LUND UNIVERSITY

Monitoring insect defoliation in forests with time-series of satellite based remote sensing data - near real-time methods and impact on the carbon balance

Olsson, Per-Ola

2016

Citation for published version (APA):
Olsson, P.-O. (2016). *Monitoring insect defoliation in forests with time-series of satellite based remote sensing data - near real-time methods and impact on the carbon balance*. [Doctoral Thesis (compilation), Dept of Physical Geography and Ecosystem Science]. Department of Physical Geography and Ecosystem Science, Lund University.

Total number of authors:
1

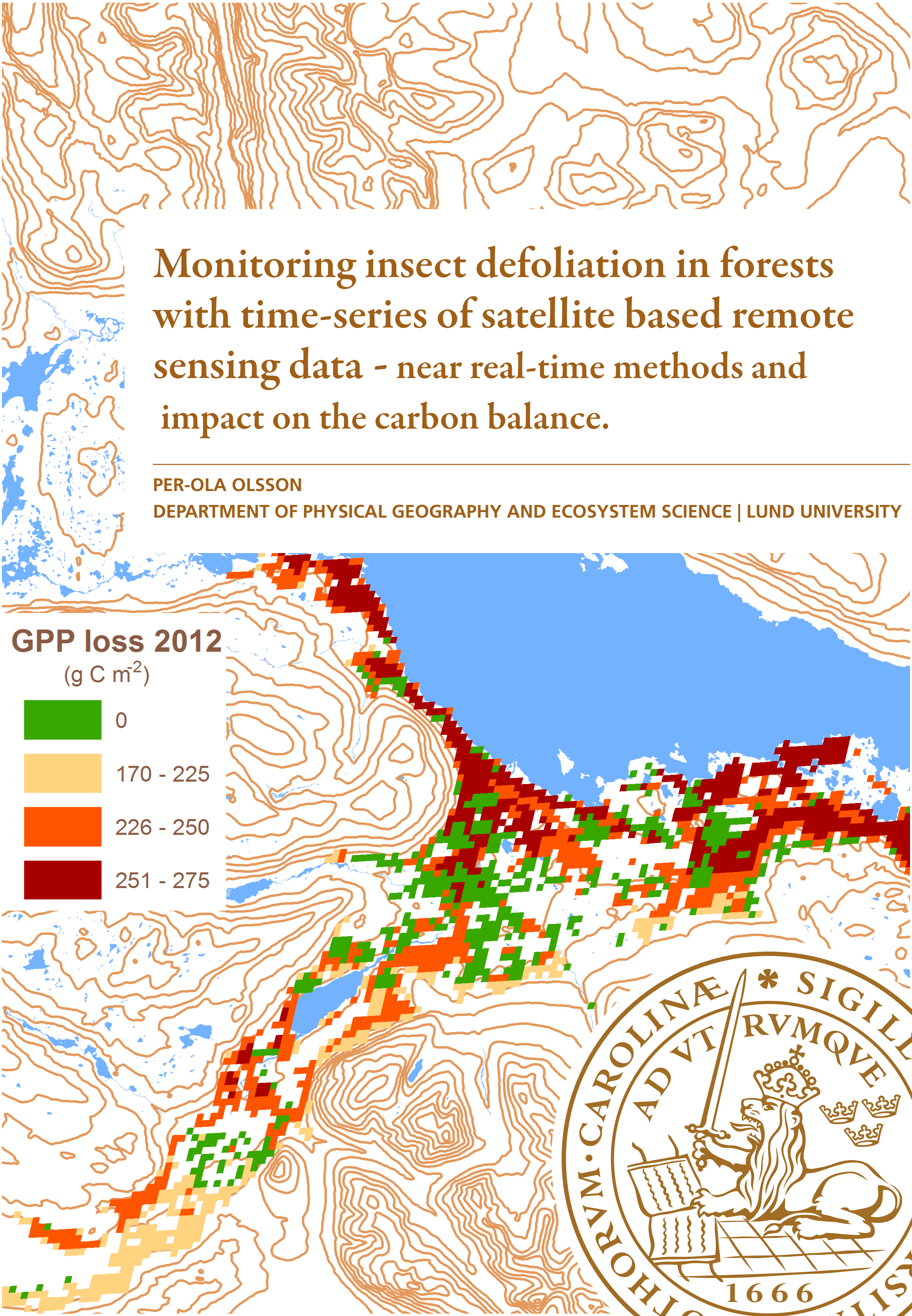
LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Monitoring insect defoliation in forests with time-series of satellite based remote sensing data - near real-time methods and impact on the carbon balance.

PER-OLA OLSSON

DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE | LUND UNIVERSITY



Monitoring insect defoliation in forests with time-series of satellite based remote sensing data

Near real-time methods and impact on the carbon balance

Per-Ola Olsson

LUND
UNIVERSITY

DOCTORAL DISSERTATION
by due permission of the Faculty of Science, Lund University, Sweden.
To be defended at Pangea auditorium. Thursday the 14th of April, 2016 at 10:00.

Faculty opponent
Senior Research Scientist Michael Wulder, PhD

Canadian Forest Service, Natural Resources Canada, Victoria, BC

Organization: LUND UNIVERSITY	Document name: DOCTORAL DISSERTATION
Department of Physical Geography and Ecosystem Science, Sölvegatan 12, S-223 62 Lund, Sweden	Date of issue: 2016-03-21
Author(s): Per-Ola Olsson	Sponsoring organization: The Swedish National Space Board

Title and subtitle: Monitoring insect defoliation in forests with time-series of satellite based remote sensing data - near real-time methods and impact on the carbon balance

Abstract

Forests are of major importance to climate change mitigation due to their strong capacity to sequester carbon. Nearly half of the terrestrial carbon is stored in forests, and forests contribute to half of the terrestrial primary productivity, with forests in the mid- and high latitude ecosystems as major contributors. These high latitude forests are, however, projected to be strongly influenced by climate change. A warmer climate is likely to have a positive effect on forest productivity and increase the ability to absorb CO_2 from the atmosphere. At the same time it is projected that a warmer climate will increase the impact of forest disturbances, such as insect outbreaks. Insect outbreaks are, however, generally excluded in large scale carbon modeling. In addition, there are large uncertainties in the quantitative effects of insect outbreaks on the carbon balance. Hence, it is important to develop methods to monitor insect disturbances and to quantify the impact of these disturbances on the carbon balance. The general aim of this thesis was to develop methods for mapping of insect outbreaks with satellite data, and to quantify the impact of these outbreaks on primary productivity.

The results demonstrated that time-series of satellite data could be applied to find what year an outbreak by the invasive Hungarian spruce scale in southern Sweden started, and showed the potential of developing an early warning system. An early warning system would most likely have detected the outbreak the year before it was detected in field; for invasive species early detection is important to enable rapid counter-measures to decrease the risk that new species establish populations.

The results also showed that coarse spatial resolution satellite data (MODIS 250x250 m pixels size) can be used for near real-time monitoring of insect induced defoliation with the aid of Kalman filtering and cumulative sums (CUSUM). Of the defoliated MODIS pixels in mountain birch forests in northern Sweden 74–100% were detected with a misclassification of undisturbed pixels of 39–56%, depending on threshold settings. In addition, the developed method facilitates studies of the intra-seasonal dynamics of an insect outbreak as well as mapping of potential refoliation; these are major advantages compared to methods that classify a pixel into defoliated or undisturbed for an entire season. The coarse spatial resolution of MODIS is, however, a limitation in fragmented forests. A method based on z-scores of seasonal maximum values of a vegetation index showed that detection accuracies were low in fragmented and heavily managed pine forests in eastern Finland compared to the more homogenous mountain birch forests in northern Sweden.

The thesis also demonstrated that satellite data and meteorological data can be used to map the impact of insect outbreaks on gross primary productivity (GPP) with the aid of a light use efficiency (LUE) model. The LUE model was calibrated with eddy covariance measurements, and the near real-time monitoring method was applied to monitor defoliation. An extensive set-back to the carbon uptake in deciduous semi-arctic forests due to insect defoliation was recorded. These results demonstrated the potential to develop methods to both monitor insect disturbances and to quantify the impact of these disturbances on primary productivity. Such methods would be important to decrease the uncertainties in estimates of insect outbreaks impact on the carbon balance.

Key words: insect defoliation, remote sensing, time-series, near real-time, GPP, LUE

Classification system and/or index terms (if any)		
Supplementary bibliographical information		Language: English
ISSN and key title		ISBN: 978-91-85793-55-6
Recipient's notes	Number of pages	Price
	Security classification	

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sourcespermission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature:________________________________Date: 2016-03-14

Monitoring insect defoliation in forests with time-series of satellite based remote sensing data

Near real-time methods and impact on the carbon balance

Per-Ola Olsson

LUND
UNIVERSITY

Cover design by Per-Ola Olsson. Front cover shows reduction in GPP during a birch moth outbreak in Abisko in the year 2012. Source of background map: Lantmäteriet (Dnr: I2014/00579). Back cover is a time-series of raw and Kalman filtered NDVI.

Department of Physical Geography and Ecosystem Science
Faculty of Science, Lund University

ISBN 978-91-85793-55-6

Printed in Sweden by Tryckeriet, E-huset, Lund University,
Lund 2016

List of papers

Paper I: Olsson, P.-O., Jönsson, A.M., & Eklundh, L. (2012). A new invasive insect in Sweden- Physokermes inopinatus: Tracing forest damage with satellite based remote sensing. Forest Ecology and Management, 285, 29-37.

Paper II: Olsson P.-O., Kantola T., Lyytikäinen-Saarenmaa P., Jönsson A. M., & Eklundh L. (2016). Development of a method for monitoring of insect induced forest defoliation – limitation of MODIS data in Fennoscandian forest landscapes. Silva Fennica, 50:2.

Paper III: Olsson, P.-O., Lindström, J., & Eklundh, L. Near real-time monitoring of insect induced defoliation in subalpine birch forests with MODIS derived NDVI. In revision. Remote Sensing of Environment.

Paper IV: Olsson, P.-O., Heliasz, M., Jin, H., & Eklundh, L. Substantial insect-induced GPP loss in a subalpine birch forest observed with MODIS NDVI. Manuscript.

Contributions

Paper I: The author collected insect disturbance data from forest managers as well as in field, performed all the analyses and led the writing of the manuscript.

Paper II: The author took part in one field data collection campaign in Finland and collected the field data in northern Sweden. He developed the method, performed the analyses and led the writing of the manuscript.

Paper III: The author collected the field data, developed the method and performed the analyses as well as led the writing of the manuscript

Paper IV: The author developed the light use efficiency model and performed the analyses as well as led the writing of the manuscript.

Abstract

Forests are of major importance to climate change mitigation due to their strong capacity to sequester carbon. Nearly half of the terrestrial carbon is stored in forests, and forests contribute to half of the terrestrial primary productivity, with forests in the mid- and high latitude ecosystems as major contributors. These high latitude forests are, however, projected to be strongly influenced by climate change. A warmer climate is likely to have a positive effect on forest productivity and increase the ability to absorb CO_2 from the atmosphere. At the same time it is projected that a warmer climate will increase the impact of forest disturbances, such as insect outbreaks. Insect outbreaks are, however, generally excluded in large scale carbon modeling. In addition, there are large uncertainties in the quantitative effects of insect outbreaks on the carbon balance. Hence, it is important to develop methods to monitor insect disturbances and to quantify the impact of these disturbances on the carbon balance. The general aim of this thesis was to develop methods for mapping of insect outbreaks with satellite data, and to quantify the impact of these outbreaks on primary productivity.

The results demonstrated that time-series of satellite data could be applied to find what year an outbreak by the invasive Hungarian spruce scale in southern Sweden started, and showed the potential of developing an early warning system. An early warning system would most likely have detected the outbreak the year before it was detected in field; for invasive species early detection is important to enable rapid counter-measures to decrease the risk that new species establish populations.

The results also showed that coarse spatial resolution satellite data (MODIS 250x250 m pixels size) can be used for near real-time monitoring of insect induced defoliation with the aid of Kalman filtering and cumulative sums (CUSUM). Of the defoliated MODIS pixels in mountain birch forests in northern Sweden 74–100% were detected with a misclassification of undisturbed pixels of 39–56%, depending on threshold settings. In addition, the developed method facilitates studies of the intra-seasonal dynamics of an insect outbreak as well as mapping of potential refoliation; these are major advantages compared to methods that classify a pixel into defoliated or undisturbed for an entire season. The coarse spatial resolution of MODIS is, however, a limitation in fragmented forests. A method based on z-scores of seasonal maximum values of a vegetation index showed that detection accuracies were low in fragmented and heavily managed pine forests in

eastern Finland compared to the more homogenous mountain birch forests in northern Sweden.

The thesis also demonstrated that satellite data and meteorological data can be used to map the impact of insect outbreaks on gross primary productivity (GPP) with the aid of a light use efficiency (LUE) model. The LUE model was calibrated with eddy covariance measurements, and the near real-time monitoring method was applied to monitor defoliation. An extensive set-back to the carbon uptake in deciduous semi-arctic forests due to insect defoliation was recorded. These results demonstrated the potential to develop methods to both monitor insect disturbances and to quantify the impact of these disturbances on primary productivity. Such methods would be important to decrease the uncertainties in estimates of insect outbreaks impact on the carbon balance.

