EXPLORATION OF LAND SURFACE TEMPERATURE DIURNAL RANGE AS INDICATOR TO DETECT DEFOLIATION IN FORESTS

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ABSTRACT

Forests provide many important ecosystem services, but forests are changing due to many factors including climate change and pressure from human activities. This is affecting health status of forests, and therefore monitoring forest health status is necessary. As an important indicator of forest health, forest defoliation in canopy plays an important role as thermal inertia in the energy balance between canopy and atmosphere, which can be indicated by diurnal range of Land Surface Temperature (LST). However, the relationship between defoliation and diurnal range of LST should be more clear in stable environments with little other sources of fluctuations.

Defoliation data provided by ICP Forests and LST data provided by Meteosat Second Generation (MSG) are applied in this study. Two methods (plot level analysis and "pile" analysis) of regression analysis are applied to analyze the relationship between defoliation and diurnal range of LST. Factors (altitude, latitude and forest stand) that can influence the stability of environment are introduced in this study as a principle to group the plots, in order to analyze if the relationship between diurnal range of LST and defoliation will be stronger in stable environments. The results have shown that only little percentage of variations of defoliation can be predicted by diurnal range of LST. Although no correlation has been found between average diurnal range of LST and defoliation, suggestions concentrated on improving the study are presented.

Keywords: Defoliation, (diurnal range of) Land Surface Temperature, ecosystem stability, correlation, latitude, altitude, forest stand, regression analysis

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1. INTRODUCTION

Forest provide a wide range of ecological functions including air purification, carbon sequestration and biodiversity preservation, as well as direct benefits including recreation, food and forest products. Developing in forest management (De Groot & Van der Meer, 2010), those ecosystem services make huge contributions to the nature and human society. (De Groot et al., 2010; MEA, 2005; Blanco et al., 2017; Baral et al., 2016).

Forest health, together with the ecosystem services it provides, can be influenced by many factors related to anthropogenic activities, including air pollution at national and regional scales (Percy & Ferretti, 2004), heavy metal contamination and soil acidification (Šebesta et al., 2011), and climate change (Oakes et al., 2015). What's more, anthropogenic activities can interact with climate change. In recent decades, climate change is becoming more active and has shown us how severe it can impact on the functioning of forest ecosystems (Bošel'a et al., 2014). In Boreal and Mediterranean Europe, temperature is expected to increase by up to 5°C by 2100 (Loustau et al., 2005). Air pollutants, which is affecting the health and vitality of forest (Requardt et al., 2007), can be effected by thermal infrared radiation both physically (diffusion and dilution) and chemically (chemical reaction) on ecosystem's response (Serengil et al., 2011). Therefore, monitoring of forest health status is important for scientists (Kopacková et al., 2014).

The amount of foliage in forests canopy is an important variable for evaluating forest health (Solberg et al., 2006). Forest defoliation is a natural or artificial process that usually leads to a loss of foliage. It is a physiological strategy of protection mechanism applied by plants, aiming at a reduction of the possibility of severe problems or mortality under extreme conditions (De et al., 2014). Monitoring the defoliation of forests can be utilized among several forest monitoring parameters to reflect the health of forest (Dobbertin, 2005; Marco et al., 2014). To accurately track the health status of a forest, ideally defoliation should be monitored over a long, preferably uninterrupted period across years to produce forest changes of a time sequence in order to detect the defoliation trend and then to evaluate its consequence.

Although the definition of defoliation is clearly stated, the causes have not been explored comprehensively. Forest defoliation unrelated to the annual cycle can occur when for example suitable conditions exist for forest insects to breed or a trees experience a deficiency of necessary nutrients. Defoliated trees will tend to be dead as they are more likely to be attacked by root pathogens and bark beetles (Houston, 1992). Feeding on leaves, herbivorous insects and pathogens reduce tree growth and can cause extensive defoliation and even mortality after successive years of leave consumption (Townsend et al., 2014). The positive fluctuation of temperature in recent years has increased the living ranges of many forest insects northward, which may intensify forest defoliation in Boreal forests (Wolf et al. 2008; Jepsen et al. 2011). Marco et al. (2014) has shown that tree species such as F. excelsior and Q. petraea that tend to maintain cooler canopies are more able to maintain their evapo-transpiration fluxes and a decrease of foliage is less likely to happen because of a storage of more water in the canopy foliage under an increment of summer (June and July) average temperature. Sometimes the occurrence is because of the drought or the use of chemicals by human. Haemmerli et al. (2008) have found that ozone levels in Switzerland should be considered as an exceptional risk factor of crown defoliation. The recovery process of foliage, tree stem and biodiversity will take a long period, especially after severe defoliation (Långström et al., 1990). Irreversible damage to plant can happen if severe defoliation sustains its occurrence.

