, using Variation Partitioning Analysis for Central Sweden. 1850-1950. "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" – Storm damages (m^3/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified (yellow) the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation (pink) explained by these groups (how much of the behavior of species is explained by these factors).

Variation Partitioning Results for Two Groups in Analysis 'Var-part-2groups-Simple-effects-tested'					
Explained variation					
Fraction	Variation	of Explain	% of All	DF	Mean Square
a	0.11266	76.6	11.3	2	0.05633
b	0.03295	22.4	3.3	1	0.03295
c	0.0015622	1.1	0.2	--	--
Total Explained	0.14717	100	14.7	3	0.04906
All Variation	1	--	100	42	--
Significance tests					
Tested Fraction	F	P			
a+b+c	2.2	0.022			
a+c	2.6	0.009			
b+c	1.5	0.135			

Table 28 – Summary of results for the behavior of insect species in correlation with additional parameters, like Temperature, Precipitation and Storm damages, using Variation Partitioning Analysis for Central Sweden. 1961-2014. "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" – Storm damages (m^3/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified (yellow) the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation (pink) explained by these groups (how much of the behavior of species is explained by these factors).

Northern Sweden:

Variation Partitioning Results for Two Groups in Analysis 'Var-part-2groups-Simple-effects-tested'					
Explained variation					
Fraction	Variation	% of Explained	% of All	DF	lean Squa
a	0.10019	72.4	10	2	0.05009
b	0.02379	17.2	2.4	1	0.02379
c	0.01436	10.4	1.4	--	--
Total Explained	0.13834	100	13.8	3	0.04611
All Variation	1	--	100	49	--
Significance tests					
Tested Fraction	F	P			
a+b+c	2.5	0.012			
a+c	3	0.011			
b+c	1.9	0.095			

Table 29 – Summary of results for the behavior of insect species in correlation with additional parameters, like Temperature, Precipitation and Storm damages, using Variation Partitioning Analysis for Northern Sweden. 1850-1950. "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" – Storm damages (m^3/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified (yellow) the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation (pink) explained by these groups (how much of the behavior of species is explained by these factors).

Variation Partitioning Results for Two Groups in Analysis 'Var-part-2groups-Simple-effects-tested'					
Explained variation					
Fraction	Variation	% of Explained	% of All	DF	Mean Square
a	0.10519	91.7	10.5	2	0.05259
b	0.00753	6.6	0.8	1	0.00753
c	0.00203	1.8	0.2	--	--
Total Explained	0.11475	100	11.5	3	0.03825
All Variation	1	--	100	43	--
Significance tests					
Tested Fraction	F	P			
a+b+c	1.7	0.089			
a+c	2.5	0.022			
b+c	0.4	0.731			

Table 30 – Summary of results for the behavior of insect species in correlation with additional parameters, like Temperature, Precipitation and Storm damages, using Variation Partitioning Analysis for Northern Sweden. 1961-2014. "a" stands for the effect of the first group – Temperature (°C) and Precipitation (mm), "b" – Storm damages (m^3/ha) and "c" is the combined effect of both the two groups. For each one of "a", "b" and "c" it was specified (yellow) the percentage of explained variation (percentage of the individually influence of each factor), and the percentage of all variation (pink) explained by these groups (how much of the behavior of species is explained by these factors).

Summary tables of the RDA analysis:

Southern Sweden:

Analysis 'Var-part-2groups-Simple-effects-tested-2', step 'SharedEffect'				
Method: RDA				
Total variation is 82.30000, explanatory variables account for 8.6%				
(adjusted explained variation is 2.7%)				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.0485	0.0323	0.0057	0.3354
Explained variation (cumulative)	4.85	8.07	8.65	42.19
Pseudo-canonical correlation	0.3958	0.4264	0.207	0
Explained fitted variation (cumulative)	56.08	93.38	100.00	
Permutation Test Results:				
On All Axes pseudo-F=1.5, P=0.116				