Sammanfattning

Skogar är av stor betydelse ur klimatsynpunkt på grund av deras stora förmåga att binda kol. Skogar på de nordligare breddgraderna spelar en viktig roll med sitt stora kolupptag, men eftersom dessa nordliga skogar troligen kommer att påverkas av klimatförändringarna i hög grad är det osäkert hur framtida kolupptag kommer att utvecklas. Ett varmare klimat kommer sannolikt att öka tillväxten och därmed öka skogarnas upptag av koldioxid från atmosfären. Samtidigt beräknas det att ett varmare klimat kommer att öka mängden skogsskador, såsom insektsangrepp, vilket kan resultera i stora förluster av koldioxid till atmosfären. Insektangrepp är i allmänhet inte inkluderade i kolbudgetar vilket kan resultera i överskattningar av mängden kol som binds i skogar. Därför är det viktigt att utveckla metoder för att kartera insektsangrepp samt att beräkna hur dessa angrepp påverkar kolbalansen. Det övergripande syftet med avhandlingen var att utveckla metoder för kartläggning av insektsangrepp med satellitdata samt att beräkna effekterna av dessa angrepp på skogens kolupptag.

Studien visade att tidsserieanalyser av satellitdata kunde användas för att bestämma vilket år ett utbrott av den invasiva ungerska gransköldlusen i sydvästra Skåne startade. Resultaten visade också på möjligheten att utveckla system för övervakning av skogsskador med hjälp av satellitdata. Om ett sådant övervakningssystem hade varit aktivt hade sannolikt angreppen av gransköldlusen upptäckts redan samma år som de startade, vilket var ett år tidigare än det upptäcktes i fält. För invasiva insektsarter är en tidig upptäckt viktig för att minska risken för vidare spridning.

Studien visade också att satellitdata med låg rumslig upplösning (pixelstorlek 250x250 m) kan användas för nära realtidsövervakning av insektsskador. 74-100% av pixlarna med björkmätarangrepp i fjällbjörkskog i norra Sverige detekterades med en felklassning av ostörd björkskog på 39-56%, beroende på tröskelvärden i detekteringsmetoden. Metoden kan även användas för att studera hur ett insektsangrepp utvecklas över tid och kartera björkskog som återhämtar sig senare under samma växtsäsong som insektsangreppen. Detta är stora fördelar jämfört med metoder som klassificerar pixlar som angripna eller ostörda för en hel växtsäsong. Den låga rumsliga upplösningen är emellertid en begränsning i fragmenterade skogar som är uppsplittrade i många mindre skogsbestånd av varierande storlek och ålder. En metod för kartering av insektsangrepp baserad på säsongsmax av ett vegetationsindex visade att detektionsgraden för tallstekelskador i fragmenterade tallskogar med intensivt skogsbruk i östra Finland var låg i jämförelse med de mer homogena fjällbjörkskogarna i norra Sverige.

Studien visade också att satellitdata i kombination med meteorologiska data kan användas för att kartera effekterna av insektsangrepp på skogens kolupptag med hjälp av en s.k. light use efficience (LUE) modell. LUE modellen kalibrerades med fluxmätningar av skogens kolupptag och metoden för nära realtidsövervakning användas för att kartera angreppen. Dessa resultat visade på stora effekter på kolupptaget orsakade av insektsangrepp samt att det är möjligt att utveckla metoder för att övervaka och kartera insektsangrepp samt att kvantifiera effekterna av dessa angrepp på kolupptaget med satellitdata. Sådana metoder är viktiga för att minska osäkerheten i hur insektsangrepp påverkar skogarnas kolupptag.

Contents

1 Introduction

1.1 Forests and climate change

There is a strong scientific consensus that a higher atmospheric concentration of CO_2 is a key driver of global warming (IPCC 2013), and that forests are of major importance to mitigate climate change (Nabuurs et al. 2007). Forests store about 45% of the terrestrial carbon and it is estimated that half of the terrestrial primary productivity can be attributed to forests (Bonan 2008a). This productivity results in large absorptions of atmospheric CO_2. Forests in the northern hemisphere contribute to a significant portion of this carbon sink, with the mid- and high latitude ecosystems appearing to be the major contributors (Goodale et al. 2002; Kurz et al. 2008b). These high latitude forests are projected to be strongly influenced by climate change, which can influence the carbon balance in both positive and negative directions (Kurz et al. 2008b): a warmer climate is likely to have a positive effect on forest productivity, with e.g. longer growing seasons, and increase the ability to absorb CO_2 from the atmosphere. At the same time, it is projected that a warmer climate will increase the impact of forest disturbances (Seidl et al. 2014). Wind, fires, and insect outbreaks have already led to signs of saturation of the carbon sink in European forests (Nabuurs et al. 2012). Global warming is likely to further influence the temporal and spatial dynamics, as well as the intensities and ranges of insect herbivore outbreaks (Vanhanen 2007; Battisti 2008; Jepsen et al. 2008; Netherer & Schopf 2012; Hicke et al. 2012). Insect outbreaks are, however, generally excluded in large scale carbon modelling, which may result in overestimated carbon sequestration capabilities of forests (Kurz et al. 2008b; Hicke et al. 2012). In addition, there are large uncertainties in the quantitative effects of insect outbreaks on the carbon balance (Clark et al. 2010; Schäfer et al. 2010; Hicke et al. 2012). Hence, it is important to develop methods to monitor insect disturbances and to quantify the impact of these disturbances on the carbon balance.

1.2 Insects in a changing climate and insect disturbances in forests

1.2.1 Insect disturbances and impact on the carbon balance

Insect outbreaks can have substantial impacts on forests. Insect outbreaks can alter tree species composition, reduce tree growth and change forests types, as well as influence wildlife and biodiversity (Weed et al. 2013). Insect disturbances have direct negative economic impacts on the forest industry, as well as a strong influence on other values such as recreational activities. It should, however, be noted that all insect outbreaks are not inherently undesired as they may play a natural role in forest dynamics (Liebhold 2012). Of main interest to this thesis is the potentially strong impact of insect outbreaks on the carbon uptake; two main types of insects are known to have a substantial negative impact on this uptake (Hicke et al. 2012): (1) Bark beetles (*Coleoptera: Curculionidae, Scolytinae),* which feed within the phloem and kill trees, and (2) defoliating insects which feed on leaves or needles, and that not directly kill trees, even though repeated and severe defoliation may result in tree mortality. Examples of bark beetles are the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), which have caused substantial damage over vast areas in North America (e.g. Hicke et al. 2012; Kurz et al 2008a), and the European spruce bark beetle (*Ips typographus* L.), that have caused severe damage in Europe (Rouault et al. 2006; Marini et al. 2013). Examples of defoliating insects are the gypsy moth (*Lymantria dispar* L.), which have caused major defoliation in North America (Hicke et al. 2012; Schäfer et al. 2010); the autumnal moth (*Epirrita autumnata* Borkhausen), and the winter moth (*Operophtera brumata* L.), which both have caused severe defoliation in northern Fennoscandia (Tenow 1972; Bylund 1995; Jepsen et al. 2009); and the European pine sawfly (*Neodiprion sertifer* Geoffr.), and the common pine sawfly (*Diprion pini* L.) which have caused severe defoliation in northern Europe (Lyytikäinen-Saarenmaa & Tomppo 2002).

These two types of insects can have different impacts on the carbon cycle (Hicke et al. 2012). Bark beetle outbreaks that kill trees result in immediate reductions in primary productivity and increased heterotrophic respiration that reduce net ecosystem exchange (NEE) (Hicke et al. 2012). These changes can shift an ecosystem from a carbon sink into a carbon source for decades (Kurz et al. 2008a). The most common impact on the carbon balance due to outbreaks of defoliating insects is decreased primary productivity (Hicke et al. 2012). This decrease can be substantial (Allard et al. 2008; Heliasz et al. 2011), and may turn forests from carbon sinks into carbon sources (Clark et al. 2010; Dymond et al. 2010). Severe and repeated defoliation events may result in tree mortality causing similar effects on the carbon balance as bark beetle outbreaks and change forests into carbon sources for years (Dymond et al. 2010). In addition to a direct impact on primary productivity, defoliation events can have severe impacts on entire ecosystems (Hicke et al. 2012; Ammunét et al. 2015). Defoliators release fluxes of nitrogen, carbon, and other nutrients to the ground with fragments of leaves, frass, and in the form of dead larvae (Hicke et al. 2012). Root-associated fungal communities can change (Saravesi et al. 2015), as well as chemical and physical properties of the soil (Kaukonen et al. 2013). Understorey vegetation can shift into more grass dominated communities (Karlsen et al. 2013; Jepsen et al. 2013). Large knowledge gaps need to be filled, both about how insects respond to climate change, and how insect disturbances influence forest ecosystems (Hicke et al. 2012).

1.2.2 Insects and climate change

A large number of studies have been performed to investigate how climate change influences forest insects; see e.g. Stange & Ayres (2001); Battisti (2008); Netherer & Schopf, (2010); Weed et al. (2013); and Neuvonen & Virtanen (2015) for reviews. The main abiotic factor that directly influences insects is changing temperatures. A warmer climate can lead to changing outbreak ranges for cold-limited insect species, as well as enable insects to develop more generations per season. Furthermore, a warmer climate, with fewer extremely cold winters, is likely to increase survival for insects in cold climates. There are, however, also studies suggesting that warmer winters can increase winter mortality for eggs, and result in collapsing insect populations (Baltensweiler 1993). A changing climate also influences host plants and natural enemies (Battisti, 2008). For defoliating insects it is e.g. important that egg hatch is synchronized with bud burst; changes in phenology can result in high mortality rates (Battisti 2008; Netherer & Schopf 2010; Stange & Ayres 2001). Stress, such as drought, has a strong influence on host plants resistance to insect attacks (Larsson 1989). In addition, elevated CO_2 levels may alter the nutrient properties, such as the carbon-to-nitrogen ratio of host plants, which in turn may influence insect species (Battisti 2008; Netherer & Schopf 2010). Furthermore, climate change influences interactions between insect species; how these complex interactions between antagonist species and natural enemies will be influenced is to a large extent unknown (Netherer & Schopf 2010). A warmer climate also increases the risk of invasive species (Hicke et al. 2012); even though global trade rather than climate change as such may be the reason that insects can travel between continents, a warmer climate may be required to facilitate the establishment of invasive species populations (Weed et al. 2013). There are also examples of native insects that have turned into disturbance agents (Weed et al. 2013). To conclude, there are large uncertainties in how forest ecosystems will be influenced by insects in a changing climate.

1.3 Remote sensing

1.3.1 Remote sensing and vegetation indices

Remote sensing can be defined as: “the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation” (Lillesand et al. 2015, p. 1). In this thesis remote sensing data from satellite based sensors are used. Such sensors can be utilized to derive the reflectance of features, such as vegetation, on the Earth’s surface. Typically, healthy vegetation has low reflectance in the visible wavelength bands (400–700 nm) since radiation within these wavelengths are utilized in photosynthesis, while reflectance in the near infrared (NIR) wavelength bands is high (Jones & Vaughan 2010). This large difference in reflectance between visible and NIR wavelength bands is commonly used to create vegetation indices (VI) as combinations of two or more wavelength bands. Major advantages with vegetation indices are that they have strong relationships with biophysical parameters, such as leaf area index (LAI), and that they normalize external effects such as different view and sun angles (McDonald et al. 1998; Jones & Vaughan 2010). Examples of vegetation indices used in this thesis are the normalized difference vegetation index (NDVI) (Rouse et al. 1973; Tucker 1979), and the 2-band enhanced vegetation index (EVI2) (Jiang et al. 2008). These indices are computed as:

$$NDVI = (NIR\text{-}red)/(NIR+red), \tag{1}$$

$$EVI2 = 2.5 \cdot (NIR\text{-}red)/(NIR+2.4 \cdot red+1), \tag{2}$$

where red and NIR are reflectance in the red and near infrared wavelength bands. Since these indices have a strong relationship with LAI, an insect disturbance that influences LAI will result in lower values for the vegetation indices, while healthy vegetation results in high values for these indices.

1.3.2 Satellite data resolutions and satellite sensors

Three resolutions of satellite data are discussed in this thesis: (1) Spatial resolution, which it the size of a pixel on the ground, (2) temporal resolution, which is the time-interval between images, and (3) the spectral resolution, i.e. the number of wavelength bands and their widths available from a sensor. The spatial and temporal resolutions are of major importance to remote sensing of forest disturbances: A finer spatial resolution enables disturbance detection with higher accuracy, but there is a trade-off since finer spatial resolution data generally have lower temporal resolution; the higher temporal resolution of coarse spatial resolution sensors enables studies of temporal dynamics and increase the chance of obtaining cloud-free images. In addition, finer spatial resolution images have narrower swath widths, i.e. cover smaller areas on the ground, which means larger numbers of fine spatial resolution images are required to cover the same areas as one coarse resolution image. For insect outbreaks that kill trees the temporal resolution is of less importance since the damage is long lasting and the chance to obtain cloud-free images is high; for ephemeral outbreaks by defoliating insects on the other hand, high temporal resolution is sometimes required to enable detection of the outbreak (Hicke et al. 2012, Rullan-Silva et al. 2013), especially in areas with frequent cloud cover.