Admitted that climate change can trigger forest defoliation, it is still unclear that how the meteorology parameters will react with defoliation. While defoliation happens, thermal infrared radiation (TIR) absorbing area of foliage reduces at the same time. This reduction will cause a decrease of the photosynthesis rate of the forest and an increment of canopy temperature (De et al., 2014). What's more, since defoliation usually comes with a mass loss of canopy which is acting as a thermal resistance at the macro scale, it can be expected that the heat exchange between earth surface and atmosphere will intensify after defoliation happens, which will change present heat fluctuation characteristics. Recently, research has proven that some thermal factors, especially average temperature in April and June can be indicators to forest defoliation in Spain (De et al., 2014). Therefore, a thermal parameter that can indicate forest defoliation should be introduced to this study to evaluate the defoliation status in the forest.

Land Surface Temperature (LST) is an important weather variable which records the temperature of the juncture between the atmosphere and earth surface (Jin & Liang, 2006). LST have reflected most of the natural process on the land surface (Pu et al., 2006). Above all, LST is one of the most important meteorological observation parameters related to the research of the interactions between thermal state of ground based observation target and atmosphere and their energy balance. In the past, LST referred to standard surface-air temperature (Dickinson, 1994) measured by a sheltered thermometer 1.5 to 3.5 m above a flat grassy, well-ventilated surface. With the popularization of satellite remote sensing technology, satellite based LST, regarded as skin temperature of earth surface, is treated as a substitute of the former standard to detect LST by a different platform (Dickinson, 1994).

LST indicate energy balance at Earth's surface and atmosphere on a regional as well as global scale (Khandelwal et al., 2017). The temperature differences between the earth surface and the atmosphere determines the energy exchange flux at their boundary, which can trigger heat convection at the boundary and cause a series of changes in parameters such as air moisture, cloudiness and (potentially) precipitation (Aires et al., 2001; Mannstein, 1987; Sellers et al., 1988, sumit indian paper). LST is determined by the intensity of water exchange between soil surface and the atmosphere (Yuan & Bauer, 2007). Above all, LST is a synthetic parameter that has the capacity of reflecting the dynamic heat exchange reaction between atmosphere and land surface in different time points and space scales (Becker & Li, 1995).

LST has a wide use in detection of vegetation status including water stress, disease and change monitoring studies in a macro scale among other uses (Pinheiro et al., 2006; Bhattacharya et al., 2010; Fall et al., 2010). The earth boundary layer stores heat which delays the heat exchange between earth surface and atmosphere. This delay is termed thermal inertia, which is affected by a number of surface properties, such as the canopy of forest in the forest ecosystem (Hall et al., 1992). Canopy plays the role of thermal resistance and when defoliation happens, a loss of foliage also means a loss of heat. In forests, since upward thermal emission and heat resistance capacity of canopy (thermal inertia) works together to reflect LST, and also due to the effect of convection and heat exchange in land surface, most of the LST records the dynamic thermal balance of the soil surface, vegetation body and vegetation canopy top temperatures in forest (Betts et al., 1996; Qin and Karnieli, 1999; http://land.copernicus.eu/global).

Therefore, it is reasonable to infer that less canopy, which means less capacity in the heat storage, would result in more variability in LST. Studies have been done to reveal how variations in LST would explain the vegetation growth in forests. Gaudio et al. (2016) has analyzed that the diurnal maximum of LST during daytime is lower while diurnal minimum of LST at night is higher in forests than other land uses. This effect was more pronounced in more dense forests than the less dense ones. Such results would be an evidence which can indicate how thermal inertia works in the canopy. A study conducted by Göttsche and Olesen (2001) also proves that dynamic LST are more informative than LST itself while being related to surface characteristics of vegetation structure. An analysis of diurnal range of LST data would be better than LST itself to predict forest defoliation.