Table 31 – Summary of results for the influence of climatic parameters on the behavior of insect species using Redundancy Analysis (RDA) for Southern Sweden (1901-1950)

Analysis 'Var-part-2groups-Simple-effects-tested-2', step 'SharedEffect'				
Method: RDA				
Total variation is 57.54000, explanatory variables account for 8.7%				
(adjusted explained variation is 2.8%)				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.07	0.0118	0.0055	0.3432
Explained variation (cumulative)	7	8.18	8.73	43.05
Pseudo-canonical correlation	0.4203	0.2448	0.2227	0
Explained fitted variation (cumulative)	80.25	93.73	100.00	
Permutation Test Results:				
On All Axes pseudo-F=1.5, P=0.152				

Table 32 – Summary of results for the influence of climatic parameters on the behavior of insect species using Redundancy Analysis (RDA) for Southern Sweden (1961-2011)

Central Sweden:

Analysis 'Var-part-2groups-Simple-effects-tested-2', step 'SharedEffect'				
Method: RDA				
Total variation is 40.97674, explanatory variables account for 10.7%				
(adjusted explained variation is 3.8%)				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.0651	0.0341	0.0078	0.344
Explained variation (cumulative)	6.51	9.92	10.71	45.1
Pseudo-canonical correlation	0.4218	0.4414	0.3206	0
Explained fitted variation (cumulative)	60.81	92.67	100.00	
Permutation Test Results:				
On All Axes pseudo-F=1.6, P=0.112				

Table 33 – Summary of results for the influence of climatic parameters on the behavior of insect species using Redundancy Analysis (RDA) for Central Sweden (1901-1950)

Analysis 'Var-part-2groups-Simple-effects-tested-2', step 'SharedEffect'				
Method: RDA				
Total variation is 38.88372, explanatory variables account for 14.7%				
(adjusted explained variation is 8.2%)				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.0935	0.0305	0.0231	0.3640
Explained variation (cumulative)	9.35	12.4	14.72	51.12
Pseudo-canonical correlation	0.5527	0.325	0.4115	0
Explained fitted variation (cumulative)	63.52	84.28	100.00	
Permutation Test Results:				
On All Axes pseudo-F=2.2, P=0.022				

Table 34 – Summary of results for the influence of climatic parameters on the behavior of insect species using Redundancy Analysis (RDA) for Central Sweden (1961-2011)

Northern Sweden:

Analysis 'Var-part-2groups-Simple-effects-tested-2', step 'SharedEffect'				
Method: RDA				
Total variation is 105.52000, explanatory variables account for 13.8%				
(adjusted explained variation is 8.2%)				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.0997	0.0267	0.012	0.3968
Explained variation (cumulative)	9.97	12.63	13.83	53.52
Pseudo-canonical correlation	0.4657	0.4317	0.3877	0
Explained fitted variation (cumulative)	72.04	91.32	100.00	
Permutation Test Results:				
On All Axes pseudo-F=2.5, P=0.012				

Table 35 – Summary of results for the influence of climatic parameters on the behavior of insect species using Redundancy Analysis (RDA) for Northern Sweden (1901-1950)

Analysis 'Var-part-2groups-Simple-effects-tested-2', step 'SharedEffect'				
Method: RDA				
Total variation is 32.31818, explanatory variables account for 11.5%				
(adjusted explained variation is 4.8%)				
Summary Table:				
Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.1053	0.009	0.0005	0.408
Explained variation (cumulative)	10.53	11.43	11.47	52.28
Pseudo-canonical correlation	0.5989	0.1687	0.0455	0
Explained fitted variation (cumulative)	91.73	99.58	100.00	
Permutation Test Results:				
On All Axes pseudo-F=1.7, P=0.089				

Table 36 – Summary of results for the influence of climatic parameters on the behavior of insect species using Redundancy Analysis (RDA) for Northern Sweden (1961-2011)

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