Two examples of satellite systems with high spatial resolution are IKONOS (4x4 m; 11 km swath width) and Quickbird (2.5x2.5 m; 16 k swath width); these are both commercial sensors (Lillesand et al. 2015). Two examples of satellite sensors with medium spatial and low temporal resolution are Landsat and SPOT. The Landsat program has delivered satellite images since 1972 (Lillesand et al. 2015). Since Landsat 4, launched in 1982, the spatial resolution has been 30x30 m with a swath width of 185 km, and a revisit time of 16 days. The Landsat program provides the longest uninterrupted time-series of Earth observation data (Wulder et al. 2015). The Système Pour l'Observation de la Terre (SPOT) is a series of satellites with the first one launched in 1986 (Lillesand et al. 2015). Since the launch of SPOT 4 in 1998, the satellites have provided images with a spatial resolution of 10x10 m, a swath width of 60–80 km, and a revisit time of 26 days. One coarse spatial and high temporal resolution satellite sensor that has been utilized for insect disturbance detection is the Moderate Resolution Imaging Spectroradiometer (MODIS) that is carried by the Terra and Aqua satellites (Lillesand et al. 2015); a large number of MODIS products are available with time intervals of 1-, 8-, 16-days or longer, and with spatial resolutions of 250x250 m, 500x500 m, or coarser, and a swath width of 2330 km (LPDAAC 2016a). Two other sensors with daily temporal resolution and spatial resolution of around 1x1 km, and swath widths of 2250 and 2900 km, are SPOT Vegetation, that was carried onboard the SPOT satellites until 2014, and the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the National Oceanic and Atmospheric Administration (NOAA) satellites (Lillesand et al. 2015). In this thesis the focus is on data from the MODIS sensor with a spatial resolution of 250x250 m, and a temporal resolution of eight days.

1.3.3 Remote sensing of insect disturbances

A large number of studies have demonstrated that remote sensing techniques can be applied to detect insect induced disturbances, see e.g. Wulder et al. (2006); Adelabu et al. (2012); and Rullan-Silva et al. (2013) for reviews. The fine spatial resolution of IKONOS (White et al. 2005) and Quickbird (Coops et al. 2006; Wulder et al. 2008) have been utilized to map mountain pine beetle infestations in North America. Several remote sensing applications based on Landsat data have been developed for mapping of damage by the mountain pine beetle in North America (e.g. Franklin et al. 2003; Skakun et al. 2003; Goodwin et al. 2008; Coops et al. 2010). With the opening of the Landsat archive (Wulder et al. 2012), remote sensing data were provided for large areas, and methods to map different forest disturbance types from the long record of Landsat data have been successfully developed (Cohen et al. 2010; Kennedy et al. 2010; Meigs et al. 2011; Zhu et al. 2012), and annual global forest cover change maps have been created (Townshend et al. 2012; Hansen et al. 2013). The low temporal resolution of Landsat can, however, be a limitation for insect defoliation monitoring since many insects only have a short period when an outbreak is detectable (Rullan-Silva et al. 2013), and cloudy conditions may result in a situation with no available images during an outbreak.

Given the value of the high temporal resolution provided by coarse spatial resolution for monitoring of ephemeral insect defoliation events, data from such sensors are of particular interest to this thesis. Several coarse spatial resolution sensor systems with high temporal resolution have been used for insect disturbance mapping; for example, data from NOAA AVHRR, MODIS, and SPOT VEGETATION were utilized by Kharuk et al. (2004, 2007, 2009) to monitor damage by the Siberian silk moth (*Dendrolimus superans sibiricus* Tschetverikov) in Siberia. MODIS data have also been used to detect defoliation by the gypsy moth (de Beurs & Townsend 2008; Spruce et al. 2011) in North America, and SPOT VEGETATION and NOAA AVHRR data were used by Fraser et al. (2005) to monitor changes in forest cover at continental scale. The high acquiring frequency of MODIS has been utilized in several studies to perform time-series analysis to detect insect disturbance: Jepsen et al. (2009) used MODIS derived NDVI to monitor outbreaks of the autumnal moth and the winter moth in mountain birch forests in northern Fennoscandia; Eklundh et al. (2009) successfully mapped defoliation by the European pine sawfly in south-eastern Norway; and Sulla-Menashe et al. (2014) included insect disturbances in a general forest disturbance monitoring methods based on MODIS data. The high temporal resolution of MODIS has also been utilized to develop methods for near real-time monitoring of bark beetle outbreaks (Anees & Aryal 2014).

1.4 Estimating the impact of insect disturbances on the carbon balance

1.4.1 Modelling and eddy covariance measurements

There are studies that have applied process based modelling approaches to estimate the impact on the carbon balance due to insect outbreaks: Kurz et al. (2008a) demonstrated that mountain pine beetle outbreaks turned forests from carbon sinks into carbon sources for decades, and Dymond et al. (2010) showed that spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks could turn forest into carbon sources. Schäfer et al. (2010) showed a substantial decrease in carbon uptake due to a gypsy moth outbreak, and Medvigy et al. 2012, demonstrated that the spatial pattern of gypsy moth defoliation influenced the impact of an outbreak, with stronger reduction in carbon uptake for severe defoliation in scattered areas, compared to less intense defoliation over larger areas; this suggests that mapping of the spatial extent of insect outbreaks is important. Strong negative impacts on the carbon balance due to outbreaks of mountain pine beetle (Brown et al. 2010, 2012) and defoliating insects (Heliasz et al. 2011; Clark et al. 2010) have also been estimated with eddy covariance (EC) measurements. EC systems measure NEE, which is the integrated flux of gross primary productivity (GPP) and ecosystem respiration (R_{eco}) (Bonan 2008b; Heliasz et al. 2011), where GPP is the uptake of carbon during photosynthesis, and R_{eco} is the sum of the autotrophic respiration, i.e. loss of carbon due to plants' growth and maintenance, and heterotrophic respiration, i.e. loss of carbon during decomposition of organic debris (Bonan 2008b). These methods do, however, not generate spatially explicit estimates as they lack spatial observations of the defoliated canopies.

1.4.2 Light use efficiency and remote sensing

Methods have been developed to estimate the primary productivity of vegetation with the aid of remote sensing data and meteorological data by applying light use efficiency (LUE) models (e.g. Prince 1991; Ruimy et al. 1994; Running et al. 2004; Xiao et al. 2004; Wu et al. 2010; McCallum et al. 2013; Gamon 2015). A LUE model is based on the concept that the amount of the photosynthetically active radiation (PAR) i.e. solar radiation in the spectral range 400–700 nm, that is absorbed by the plant is linearly related to the primary productivity (Monteith 1972, 1977). This can be formulated as:

$GPP = \varepsilon \cdot APAR,$

where ε is the light use efficiency, and $APAR$ is the amount of PAR that is absorbed by the vegetation, referred to as absorbed photosynthetically active radiation. The fraction APAR that is absorbed by the vegetation (fAPAR) can be derived from satellite data since near-linear relationships between satellite derived vegetation indices, such as NDVI, and fAPAR have been established (e.g. Asrar et al. 1984; Sellers 1987; Goward & Huemmrich 1992; Myneni & Williams 1994; Olofsson and Eklundh 2007). Hence, a LUE model can be formulated as (Prince 1991; Running et al. 2004):

$$GPP = \varepsilon \cdot fAPAR \cdot PAR,$$

where $fAPAR$ is estimated as: $fAPAR = a + b \cdot NDVI$ (Myneni & Williams 1994). The light use efficiency varies between vegetation types; in addition, there is a strong temporal variability in ε e.g. due to stress factors such as temperature and water availability which increase uncertainties in LUE models (e.g. Gamon 2015). Hence, it is common to model ε with a maximum efficiency depending on vegetation type, and reduction factors based on meteorological data (e.g. Field et al. 1995; Prince & Goward 1995; Potter et al. 1999; Turner et al. 2003). EC data (Turner et al. 2003; Lagergren et al. 2005; Gamon 2015) or ecosystem models (Running et al. 2004) can be utilized to calibrate the LUE model. A major advantage with LUE models is that wall-to-wall mapping of primary productivity can be performed if ε can be estimated with high accuracy; if the light use efficiency can be estimated also during defoliation it would be possible to quantify the impact of insect outbreaks on primary productivity with LUE models.

1.5 Objectives

The general aim of this thesis was to develop methods for mapping and monitoring of spatio-temporal patterns of insect outbreaks with time-series of satellite data, and to quantify the impact of these outbreaks on carbon uptake. Specific research questions were:

- To map insect defoliation with medium spatial resolution satellite data and to find what year the studied insect outbreak started with the aid of a time-series of high temporal resolution satellite data.
- To develop a method for mapping of insect outbreaks with time-series of high temporal, coarse resolution satellite data, and to evaluate detection accuracies in fragmented and heavily managed forests.
- To develop a method for monitoring of insect outbreaks in near real-time, and to map the spatial and temporal dynamics of insect outbreaks, with high temporal resolution satellite data.
- To quantify the impact of the mapped insect disturbances on primary productivity.

2 Material and methods

2.1 Study areas and insect species

Insect outbreaks in four areas were studied in this thesis (Figure 1): Southwest Scania in southernmost Sweden (Paper I), Outokumpu and Ilomantsi in eastern Finland (Paper II), and Abisko in northern Sweden (Paper II-IV). The insect outbreaks in these areas are described below.

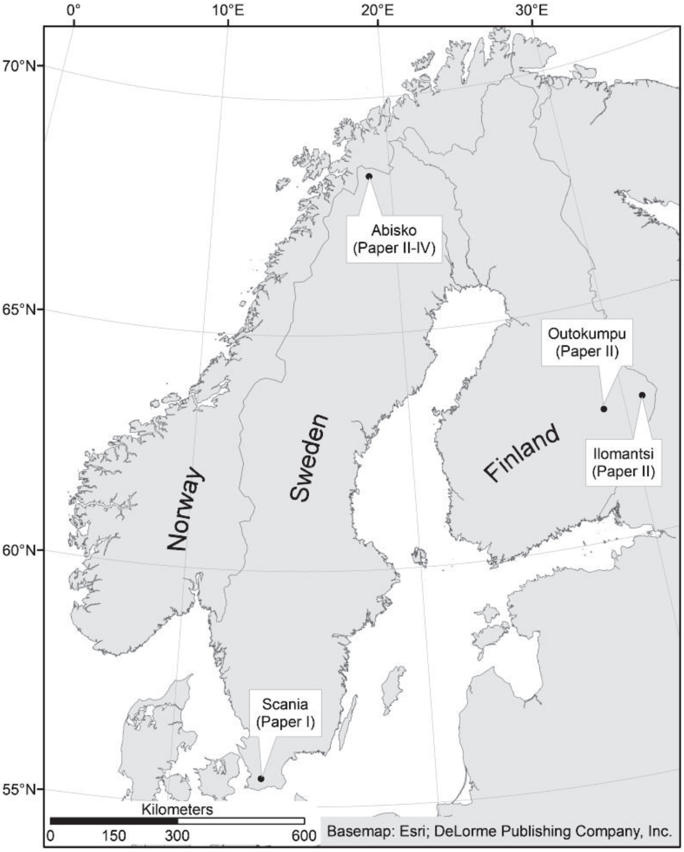


Figure 1. The four areas with insect outbreaks included in this thesis. Reference system is WGS84, UTM zone 33N.

2.1.1 Hungarian spruce scale in southernmost Sweden

Study I was conducted in the southwestern part of Scania (55.5°N, 13.5°E), the southernmost district of Sweden. The area is dominated by agricultural fields with some larger forested areas covering just over 10% of the total area, with about 25% of the forest stands consisting of Norway spruce (*Picea abies* L. Karst). Some of these spruce forests were infested by the invasive Hungarian spruce scale (*Physokermes inopinatus* Danzig & Kozár) in 2009 and 2010. The Hungarian spruce scale is a soft scale that was first recorded in Hungary (Danzig & Kozár 1973) and that has been found mainly in Central and Eastern Europe (Danzig & Kozár 1973; Fetykó et al. 2010; Ben-Dov et al., 2012; Stathas & Kozár, 2010). The Hungarian spruce scale feeds on the sap from needles, which causes direct damage to the host tree (Vranjic, 1997). In addition, the scales produce honeydew, which can facilitate the growth of sooty mold and result in a strong sooty-colored encrustation on the needles (Isacsson, 2010; Carter, 1973). The studied outbreak was the first known appearance of this invasive insect in Sweden, and the outbreak was most likely a product of international trade (Gertsson & Isacsson 2014).

2.1.2 Pine sawflies in eastern Finland

Study II included two areas in eastern Finland: One area in the municipalities of Ilomantsi (62.9°N, 30.9°E) and one in Outokumpu (62.8°N, 28.9°E). These landscapes are generally flat and mostly covered by heavily managed and fragmented forests dominated by Scots pine (*Pinus sylvestris* L.) that were infested by the common pine sawfly and the European pine sawfly. Both the common and the European pine sawflies have caused severe defoliation on Scots pine in northern Europe (Lyytikäinen-Saarenmaa 1999; Veteli et al. 2005). These defoliation events normally results in reduced growth; a single year of defoliation only to a limited extent leads to tree mortality (Långström et al. 2001). Of the two species, the common pine sawfly, which is a late defoliator feeding on both old and fresh needles, causes a larger degree of tree mortality, compared to the European pine sawfly, which is an early defoliator feeding mainly on old needles. It has been suggested that the northern outbreak ranges of both species to a large extent are limited by cold winter temperatures, and that a warmer climate will enable the sawflies to expand their outbreak ranges further to the north (Virtanen et al. 1996; Veteli et al. 2005).

2.1.3 Birch moths in northern Sweden

Study III, IV, and part of study II were conducted in Abisko (68.35°N, 18.82°E) in northern Sweden. The area is mainly covered by mountain birch (*Betula pubescens ssp. Czerepanovii* N.I. Orlova) forests, mires, and heath vegetation with dwarf shrubs, grasses, and lichens (Wielgolaski 2001). These birch forests were defoliated by the autumnal moth and the winter moth (Figure 2). Both moth species have caused severe defoliation in mountain birch forests in northern Fennoscandia in time intervals of 9–10 years (Bylund 1995; Tenow et al. 2007; Ammunét et al. 2015). Outbreaks of the autumnal moth have been reported in northern Fennoscandia since 1862, but it is likely that the insect has been present in the area longer, while the first outbreaks of the winter moth were reported in the northern parts of Fennoscandia in 1893 (Tenow 1972). A warmer climate, especially a lower frequency of years with extremely cold winters, as reported by Callaghan et al. (2010), strongly influences birch moth populations (Babst et al. 2010). Expanded northern outbreak ranges for both moth species have been documented in Fennoscandia with the autumnal moth outbreaks expanding into colder, more continental regions, and the winter moth outbreaks expanding towards north-east into areas previously dominated by the autumnal moth (Jepsen et al. 2008). These moth outbreaks can have a substantial impact on the birch forests (Tenow 1996; Ammunét et al. 2015), and a strong impact on the carbon balance (Heliasz et al. 2011).

Figure 2. Defoliated birch trees (left); defoliated and undisturbed birch forest (right) near Abisko in late June 2013.

2.2 Insect disturbance data

For paper I, insect damage data were obtained from forest managers and the Swedish forest agency (Skogsstyrelsen). These data were used as training data, and a mapping of damaged forest stands was done visually with the aid of high spatial resolution orthophotos (0.25x0.25 m) that were taken during the Hungarian spruce scale outbreak in 2010. In Finland, a long time-series of annual assessments of insect defoliation had been collected with the purpose of monitoring the European and common pine sawfly outbreaks. These data were utilized as training data during method development. In addition, a defoliation assessment at stand level had been performed in the year 2010. These data were used as evaluation data. In northern Sweden, defoliation data were collected in field during an autumnal and winter moth outbreak in 2013. These data were collected as training and evaluation data for the defoliation method developed; hence, in study IV defoliation assessments were made over sampling areas with the size of a nominal MODIS pixel with 250x250 m spatial resolution.

2.3 fAPAR and eddy covariance data (study IV)

In study IV, fraction canopy absorbed PAR ($fAPAR_{canopy}$) measured at a spectral tower located in birch forest in the study area was used (Eklundh et al. 2011). $fAPAR_{canopy}$ was obtained using the four-component method, i.e. measurements of incoming PAR above canopy, the total reflected PAR above the canopy, the transmitted PAR below the canopy, and the reflected PAR by the understorey vegetation and ground below the canopy (see Eklundh et al. 2011 for details). $fAPAR_{canopy}$ data were available for the years 2010 and 2011; due to the insect outbreaks in 2012 and 2013, and sensor failure in 2014 no more data were available. An ordinary least squares regression was performed to find the relationship between $fAPAR_{canopy}$ and NDVI fitted with double logistic functions in the TIMESAT software (Jönsson & Eklundh 2002, 2004). The linear equation derived was used in the LUE model to obtain fAPAR from MODIS derived NDVI.

The EC data used in study IV were an extended time-series of the data used by Heliasz et al. (2011). EC measurements were made with a 3-dimensional sonic anemometer (Metek USA-1; METEK Gmbh., Germany) and an open path infrared gas analyzer (Licor 7500, LI-COR Inc., USA) at a height of 8 m above ground and around 3 m above the canopy. Additional measurements of air temperature (Vaisala WXT510; Vaisala, Finland) and incoming photosynthetic flux density (PPFD; JYP 1000, SDEC, France), were done at the flux tower. Data were obtained during the period May 1 to September 30, which is from before the start of the growing season until late growing season. EC flux calculations were done with the EddyPro software ver. 5.2.1 (LI-COR Inc., USA). Data gaps were filled with the online model: Eddy covariance gap-filling & flux-partitioning tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc), and a model from the same website was used to partition NEE into GPP and R_{eco}. Details about gap filling and flux partitioning are described in Reichstein et al. (2005). EC data were available from five years without disturbances and from one full growing season with disturbances.

2.4 Satellite data

In study I, data from SPOT 5 with 10x10 m spatial resolution were used to map the Hungarian spruce scale outbreak. SPOT data from the years 2008, 2009, and 2010 were obtained from the Saccess web-service provided by the Swedish mapping, cadastral, and land registration authority (Lantmäteriet) (Saccess 2016). Time-series of NDVI, obtained from the MODIS product MOD13Q1, with 16 days temporal resolution and 250x250 m spatial resolution (LPDAAC 2016b), were used to study what year the outbreak started.

For study II–IV, MODIS data with a temporal resolution of eight days from the products MOD09Q1 (LPDAAC 2016c) and MOD09A1 (LPDAAC 2016d) were used. MOD09Q1 has a spatial resolution of 250x250 m, and was used to obtain surface reflectance in the red and NIR wavelength bands to compute vegetation indices, as well as to obtain quality assurance (QA) information, i.e. information about the quality of the data. MOD09A1 has a spatial resolution of 500x500 m and was used solely to derive QA-data, since these quality data are more comprehensive compared to MOD09Q1.

2.5 Insect disturbance detection

2.5.1 Study I

In study I, the outbreak of the Hungarian spruce scale was mapped with SPOT data. Spectral signatures for undisturbed spruce stands, and stands infested by the scale insect suggested that the impact of the spruce scale was larger in the green wavelength band than in the red (Figure 3). Consequently, both NDVI and green

NDVI (GNDVI) (Gitelson et al. 1996) were tested in the study, where NDVI was computed according to Equation 1 and GNDVI according to Equation 3:

$$GNDVI = (NIR\text{-}green)/(NIR+green), \tag{3}$$

where $green$ is reflectance in the green wavelength band. NDVI and GNDVI were computed for all pixels with spruce forest in the SPOT images from 2008, 2009, and 2010. The year 2008 was used as reference year and difference images were computed for the years with insect outbreak as the difference in VI between outbreak years and 2008. These difference images were used to classify pixels as undisturbed or infested based on thresholds for NDVI and GNDVI.

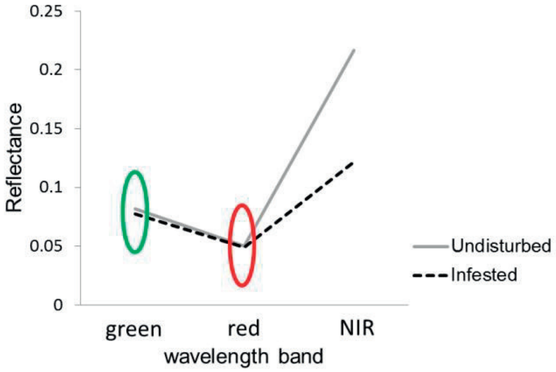


Figure 3. Spectral signatures for undisturbed spruce stands and spruce stands infested by the Hungarian spruce scale in the year 2010, showing that the difference between undisturbed and infested stands is larger in the green wavelength band compared to the red.

To find which year the Hungarian spruce scale outbreak started, time-series of NDVI for the years 2001–2010 were obtained from the MOD13Q1 product for MODIS pixels that were infested in the year 2010. These time-series were smoothed with a Savitzky-Golay filter in the TIMESAT software to reduce the influence of noise in the data. TIMESAT is a software package that fits smoothed functions to time-series of data, such as vegetation indices, to reduce the influence of noise and to enable extraction of seasonality parameters (Jönsson & Eklundh 2002, 2004).

2.5.2 Study II

In study II, a method to map insect defoliation with z-scores of MODIS derived EVI2 was developed. The method was tested with both NDVI and EVI2; EVI2 only is described below, but NDVI was processed analogously. Time-series of

EVI2 for the years 2001−2011 were created for all MODIS pixels and smoothed with double logistic functions in TIMESAT. The seasonality parameter giving the maximum value of the fitted function during the growing season, referred to as *season max*, was obtained for each year and pixel, see Figure 4. The n years with highest season max were found for each MODIS pixel and considered to represent undisturbed conditions. Mean and standard deviation of season max was computed pixel-wise for these n years and z-scores were computed for all years with outbreak as:

$$z_{p,y} = (sm_{p,y} - \mu_p)/\sigma_p, \tag{4}$$

where $z_{p,y}$ is the z-score for pixel p and year y; $sm_{p,y}$ is season max for pixel p and year y; μ_p is the mean of season max for pixel p; and σ_p is the standard deviation of season max for pixel p. MODIS pixels were then classified as damaged or healthy based on a z-score threshold. Receiver operating characteristic (ROC) curves were used to find how many years to include when computing mean and standard deviation of season max, and to find the z-score threshold to apply to detect damaged pixels. ROC curves is a method to depict the trade-off between correctly classified damaged pixels, and healthy pixels that were misclassified as damaged (Fawcett, 2006); the ratio of the damaged samples that are classified as damaged is termed true positive rate (TPR) and plotted on the y-axis; and the ratio of the non-damaged samples that are classified as damaged (i.e. false alarm) is termed false positive rate (FPR) and plotted on the x-axis. The point (FPR = 0, TPR = 1) in an ROC graph represents a perfect classification, and the diagonal (0,0−1,1) represents a random classifier.

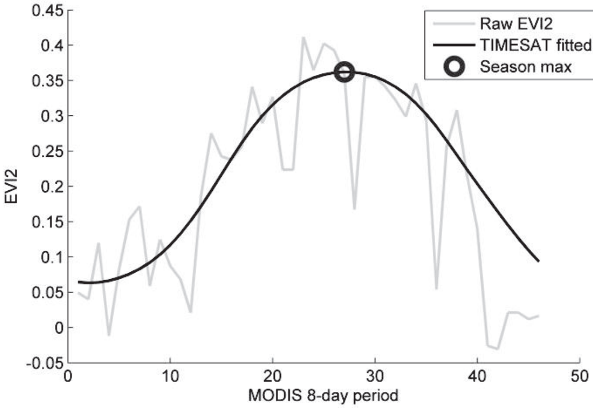


Figure 4. Raw EVI2 and EVI2 fitted with double logistic functions in TIMESAT. Season max (gray circle) is the maximum value of the fitted function during a growing season.

2.5.2 Study III and IV

In study III, a method for near real-time monitoring of insect induced defoliation was developed; the method was later used in study IV. The method was tested with both NDVI and EVI2; NDVI only is described below, but EVI2 was processed analogously. Time-series of NDVI for all MODIS pixels in the study area were computed for the years 2000−2013 and smoothed with double logistic functions in TIMESAT. A "typical" seasonal trajectory of NDVI for years without disturbances, referred to as the *stable season*, was identified as the mean of the double logistic functions for the *n* years with highest NDVI values, and estimated from pixels with nearly full forest cover. A Kalman filter (Kalman 1960) was implemented to reduce the influence of noise, and to estimate the value of NDVI for observations with low quality, see Figure 5. Kalman filters give the optimal linear estimate of the state of time-varying processes (Welch & Bishop 2006) and have been used extensively for signal processing. As an example, a Kalman filter was applied in a potential sea-state warning system based on near real-time satellite data (Malmberg et al. 2008).

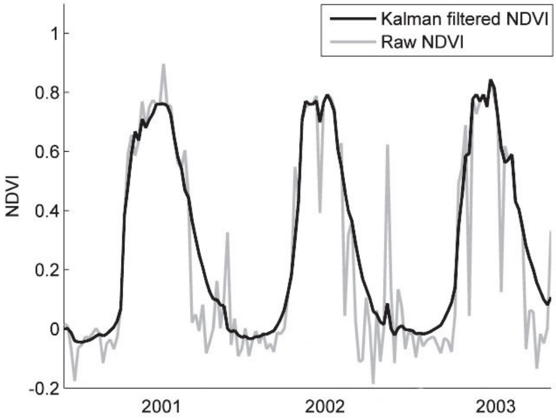


Figure 5. Raw NDVI and Kalman filtered NDVI for the years 2001–2003 obtained for one MODIS pixel with mountain birch forest.

Defoliation was detected with the aid of cumulative sums (CUSUM; Page 1954) of the deviations of the Kalman filtered NDVI from the stable season during the growing season; insect defoliation results in lower NDVI and hence, large deviations (Figure 6). The stable season was adjusted locally to adjust for differences in levels of NDVI between pixels, and an annual offset was applied to the stable season to adjust for the start of the season. ROC curves were utilized to optimize the method, i.e. to find the number of years to base the stable season on, to find the fraction canopy cover required in a MODIS pixel for high detection accuracy, and to find the threshold applied in CUSUM to detect defoliation.

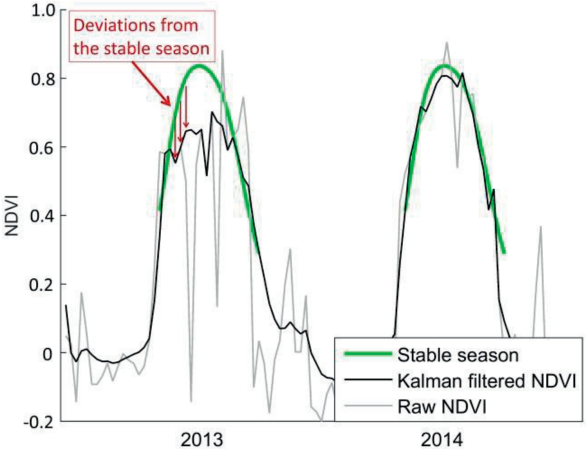


Figure 6. Stable season, raw NDVI, and Kalman filtered NDVI for one MODIS pixels in the study area with defoliation in the year 2013, and no disturbance in the year 2014. Red arrows show the deviation of the Kalman filtered NDVI from the stable season that are used by the CUSUM filter to detect defoliation.

2.6 Quantifying the impact of insect defoliation on GPP

2.6.1 LUE model

In study IV, a LUE model with mean values of daily GPP in eight day intervals (GPP_{lue}) (g C m^{-2} day^{-1}), corresponding to the time interval of the MODIS data was developed as:

$$GPP_{lue} = \varepsilon \cdot fAPAR_{8day} \cdot PAR_{8day}, \quad (5)$$

where ε (g C MJ^{-1}) is the light use efficiency, $fAPAR_{8day}$ is fAPAR for a MODIS eight day period derived from NDVI as: $fAPAR = a + b \cdot NDVI$, and PAR_{8day} (MJ day^{-1}) is mean daily PAR measured at the EC tower over the eight day period. The light use efficiency was computed as:

$$\varepsilon = \varepsilon_{max} \cdot f_{8day}, \quad (6)$$

where ε_{max} is the maximum efficiency applied in the model and f_{8day} is a reduction factor introduced to model the variability in ε depending on temperature and time of the season. Two models were created to describe f_{8day}, as in Lagergren et al. (2005): One model for the first part of the growing season and one model for the second part of the growing season. During the first part of the growing season f_{8day} was influenced by growing degree days (GDD), with a base temperature of 5 °C, and frost events. During the second part of the growing season f_{8day} was controlled by mean temperatures. ε_{max} was computed as the mean value of the light use efficiency for all MODIS periods with maximum efficiency i.e. $f_{8day} = 1$, where the efficiency was derived from EC measured GPP and APAR derived from MODIS NDVI.

The LUE model was applied to all MODIS pixels in the study area with a forest cover of at least 50%, and the mean of annual GPP for the five years without disturbances was computed for each pixel as the reference GPP for undisturbed conditions.

2.6.2 Quantifying the impact of defoliation on GPP

Two methods were applied to quantify the impact on GPP from the insect induced defoliation: Method 1 applied a common reduction factor to all defoliated pixels to estimate the GPP loss. The reduction factor was derived as the reduction in GPP at the EC tower during an outbreak in 2012. The reduction in annual GPP was computed for each pixel by multiplying the reduction factor to GPP for undisturbed years. Method 2 applied a LUE model to estimate GPP also for defoliated pixels, and the decrease in GPP was computed as the difference in GPP between defoliated years and undisturbed years. The maximum light use efficiency for defoliated pixels ($\varepsilon_{max,\ def}$) was estimated from the outbreak in 2012. The assumption was that Method 2 would be more adaptive and adjust for differences in defoliation intensities between MODIS pixels. Since the level of defoliation, as well as understorey responses to the defoliation, are likely to influence NDVI, which in turn will influence fAPAR, it was anticipated that a method based on a LUE model to derive GPP also during defoliation events would capture variability in defoliation levels and understory responses between MODIS pixels. Method 1, on the other hand, does not account for local differences between pixels and is similar to upscaling the local conditions at the EC-tower, even though the method has the advantage that annual GPP for each pixels is derived with a LUE model and hence, should be more accurate than assuming that GPP for all MODIS pixels is identical to GPP at the EC-tower.

3 Results and discussion

3.1 The Hungarian spruce scale outbreak (Paper I)

The GNDVI difference images from the SPOT images enabled detection of 78% of the pixels infested by the Hungarian spruce scale in the year 2010 with an overestimation of 46%. NDVI resulted in lower detection and were not included in the results. The detection accuracy is, however, a trade-off between detection rate and overestimation. It would be possible to increase the detection rate, but at the cost of higher overestimation. A manual evaluation at stand level indicated that nearly all (98%) of the damaged stands were detected with an overestimation of around 50%. Much of the overestimation consisted of small scattered areas, and many were due to erroneous land cover data, or due to forestry activities such as thinning. This result shows that a high accuracy can be attained at stand level.

The Hungarian spruce scale outbreak was first detected by forest managers in the year 2010, but dead scales on the ground and reduced growth indicated that the scale had been present earlier. Hence, we studied time-series of NDVI for the period 2001–2010 and found that the outbreak most likely started in the year 2009, i.e. one year before it was detected in the field; see Figure 7 where NDVI reached around 0.9 each growing season in the time period 2001–2008, while NDVI stayed around 0.8 in 2009 and 2010. The SPOT data from 2009 showed that 11% of the areas infested in 2010 were attacked already in 2009.

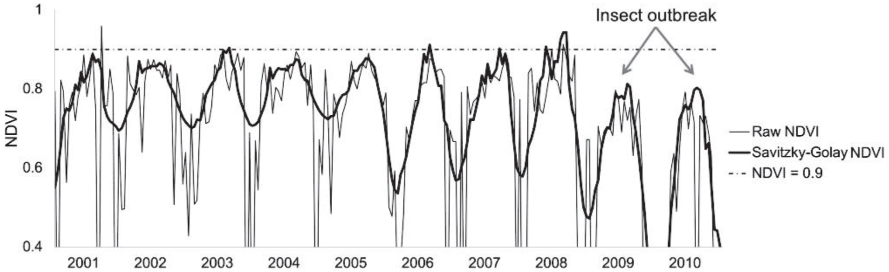


Figure 7. Raw and Savitzky-Golay filtered NDVI for the years 2001–2010 show that the Hungarian scale outbreak most likely started in 2009, i.e. one year before it was detected in the field. NDVI were obtained from MOD13Q1 with 250x250 m spatial and 16 days temporal resolution, and TIMESAT was used to apply the Savitzky-Golay filter.

The results of study I highlight one major advantage with time-series of satellite data: Forest disturbances can be traced back in time. Figure 7 also illustrates the possibility to utilize high temporal resolution satellite data to build early warning systems. The forests in the study area are frequently visited; despite this the outbreak was not detected in 2009. An early warning system would have enabled the forest managers to detect the Hungarian spruce scale outbreak one year earlier than it was detected in the field. For invasive species early detection is of major importance to take rapid counter measures to decrease the risk that the invasive insect establishes a population (Liebhold 2012).

3.2 Mapping insect defoliation with z-scores (Paper II)

The results showed that the developed method, based on z-scores of the seasonal maximum of a vegetation index, could be applied to map insect defoliation with high accuracy in the mountain birch forests in northern Sweden. 75% of the damaged pixels were detected with a misclassification of healthy samples of 19%. In the fragmented and heavily managed forests in Finland, on the other hand, detection accuracies were low. In areas with a short history of defoliation only 50–63% of the defoliated stands were detected with a misclassification of healthy stands of 22–37%. In areas with a long history of defoliation the method resulted in extensive misclassification rates. NDVI was more sensitive than EVI2 to the number of years included to estimate healthy conditions, and resulted in larger misclassification of healthy samples. However, if large misclassification of healthy samples is acceptable, NDVI may be suitable since NDVI gives lower misclassification rates for the highest detection rates. The low detection accuracies in the fragmented forests in Finland is most likely due to the coarse spatial resolution of MODIS, which results in MODIS pixels containing fractions of several forest stands. In addition, the spatial precision of MODIS is low and the reflectance signals are obtained over areas larger than the nominal pixels (Tan et al. 2006). It is also likely that the lower defoliation intensities in Finland compared to northern Sweden influence detection accuracy.

Despite the low detection accuracies in heavily managed and fragmented forests landscapes, MODIS and other coarse spatial resolution satellite data may still have an important role to play in disturbance monitoring, especially in regions where cloudy conditions limit the number of available medium resolution images. As an example, only small fractions of the study area in Abisko were visible in any Landsat image during the outbreak in 2013. However, it must be realized that in areas with fragmented forest landscapes coarse spatial resolution satellite data results in low detection accuracies, and where the disturbance history is longer than the satellite time-series record, damage might be undetected. Hence, it is quite likely that forest damage based on MODIS data alone in these areas is underestimated.

Furthermore, the developed method based on TIMESAT, z-scores, and ROC curves developed in this paper is robust, and succeeded in detecting defoliation events with high accuracy in the more homogenous forests in Abisko. Hence, it might be possible to apply the developed method to other future satellite data such as Sentinel-2 data with its high spatial and temporal resolutions.

3.3 Near real-time monitoring (Paper III)

The results showed that defoliation by the autumnal moth and winter moth in birch forests could be monitored in near real-time with the aid of a Kalman filter and CUSUM, if MODIS pixels contained at least 50% birch forest. In addition, the method supports monitoring of the intra-seasonal dynamics of an insect outbreak (Figure 8) as well as enables monitoring of within-season refoliation. The method detected 74% of the defoliated MODIS pixels with a misclassification of undisturbed pixels of 39%. These accuracies could be changed by adapting the defoliation detection threshold applied in CUSUM. With a lower CUSUM threshold, 100% of the defoliated MODIS pixels were detected with a misclassification of undisturbed pixels of 56%. Hence, the method can be adjusted to favor high detection accuracy or avoid misclassification of undisturbed pixels depending on the purpose of a study. The detection delay could not be estimated with high accuracy due to lack of field data on the starting date of the outbreak, though the behavior of CUSUM indicated average detection delays of 1–3 MODIS 8-day periods depending on the thresholds applied in CUSUM. Thresholds that resulted in short detection delays resulted in larger numbers of MODIS pixels being detected, but at a cost of higher misclassification of undisturbed pixels.

EVI2 resulted in lower detection accuracies compared to NDVI. These lower accuracies might be due to the higher sensitivity to leaf area of EVI2 (Jiang et al. 2008), which results in seasonal trajectories that are narrower and with sharper growing season peaks compared to NDVI (Figure 9). It is likely that the narrower peaks make EVI2 more sensitive to noise since there are less MODIS 8-day periods with high values compared to NDVI. It is also possible that the lower EVI2 values compared to maximum EVI2 at mid-growing season reduce the chance to detect changes in leaf area in the early part of the growing season, while the potential saturation of NDVI has little influence on detection abilities since the drop in NDVI due to insect defoliation is sufficiently large to fall below the level of saturation.

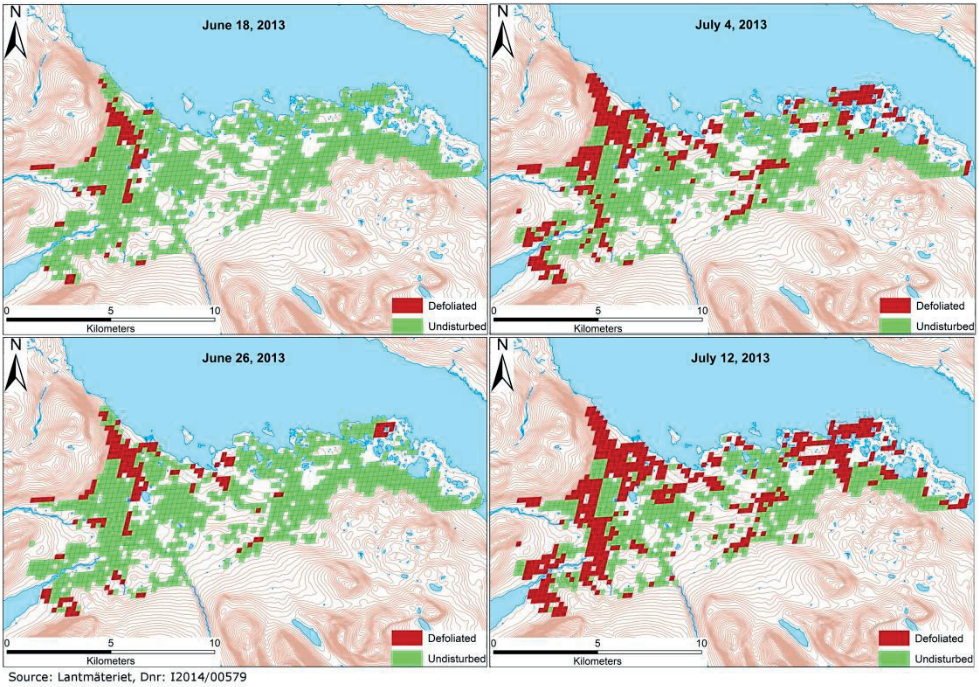


Figure 8. The development of the insect outbreak for the period June 18 to July 12 in 2013. Dates are MODIS 8-day periods. Areas with only background map have a canopy cover less than 50% or are outside the studied area. Reference system is SWEREF99 TM and source of the background map is Lantmäteriet (Dnr: I2014/00579).

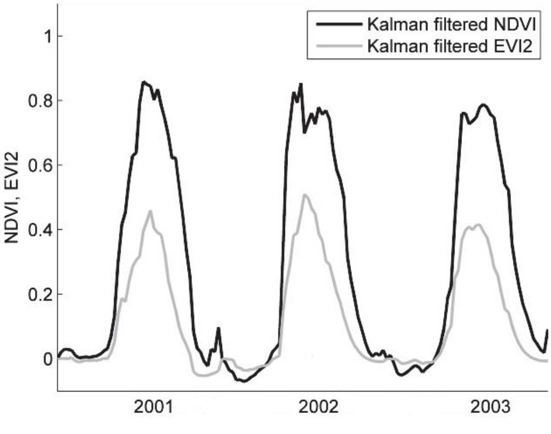


Figure 9. Kalman filtered NDVI and EVI2 for one MODIS pixel with birch forest. The seasonal trajectories of EVI2 are narrower, and with sharper growing season peaks compared to NDVI, which might be a reason for the lower detection accuracies for EVI2.

The near real-time capability is a major advantage compared to remote sensing methods that classify pixels into defoliated or undisturbed based on data from the entire growing season (e.g. Jepsen et al. 2009; Eklundh et al. 2009). This opens up possibilities for early warning systems that could be valuable for forest management and nature conservation since it would facilitate more rapid counter measures, as well as facilitate timely field studies of insect outbreaks. Even though the method was developed and applied to subalpine mountain birch forest it would be possible to apply the method also to other forest ecosystems and disturbances, such as fire and wind. Furthermore, the method demonstrated the potential of remote sensing methods to support studies of intra-seasonal dynamics during an insect outbreak. Synchrony of insect outbreaks (e.g. Williams & Liebhold 2000; Aukema et al. 2006) and travelling waves (Johnson et al. 2004; Tenow et al. 2007, 2013) have previously been studied based on annual outbreak data. The method and data presented here reveals intra-seasonal spatio-temporal patterns in the studied outbreak in 2013 (Figure 8) that might provide valuable insights into the ecology of the birch moths.

3.4 Impact of insect defoliation on GPP (Paper IV)

The three years with insect outbreak since the year 2000 (Figure 10) resulted in an estimated total reduction in carbon uptake of 44 Gg C in the study area, which is just over the average annual GPP of 41 Gg C year^{-1}. During the largest insect outbreak (2012), 76% of the 100 km^{2} forest included in the study area was defoliated; in the two other outbreak years 2004 and 2013, 53% and 55% respectively of the birch forests were defoliated. In the year 2012, annual GPP was merely half (51%) of GPP for undisturbed years. In the years 2004 and 2013, GPP was 33% and 25% respectively lower than for undisturbed years. Even though there are uncertainties in the absolute GPP values derived from the EC-tower depending e.g. on how well the respiration is modelled, the estimated impacts on GPP are considered reliable since they are based on relative values. The GPP losses per area unit were 252, 265, and 188 g C m^{-2} year^{-1} for the years 2004, 2012, and 2013 respectively. These GPP reductions were estimated with the method where a LUE model is applied to estimate GPP also for years with defoliation (Method 2). Which method that gives the most accurate estimate of the GPP loss can be discussed. Method 1, based on a common reduction factor, has the advantage that the factor is derived from measured GPP at the EC tower; hence, the factor should be accurate. This, however, only holds when the actual reduction in GPP in each pixel is the same as at the EC-tower; it is likely that the level of defoliation, as well as the understorey vegetation will influence the reduction factor.

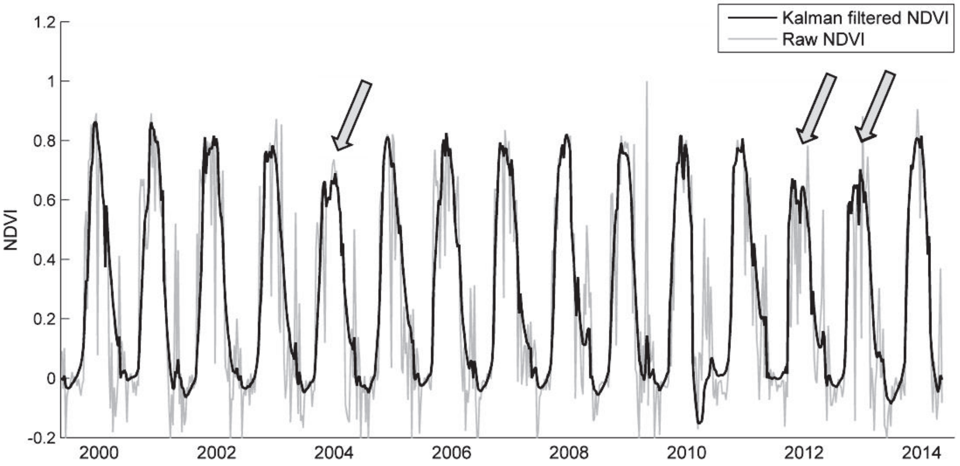


Figure 10. Raw NDVI and Kalman filtered NDVI for the years 2000–2014 where the outbreaks in 2004 and 2012–2013 have resulted in lower seasonal trajectories of NDVI.

Method 2, on the other hand, is influenced by how well the LUE model can estimate GPP for years with defoliation, and since the level of defoliation, as well as understorey responses to the defoliation, are likely to influence NDVI, which in turn will influence fAPAR, it is possible that a method based on a LUE model to derive GPP during defoliation handles variability in defoliation levels and understory responses better than a fixed reduction factor. For the years 2012 and 2004, both methods resulted in similar GPP losses with larger decreases for Method 2. In the year 2013 differences between the two methods were larger with Method 2 estimating 26% lower GPP loss compared to Method 1. The lower GPP loss for Method 2 in 2013 could be due to substantial refoliation, which was captured by the method. However, since there was refoliation also in the year 2004, when there were only minor differences between the methods, the large differences could also be due to uncertainties in maximum light use efficiency ($\varepsilon_{max, def}$), which was estimated from one year (2012) with defoliation only. Hence, more data from the EC tower would be required to draw any conclusions.

Several studies have estimated the impact of insect outbreaks on the carbon balance with EC data (Allard et al. 2008; Clark et al. 2010; Heliasz et al. 2011; Brown et al. 2010, 2012) or with modelling approaches (Kurz et al. 2008a; Dymond et al. 2010; Schäfer et al. 2010; Medvigy et al. 2012). These studies have, however, only studied the impact locally, or used auxiliary disturbance data to extrapolate the impact over larger areas. The method presented here, based on remote sensing data, meteorological data, and a LUE model, has the advantage that both the spatial extent and the impact on GPP of an insect outbreak can be mapped (Figure 11).

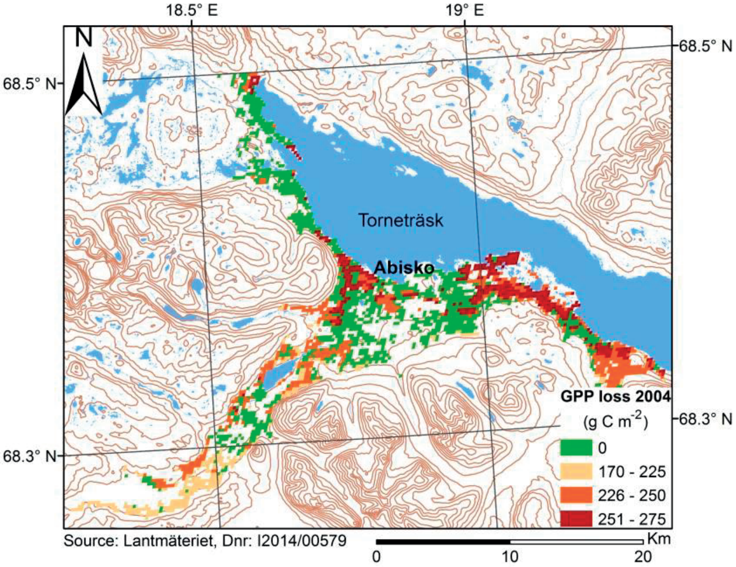


Figure 11. Reduction in annual GPP (g C m^{-2}) due to the birch moth outbreak in 2004 computed with a common reduction factor. Areas with only background map have a canopy cover less than 50% or are outside the study area. Reference system is SWEREF99 TM, latitude and longitude are in WGS 84, and source of the background map is Lantmäteriet (Dnr: I2014/00579).

3.5 Regional and local mapping of insect outbreaks

Different vegetation indices gave the highest detection accuracy for the three types of insect outbreaks that were studied in this thesis. For the spruce forests in southern Sweden GNDVI resulted in the highest accuracy, most likely since the dark color caused by the sooty mold had a stronger impact on the green wavelength band than on the red (Figure 3). In the pine forests in eastern Finland EVI2 resulted in the highest detection accuracies, and for near real-time monitoring in the mountain birch forests in northern Sweden, NDVI performed best. As mentioned in section 3.3 and illustrated in Figure 9, it is likely that the larger number of MODIS periods with high values during the main growing season is an advantage for the near real-time monitoring method. For the method based on z-scores, on the other hand, it is likely that the higher sensitivity to leaf area is an advantage when only the maximum value of the fitted function is utilized for damage detection. These results suggest that to find a general method for disturbance monitoring over larger areas, such as nations and regions, the choice of method and vegetation index will be a compromise. Once a disturbance is detected, it is most likely that other methods and vegetation indices, tailored for specific forest and insect species, can be applied locally to achieve higher detection accuracies. Furthermore, the spatial resolution dictates which spectral bands are available. Longer wavelength bands, e.g. shortwave infrared (SWIR) wavelength bands are e.g. available from MODIS with a spatial resolution of 500x500 m (NASA 2016). Such SWIR wavelength bands derived from Landsat data have been proved successful for accurate detection of insect defoliation (Skakun et al. 2003; Goodwin et al. 2008; Coops et al. 2010), but in the study areas included in this thesis the finest available spatial resolution from MODIS were required due to the level of landscape fragmentation. This implies that if MODIS data are utilized for large scale monitoring of disturbances and finer spatial resolution satellite data are used for more detailed mapping on a local scale there is a range of vegetation indices that could be tested.

4 Conclusions

This thesis has demonstrated that coarse spatial resolution satellite data with high temporal resolution can be utilized to monitor insect induced defoliation in near real-time, as well as to map the intra-seasonal dynamics of insect outbreaks. Furthermore, the results have shown that the impact of these insect outbreaks on primary productivity can be quantified with the aid of satellite based remote sensing data and meteorological data by applying LUE models. The following conclusions can be drawn from this thesis:

- Time-series of satellite data can be applied to trace insect disturbances back in time. In addition, there is a potential to develop early warning systems with satellite based remote sensing. Such a system would most likely have detected the outbreak of the invasive Hungarian spruce scale the year before it was detected in the field.
- Insect induced defoliation can be mapped with z-scores of seasonal maximum of a vegetation index. Coarse spatial resolution satellite data do, however, have limitations in fragmented forest landscapes, and disturbance monitoring relying solely on coarse resolution data may underestimate damage, especially if the disturbance history is long. Nevertheless, the high temporal resolution of these coarse spatial resolution images might be required to detect ephemeral insect outbreaks, especially in areas where frequent cloudy may result in an insufficient number of finer resolution images during an outbreak.
- Insect induced defoliation can be monitored in near real-time with high temporal resolution satellite data with the aid of Kalman filtering and CUSUM. The near real-time capabilities can be utilized to develop early warning systems as well as to study the intra-seasonal development of an insect outbreak, and to monitor potential within-season refoliation.
- The impact on primary productivity due to insect outbreaks can be quantified with the aid of LUE models, driven by satellite based remote sensing data and meteorological data, and calibrated with EC data. This enables studies of both the spatial extent of insect disturbances and the impact on primary productivity.

Outlook

This thesis has demonstrated the ability to monitor insect induced defoliation in near real-time with high temporal resolution satellite data. With the recent launch of the Sentinel-2A satellite and the approaching launch of Sentinel-2B, satellite data with both high temporal and high spatial resolution, as well as a wider range of wavelength bands, will be available (Drusch et al. 2012). It would be of major interest to study if the near real-time monitoring method developed in this thesis could be applied to Sentinel-2 data to enable near real-time monitoring of insect disturbances also in more fragmented forest landscapes, and if detection accuracies will be higher. However, before the method can be applied to Sentinel-2 data, the seasonal trajectory of a vegetation index for years without disturbances must be identified. This might be possible to achieve with the seasonal trajectory derived from MODIS data and just a few years with Sentinel-2 data, or by applying data fusion methods (Gao et al. 2006; Zhu et al. 2010) to combine MODIS data with higher spatial resolution data. It would also be interesting to extend and test the near real-time monitoring method to other forest types than the mountain birch forests in this study. The method as such should be possible to apply, but it would be interesting to study how general the settings in the Kalman filter are to other land cover types and over how large regions the same stable season can be applied. It would also be interesting to apply the method to studies of intra-seasonal patterns of insect outbreaks, to see if any spatio-temporal patterns emerge and to study potential causes of these outbreak patterns. Furthermore, it would be useful to have more EC data from insect outbreaks to study how the light use efficiency is influenced by insect defoliation, and hence, enable more accurate calibration of the LUE model for disturbance events. A robust method to find the light use efficiency for outbreaks caused by different insect species would enable wall-to-wall mapping of insect outbreaks caused by different insect species with low uncertainties.

Acknowledgement

Firstly, I want to thank my main supervisor Lars Eklundh for all advice and comments that guided me through my PhD studies. I also thank my co-supervisor Anna Maria Jönsson, and co-authors for all help with analyses and manuscripts: Johan Lindström, Michal Heliasz, Hongxiao Jin, Tuula Kantola, and Päivi Lyytikäinen-Saarenmaa. Thanks to all colleagues at the Department of Physical Geography and Ecosystem Science for creating a friendly atmosphere.

I also want to acknowledge the large number of "participants" that made this study possible. Thanks to all autumnal and winter moths for planning the large outbreak in Abisko in 2012-2013 to provide me with necessary field data. That timing was as important as hatching at budburst. I also send a special thanks to the Hungarian spruce scales that travelled all the way to Sweden to provide me with field data just outside Lund.

Finally, big thanks to my family: my wife Maureen and my son Alfred for all patience when daddy was busy with the thesis. Here you have a bedtime story that will last for many nights......

References

Adelabu, S., Mutanga, O., & Cho, M.A. (2012). A review of remote sensing of insect defoliation and its implications for the detection and mapping of Imbrasia belina defoliation of Mopane Woodland. The African Journal of Plant Science and Biotechnology, 6, 1-13

Allard, V., Ourcival, J.M., Rambal, S., Joffre, R., & Rocheteau, A. (2008). Seasonal and annual variation of carbon exchange in an evergreen Mediterranean forest in southern France. Global Change Biology, 14, 714-725

Ammunét, T., Bylund, H., & Jepsen, J.U. (2015). Northern Geometrids and Climate Change: From Abiotic Factors to Trophic Interactions. In Björkman., C., & Niemelä, P. (Eds.), Climate Change and Insect Pests (pp. 235-247). Boston: CABI

Anees, A., & Aryal, J. (2014). Near-Real Time Detection of Beetle Infestation in Pine Forests Using MODIS Data. Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of, 7, 3713-3723

Asrar, G., Fuchs, M., Kanemasu, E.T., & Hatfield, J.L. (1984). Estimating Absorbed Photosynthetic Radiation and Leaf Area Index from Spectral Reflectance in Wheat1. Agronomy Journal, 76

Aukema, B.H., Carroll, A.L., Zhu, J., Raffa, K.F., Sickley, T.A., & Taylor, S.W. (2006). Landscape level analysis of mountain pine beetle in British Columbia, Canada: spatiotemporal development and spatial synchrony within the present outbreak. Ecography, 29, 427-441

Babst, F., Esper, J., & Parlow, E. (2010). Landsat TM/ETM+ and tree-ring based assessment of spatiotemporal patterns of the autumnal moth (Epirrita autumnata) in northernmost Fennoscandia. Remote Sensing of Environment, 114, 637-646

Baltensweiler, W. (1993). Why the larch bud-moth cycle collapsed in the subalpine larch-cembran pine forests in the year 1990 for the first time since 1850. Oecologia, 94, 62-66

Battisti, A. (2008). Forests and climate change - lessons from insects. IFOREST-BIOGEOSCIENCES AND FORESTRY, 1, 1-5

Ben-Dov, Y., Miller, D.R., & Gibson. G.A.P. (2012). ScaleNet - Database of the Scale Insects of the World. http://www.sel.barc.usda.gov/scalenet/scalnet.htm. (accessed 24-02-2012)

Bonan, G.B. (2008a). Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. Science, 320, 1444-1449

Bonan, G.B. (2008b). Ecological Climatology, 2nd edition. Cambridge, United Kingdom. Cambridge University Press

Brown, M., Black, T.A., Nesic, Z., Foord, V.N., Spittlehouse, D.L., Fredeen, A.L., Grant, N.J., Burton, P.J., & Trofymow, J.A. (2010). Impact of mountain pine beetle on the net ecosystem production of lodgepole pine stands in British Columbia. Agricultural and Forest Meteorology, 150, 254-264

Brown, M.G., Black, T.A., Nesic, Z., Fredeen, A.L., Foord, V.N., Spittlehouse, D.L., Bowler, R., Burton, P.J., Trofymow, J.A., Grant, N.J., & Lessard, D. (2012). The carbon balance of two lodgepole pine stands recovering from mountain pine beetle attack in British Columbia. Agricultural and Forest Meteorology, 153, 82-93

Bylund, H. (1995). Long-term interactions between the autumnal moth and mountain birch: the role of resources, competitors, natural enemies, and weather. PhD-thesis, Swedish University of Agricultural Sciences, Uppsala.

Callaghan, T.V., Bergholm, F., Christensen, T.R., Jonasson, C., Kokfelt, U., & Johansson, M. (2010). A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. Geophysical Research Letters, 37, L14705

Carter, W. (1973). Insects in relation to Plant disease, 2nd edition. John Wiley and Sons, New York

Clark, K.L., Skowronski, N., & Hom, J. (2010). Invasive insects impact forest carbon dynamics. Global Change Biology, 16, 88-101

Cohen, W.B., Yang, Z., & Kennedy, R. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync - Tools for calibration and validation. Remote Sensing of Environment, 114, 2911-2924

Coops, N.C., Gillanders, S.N., Wulder, M.A., Gergel, S.E., Nelson, T., & Goodwin, N.R. (2010). Assessing changes in forest fragmentation following infestation using time series Landsat imagery. Forest Ecology and Management, 259, 2355-2365

Coops, N.C., Johnson, M., Wulder, M.A., & White, J.C. (2006). Assessment of QuickBird high spatial resolution imagery to detect red attack damage due to mountain pine beetle infestation. Remote Sensing of Environment, 103

de Beurs, K.M., & Townsend, P.A. (2008). Estimating the effect of gypsy moth defoliation using MODIS. Remote Sensing of Environment, 112, 3983-3990

Danzig, E., & Kozár, F. (1973). A new species of soft scale, Physokermes inopinatus (Homoptera, Coccoidea) from Hungary. Entomological review, 52, 532-533

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. Remote Sensing of Environment, 120, 25-36

Dymond, C.C., Neilson, E.T., Stinson, G., Porter, K., MacLean, D.A., Gray, D.R., Campagna, M., & Kurz, W.A. (2010). Future Spruce Budworm Outbreak May Create a Carbon Source in Eastern Canadian Forests. Ecosystems, 13, 917-931

Eklundh, L., Jin, H., Schubert, P., Guzinski, R., & Heliasz, M. (2011). An optical sensor network for vegetation phenology monitoring and satellite data calibration. Sensors, 11, 7678-7709

Eklundh, L., Johansson, T., & Solberg, S. (2009). Mapping insect defoliation in Scots pine with MODIS time-series data. Remote Sensing of Environment, 113, 1566-1573

Fawcett, T. (2006). An introduction to ROC analysis. Pattern Recognition Letters, 27, 861-874

Fetykó, K., Kozár, F., & Daróczi, K. (2010). Species list of the scale insects (Hemiptera, Coccoidea) of Romania, with new data. Acta Phytopathologica Hungarica, 45, 291-302

Field, C.B., Randerson, J.T., & Malmström, C.M. (1995). Global net primary production: Combining ecology and remote sensing. Remote Sensing of Environment, 51, 74-88

Franklin, S., Wulder, M., Skakun, R., & Carroll, A. (2003). Mountain pine beetle red attack damage classification using stratified Landsat TM data in British Columbia, Canada. Photogrammetric Engineering and Remote Sensing, 69, 283-288

Fraser, R.H., Abuelgasim, A., & Latifovic, R. (2005). A method for detecting large-scale forest cover change using coarse spatial resolution imagery. Remote Sensing of Environment, 95, 414-427

Gamon, J.A. (2015). Reviews and Syntheses: optical sampling of the flux tower footprint. Biogeosciences, 12, 4509-4523

Gao, F., Masek, J., Schwaller, M., & Hall, F. (2006). On the blending of the landsat and MODIS surface reflectance: Predicting daily landsat surface reflectance. IEEE Transactions on Geoscience and Remote Sensing, 44, 2207-2218

Gertsson, C.-A., & Isacsson, G. (2014). The Hungarian spruce scale, Physokermes inopinatus Danzig & Kozár (Hemiptera: Coccoidea: Coccidae), in Sweden. Acta Zoologica Bulgarica, 6, 83-86

Gitelson, A.A., Kaufman, Y.J., & Merzlyak, M.N. (1996). Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sensing of Environment, 58, 289-298

Goodwin, N.R., Coops, N.C., Wulder, M.A., Gillanders, S., Schroeder, T.A., & Nelson T. (2008). Estimation of insect infestation dynamics using a temporal sequence of Landsat data. Remote Sensing of Environment, 112, 3680-3689

Goodale, C.L., Apps, M.J., Birdsey, R.A., Field, C.B., Heath, L.S., Houghton, R.A., Jenkins, J.C., Kohlmaier, G.H., Kurz, W., Liu, S., Nabuurs, G.-J., Nilsson, S., & Shvidenko, A.Z. (2002). Forest Carbon Sinks In The Northern Hemisphere. Ecological Applications, 12, 891-899

Goodwin, N.R., Coops, N.C., Wulder, M.A., Gillanders, S., Schroeder, T.A., & Nelson, T. (2008). Estimation of insect infestation dynamics using a temporal sequence of Landsat data. Remote Sensing of Environment, 112, 3680-3689

Goward, S.N., & Huemmrich, K.F. (1992). Vegetation canopy PAR absorptance and the normalized difference vegetation index: An assessment using the SAIL model. Remote Sensing of Environment, 39, 119-140

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., & Townshend, J.R.G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. Science, 342, 850-853

Heliasz, M., Johansson, T., Lindroth, A., Mölder, M., Mastepanov, M., Friborg, T., Callaghan, T.V., & Christensen, T.R. (2011). Quantification of C uptake in subarctic birch forest after setback by an extreme insect outbreak. Geophysical Research Letters, 38, L01704

Hicke, J.A., Allen, C.D., Desai, A.R., Dietze, M.C., Hall, R.J., Hogg, E.H., Kashian, D.M., Moore, D., Raffa, K.F., Sturrock, R.N., & Vogelmann, J. (2012). Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Global Change Biology, 18, 7-34

IPCC (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis.Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change[Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Isacsson, G., (2010). PM: Ungersk gransköldlus - sammanställning av kunskapsläget november 2010 [Hungarian spruce scale – state of knowledge in November 2010]. Skogsstyrelsen, 2010-11-25. Uppdaterad 2010-12-01. (Available online: http://www.skogsstyrelsen.se/Global/aga-och-bruka/Skogsbruk/Skador%20p%C3%A5%20skog/%C3%96vriga%20insekter/Ungersk%20gransk%C3%B6ldlus%20PM%20dec%202011.pdf)

Jiang, Z., Huete, A.R., Didan, K., & Miura, T. (2008). Development of a two-band enhanced vegetation index without a blue band. Remote Sensing of Environment, 112, 3833-3845

Jepsen, J.U., Biuw, M., Ims, R.A., Kapari, L., Schott, T., Vindstad, O.P.L., & Hagen, S.B. (2013). Ecosystem impacts of a range expanding forest defoliator at the forest-tundra ecotone. Ecosystems, 16, 561-575

Jepsen, J.U., Hagen, S.B., Høgda, K.A., Ims, R.A., Karlsen, S.R., Tømmervik, H., & Yoccoz, N.G. (2009). Monitoring the spatio-temporal dynamics of geometrid moth outbreaks in birch forest using MODIS-NDVI data. Remote Sensing of Environment, 113, 1939-1947

Jepsen, J.U., Hagen, S.B., Ims, R.A., & Yoccoz, N.G. (2008). Climate change and outbreaks of the geometrids Operophtera brumata and Epirrita autumnata in subarctic birch forest: evidence of a recent outbreak range expansion. Journal of Animal Ecology, 77, 257-264

Johnson, D.M., Bjørnstad, O.N., & Liebhold, A.M. (2004). Landscape geometry and travelling waves in the larch budmoth. Ecology Letters, 7, 967-974

Jones, H.G., & Vaughan, R.A. (2010) Remote sensing of vegetation, Principles, techniques, and applications. Oxford, United Kingdom. Oxford University Press

Jönsson, P., & Eklundh, L. (2002). Seasonality extraction by function fitting to time-series of satellite sensor data. In (pp. 1824-1832). IEEE Transactions of Geoscience and Remote Sensing, 40, No 8

Jönsson, P., & Eklundh, L. (2004). TIMESAT—a program for analyzing time-series of satellite sensor data. Computers and Geosciences, 30, 833-845

Kalman, R.E. (1960). A New Approach to Linear Filtering and Prediction Problems. Journal of Fluids Engineering, 82, 35-45

Karlsen, S., Jepsen, J., Odland, A., Ims, R., & Elvebakk, A. (2013). Outbreaks by canopy-feeding geometrid moth cause state-dependent shifts in understorey plant communities. Oecologia, 173, 859-870

Kaukonen, M., Ruotsalainen, A.L., Wäli, P.R., Männistö, M.K., Setälä, H., Saravesi, K., Huusko, K., & Markkola, A. (2013). Moth herbivory enhances resource turnover in subarctic mountain birch forests? Ecology, 94, 267-272

Kennedy R.E., Yang Z., Cohen W.B. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms. Remote Sensing of Environment, 114, 2897-2910

Kharuk, V., Ranson, K.J., & Fedotova, E.V. (2007). Spatial pattern of Siberian silkmoth outbreak and taiga mortality. Scandinavian Journal of Forest Research, 22, 531-536

Kharuk, V.I., Ranson, K.J., & Im, S.T. (2009). Siberian silkmoth outbreak pattern analysis based on SPOT VEGETATION data. International Journal of Remote Sensing, 30, 2377-2388

Kharuk, V.I., Ranson, K.J., Kozuhovskaya, A.G., Kondakov, Y.P., & Pestunov, I.A. (2004). NOAA/AVHRR satellite detection of Siberian silkmoth outbreaks in eastern Siberia. International Journal of Remote Sensing, 25, 5543-5556

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., & Safranyik, L. (2008a). Mountain pine beetle and forest carbon feedback to climate change. Nature, 452, 987-990

Kurz, W.A., Stinson, G., & Rampley, G. (2008b). Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? Philosophical Transactions of the Royal Society of London B: Biological Sciences, 363, 2259-2268

Lagergren, F., Eklundh, L., Grelle, A., Lundblad, M., Mölder, M., Lankreijer, H., & Lindroth, A. (2005). Net primary production and light use efficiency in a mixed coniferous forest in Sweden. Plant, Cell & Environment, 28, 412-423

Långström, B., Annila, E., Hellqvist, C., Varama, M., & Niemelä, P. (2001). Tree Mortality, Needle Biomass Recovery and Growth Losses in Scots Pine Following Defoliation by Diprion pini (L.) and Subsequent Attack by Tomicus piniperda (L.). Scandinavian Journal of Forest Research, 16, 342-353

Larsson, S. (1989). Stressful Times for the Plant Stress - Insect Performance Hypothesis. Oikos, 56, 277-283

Liebhold, A.M. (2012). Forest pest management in a changing world. International Journal of Pest Management, 58, 289-295

Lillesand, T.M., Kiefer, R.W., & Chipman, J.W. (2015). Remote sensing and image interpretation, Seventh edition. Wiley

LPDAAC, (2016a). MODIS Overview, Land Processes Distributed Active Archive Center. https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table (accessed 25-01-16)

LPDAAC (2016b). Vegetation Indices 16-Day L3 Global 250m, Land Processes Distributed Active Archive Center. https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod13q1 (accessed 29-02-16)

LPDAAC (2016c). Surface Reflectance 8-Day L3 Global 250m, Land Processes Distributed Active Archive Center. https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod09q1 (accessed 09-02-16)

LPDAAC (2016d). Surface Reflectance 8-Day L3 Global 500m, Land Processes Distributed Active Archive Center. https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mod09a1 (accessed 09-02-16)

Lyytikäinen-Saarenmaa, P. (1999). Growth Responses Of Scots Pine (Pinaceae) to Artificial and Sawfly (Hymenoptera: Diprionidae) Defoliation. The Canadian Entomologist, 131, 455-463

Lyytikäinen-Saarenmaa, P., & Tomppo, E. (2002). Impact of sawfly defoliation on growth of Scots pine Pinus sylvestris (Pinaceae) and associated economic losses. Bulletin of entomological research, 92, 137-140

Malmberg, A., Holst, J., & Holst, U. (2008). A real-time assimilation algorithm applied to near-surface ocean wind fields. Environmetrics, 19, 319-330

Marini, L., Lindelöw, Å., Jönsson, A.M., Wulff, S., & Schroeder, L.M. (2013). Population dynamics of the spruce bark beetle: a long-term study. Oikos, 122, 1768-1776

McCallum, I., Franklin, O., Moltchanova, E., Merbold, L., Schmullius, C., Shvidenko, A., Schepaschenko, D., & Fritz, S. (2013). Improved light and temperature responses for light-use-efficiency-based GPP models. Biogeosciences, 10, 6577-6590

McDonald, A.J., Gemmell, F.M., & Lewis, P.E. (1998). Investigation of the Utility of Spectral Vegetation Indices for Determining Information on Coniferous Forests - an overview. Remote Sensing of Environment, 66, 250-272

Medvigy, D., Clark, K.L., Skowronski, N.S., & Schäfer, K.V.R. (2012). Simulated impacts of insect defoliation on forest carbon dynamics. Environmental Research Letters, 7, 045703

Meigs, G.W., Kennedy, R.E., & Cohen, W.B. (2011). A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. Remote Sensing of Environment, 115, 3707-3718

Monteith, J.L. (1972). Solar Radiation and Productivity in Tropical Ecosystems. Journal of Applied Ecology, 9, 747-766

Monteith, J.L., & Moss, C.J. (1977). Climate and the Efficiency of Crop Production in Britain [and Discussion]. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 281, 277-294

Myneni, R.B., & Williams, D.L. (1994). On the relationship between FAPAR and NDVI. Remote Sensing of Environment, 49, 200-211

Nabuurs, G.J., Masera, O., Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W.A., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., & Zhang, X. (2007). Forestry. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

NASA (2016). MODIS, Specifications. http://modis.gsfc.nasa.gov/about/specifications.php (accessed 04-03-16)

Netherer, S., & Schopf, A. (2010). Potential effects of climate change on insect herbivores in European forests—General aspects and the pine processionary moth as specific example. Forest Ecology and Management, 259, 831-838

Neuvonen, S., & Virtanen, T. (2015). Abiotic Factors, Climate Variability and Forest Insect Pests. In Björkman., C., & Niemelä, P. (Eds.), Climate Change and Insect Pests (pp. 235-247). Boston: CABI

Olofsson, P., & Eklundh, L. (2007). Estimation of absorbed PAR across Scandinavia from satellite measurements. Part II: Modeling and evaluating the fractional absorption. Remote Sensing of Environment, 110, 240-251

Page, E.S. (1954). Continuous Inspection Schemes. Biometrika, 41, 100-115

Potter, C.S., Klooster, S., & Brooks, V. (1999). Interannual Variability in Terrestrial Net Primary Production: Exploration of Trends and Controls on Regional to Global Scales. Ecosystems, 2, 36-48

Prince, S.D. (1991). A model of regional primary production for use with coarse resolution satellite data. International Journal of Remote Sensing, 12, 1313-1330

Prince, S.D., & Goward, S.N. (1995). Global Primary Production: A Remote Sensing Approach. Journal of Biogeography, 22, 815-835

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., & Valentini, R. (2005). On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology, 11, 1424-1439

Rouault, G., Candau, J.-N., Lieutier, F., Nageleisen, L.-M., Martin, J.-C., & Warzée, N. (2006). Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. Ann. For. Sci., 63, 613-624

Rouse, J.W., Haas, R.H., Shell, J.A., & Deering, D.W. (1973). Monitoring vegetation systems in the Great Plains with ERTS-1. Third Earth Resources Technology Satellite Symposium, 309-317

Ruimy, A., Saugier, B., & Dedieu, G. (1994). Methodology for the estimation of terrestrial net primary production from remotely sensed data. Journal of Geophysical Research: Atmospheres, 99, 5263-5283

Rullan-Silva, C.D., Olthoff, A.E., Delgado de la Mata, J.A., & Pajares-Alonso, J.A. (2013). Remote Monitoring of Forest Insect Defoliation -A Review. Forest Systems, 22, 377-391

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., & Hashimoto, H. (2004). A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. BioScience, 54, 547-560

Saccess (2011). https://saccess.lantmateriet.se/portal/saccess_se.htm (accessed 29-02-16)

Saravesi, K., Aikio, S., Wäli, P.R., Ruotsalainen, A.L., Kaukonen, M., Huusko, K., Suokas, M., Brown, S.P., Jumpponen, A., & Tuomi, J. (2015). Moth Outbreaks Alter Root-Associated Fungal Communities in Subarctic Mountain Birch Forests. Microbial ecology, 69, 788-797

Schäfer, K.V.R., Clark, K.L., Skowronski, N., & Hamerlynck, E.P. (2010). Impact of insect defoliation on forest carbon balance as assessed with a canopy assimilation model. Global Change Biology, 16, 546-560

Seidl, R., Schelhaas, M.J., Rammer, W., & Verkerk, P.J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage (vol 4, pg 806, 2014). Nature Climate Change, 4, 930-930

Sellers, P. (1987). Canopy reflectance, photosynthesis, and transpiration, II. The role of biophysics in the linearity of their interdependence. Remote Sensing of Environment, 21, 143-183

Skakun, R.S., Wulder, M.A., & Franklin S.E. (2003). Sensitivity of the thematic mapper enhanced wetness difference index to detect mountain pine beetle red-attack damage. Remote Sensing of Environment, 86, 433-443

Spruce, J.P., Sader, S., Ryan, R.E., Smoot, J., Kuper, P., Ross, K., Prados, D., Russell, J., Gasser, G., McKellip, R., & Hargrove, W. (2011). Assessment of MODIS NDVI time series data products for detecting forest defoliation by gypsy moth outbreaks. Remote Sensing of Environment, 115, 427-437

Stange, E.E., & Ayres, M.P. (2001). Climate Change Impacts: Insects. eLS: John Wiley & Sons, Ltd

Stathas, G.J., & Kozár, F. (2010). First record of Physokermes inopinatus Danzig & Kozár 1973 (Hemiptera: Coccidae) in Greece. Hellenic Plant protection Journal, 3, 7-8

Sulla-Menashe, D., Kennedy, R.E., Yang, Z., Braaten, J., Krankina, O.N., & Friedl, M.A. (2014). Detecting forest disturbance in the Pacific Northwest from MODIS time series using temporal segmentation. Remote Sensing of Environment, 151, 114-123

Tan, B., Woodcock, C.E., Hu, J., Zhang, P., Huang, D., Yang, W., Knyazikhin, Y., Myneni, R.B., & Ozdogan, M. (2006). The impact of gridding artifacts on the local spatial properties of MODIS data: Implications for validation, compositing, and band-to-band registration across resolutions. Remote Sensing of Environment, 105, 98-114

Tenow, O. (1972). The outbreaks of Oporinia autumnata Bkh. & Operophthera spp. (Lep., Geometridae) in the Scandinavian mountain chain and northern Finland 1862–1968. Zoologiska Bidrag Från Uppsala, Supplement 2

Tenow, O. (1996). Hazards to a Mountain Birch Forest: Abisko in Perspective. Ecological Bulletins, 45, 104-114

Tenow, O., Nilssen, A.C., Bylund, H., & Hogstad, O. (2007). Waves and synchrony in Epirrita autumnata /Operophtera brumata outbreaks. I. Lagged synchrony: regionally, locally and among species. Journal of Animal Ecology, 76, 258-268

Tenow, O., Nilssen, A.C., Bylund, H., Pettersson, R., Battisti, A., Bohn, U., Caroulle, F., Ciornei, C., Csóka, G., Delb, H., De Prins, W., Glavendekić, M., Gninenko, Y.I., Hrašovec, B., Matošević, D., Meshkova, V., Moraal, L., Netoiu, C., Pajares, J., Rubtsov, V., Tomescu, R., & Utkina, I. (2013). Geometrid outbreak waves travel across Europe. Journal of Animal Ecology, 82, 84-95

Townshend, J.R., Masek, J.G., Huang, C., Vermote, E.F., Gao, F., Channan, S., Sexton, J.O., Feng, M., Narasimhan, R., Kim, D., Song, K., Song, D., Song, X.-P., Noojipady, P., Tan, B., Hansen, M.C., Li, M., & Wolfe, R.E. (2012). Global characterization and monitoring of forest cover using Landsat data: opportunities and challenges. International Journal of Digital Earth, 5, 373-397

Tucker, C.J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment, 8, 127-150

Turner, D.P., Urbanski, S., Bremer, D., Wofsy, S.C., Meyers, T., Gower, S.T., & Gregory, M. (2003). A cross-biome comparison of daily light use efficiency for gross primary production. Global Change Biology, 9, 383-395

Vanhanen, H., Veteli, T.O., Päivinen, S., Kellomäki, S., & Niemelä, P. (2007). Climate change and range shifts in two insect defoliators: Gypsy moth and nun moth-A model study. Silva Fennica, 41, 621-638

Veteli, T.O., Lahtinen, A., Repo, T., Niemelä, P., & Varama, M. (2005). Geographic variation in winter freezing susceptibility in the eggs of the European pine sawfly (Neodiprion sertifer). Agricultural and Forest Entomology, 7, 115-120

Virtanen, T., Neuvonen, S., Nikula, A., Varama, M., & Niemelä, P. (1996). Climate change and the risk of Neodiprion sertifer outbreaks on Scots pine. Silva Fennica, 30, 169-177

Vranjic, J. A. (1997). Effects on host plants. In Ben-Dov, Y., & Hodgson, C. J. (Eds), Soft Scale Insects their Biology, Natural Enemies and Control. Volume 7, Part A (pp. 3-452). Elsevier

Weed, A.S., Ayres, M.P., & Hicke, J.A. (2013). Consequences of climate change for biotic disturbances in North American forests. Ecological Monographs, 83, 441-470

Welch, G., & Bishop, G. (2006). An Introduction to the Kalman Filter. TR 95-041, Department of Computer Science, University of North Carolina at Chapel Hill, NC, USA

Wielgolaski, F.E. (2001). Vegetation sections in northern Fennoscandian mountain birch forests. In F.E. Wielgolaski (Ed.), Nordic Mountain Birch Ecosystem. (pp. 23–46). London: The Parthenon Publishing Group

White, J.C., Wulder, M.A., Brooks, D., Reich, R., & Wheate, R.D. (2005). Detection of red attack stage mountain pine beetle infestation with high spatial resolution satellite imagery. Remote Sensing of Environment, 96, 340-351

Williams, D.W., & Liebhold, A.M. (2000). Spatial synchrony of spruce budworm outbreaks in eastern North America. Ecology, 81, 2753-2766

Wu, C., Munger, J.W., Niu, Z., & Kuang, D. (2010). Comparison of multiple models for estimating gross primary production using MODIS and eddy covariance data in Harvard Forest. Remote Sensing of Environment, 114, 2925-2939

Wulder, M.A., Dymond, C.C., White, J.C., Leckie, D.G., & Carroll, A.L. (2006). Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. Forest Ecology and Management, 221, 27-41

Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R., & Woodcock, C.E. (2012). Opening the archive: How free data has enabled the science and monitoring promise of Landsat. Remote Sensing of Environment, 122, 2-10

Wulder, M.A., White, J.C., Coops, N.C., & Butson, C.R. (2008). Multi-temporal analysis of high spatial resolution imagery for disturbance monitoring. Remote Sensing of Environment, 112, 2729-2740

Wulder, M.A., White, J.C., Loveland, T.R., Woodcock, C.E., Belward, A.S., Cohen, W.B., Fosnight, E.A., Shaw, J., Masek, J.G., & Roy, D.P. (2015). The global Landsat archive: Status, consolidation, and direction. Remote Sensing of Environment, in press

Xiao, X., Zhang, Q., Braswell, B., Urbanski, S., Boles, S., Wofsy, S., Moore, B., & Ojima, D. (2004). Modeling gross primary production of temperate deciduous broadleaf forest using satellite images and climate data. Remote Sensing of Environment, 91, 256-270

Zhu, X., Chen, J., Gao, F., Chen, X., & Masek J.G. (2010). An enhanced spatial and temporal adaptive reflectance fusion model for complex heterogeneous regions. Remote Sensing of Environment, 114, 2610-2623

Zhu, Z., Woodcock, C.E., & Olofsson, P. (2012). Continuous monitoring of forest disturbance using all available Landsat imagery. Remote Sensing of Environment, 122, 75-91