However, this relation should be more clear in stable environments with little other sources of fluctuations in LST than in unstable environments. It has been accepted that a stable ecosystem will have more biodiversity, resistance against from changing conditions or fluctuations and recovery capacities than an unstable ecosystem (SCBD, 2009). In the high altitude areas of Northern Hemisphere, higher mountains are prone to happen large scale climatic changes, for example maximum temperatures usually come higher together with low precipitation during summertime, while in the low altitude areas, low maximum temperatures during the rainy season of June and July support the growth of the forest better (Dittmar et al., 2003). Jump et al. (2009) has found that the latitudinal distribution of vegetation also have found similar results related to latitude. Also, fluctuations of LST can also be affected by land surface characteristics, such as vegetation cover and its type and land use cover. So it is reasonable to infer altitude, latitude and forest stand into this study to see how would the relation between average diurnal range of LST and defoliation will react in more stable ecosystems than less stable ones.

Remote sensing method has been widely used in the inventory and management of natural resources. Many satellites with thermal infrared sensors have been launched to derive thermal infrared data including LST. Among different sources of data, satellite based thermal infrared remote sensing images can show meteorological characteristics over a long time period over a large extent, and it is also less time and money consuming. What's more, compared with interpolation of missing records due to sparsity of ground station in ground based observation and airborne remote sensing, satellite remote sensing can generate more accurate and large scale consistent thermal information (Zelenka et al., 1999; Perez et al., 1997; Cheval and Dumitrescu, 2009). Therefore, this study chose satellite-derived LST data as remote sensing data source.

1.1. Research Objective

The first research objective is to test if average diurnal range of LST can indicate forest defoliation. The second research objective is to test if the correlation between the average diurnal range of LST in summertime (July and August) and defoliation is stronger in forests that are more stable in their temperature regime than forests that are less stable in their temperature regime.

1.2. Research Question

The main research questions in this study are:

A) Can diurnal range of LST in summertime (July and August) and forest defoliation be correlated to predict defoliation?

B) Will the correlation (if there has) between average diurnal range of LST in summertime (July and August) and defoliation be stronger in forests that are more stable in their temperature regime than forests that are less stable in their temperature regime?

The specific research questions are:

a)Is this correlation (if there has) stronger in conifer forests compared with broad-leave forests?
b)Is this correlation stronger in Southern European forests compared with Northern European forests?
c)Is this correlation stronger in low altitude forests than high altitude forests?

1. 3. Hypothesis

The main hypotheses in this study are:
A) H1: Diurnal range of LST in summertime (July and August) and forest defoliation can be correlated for defoliation prediction.
B) H1: The correlation between average diurnal range of LST in summertime (July and August) and defoliation is stronger in forests that are more stable in their temperature regime than forests that are less stable in their temperature regime.

The specific hypotheses are:
a)H1: The correlation of LST diurnal range and defoliation will be stronger in conifer forests than broad-leave forests during summertime.
b)H1: The correlation of LST diurnal range and defoliation will be stronger in low altitude forests than high altitude ones.
c)H1: The correlation of LST diurnal range and defoliation will be stronger in Southern European forests than Northern European forests.

1. 4. Research Approach

In Europe, visual field assessment of defoliation as a standard method of describing the vitality of forests has been popularly accepted (UNECE, 1994). In this study, defoliation data of trees is collected in the field. Geographic coordinates of forest inventory plots are used to extract daily time series of LST from satellite. These diurnal range were determined in a pre-processing step of the LST data set. After the extraction of defoliation and LST diurnal range subdataset, linear regression analysis was used to analyze the relationship between defoliation and LST diurnal range. Comparisons are made of correlations of different subsets of the data sets, divided according to latitude, altitude and forest stand.

2. MATERIAL AND METHOD

This chapter presents how ground and remote sensing data were collected and processed together with mapping of the study area, which has described its geographical characteristics. The research methods mentioned in this study are also introduced.

2. 1. Ground Data Source

2. 1. 1. Defoliation data

As one of the most important parameters for this study, forest defoliation has been monitored annually by International Cooperative Program on Assessment and Monitoring of Air Pollution Effects on Forests (also ICP Forests) operating under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Trans-boundary Air Pollution (CLRTAP) since 1986. The establishment of ICP Forests is in response to scientific requirement and a growing political concern over extensive forest damage observed in Europe from early 1980s. ICP Forests is chaired by Germany from the beginning on. The number of participating countries has grown to 42 countries including Canada and United States of America in 2015, rendering ICP Forests one of the largest bio-monitoring networks all over the world. The involved countries are obliged to submit their monitoring data for validation, storage and analysis.

Under the ICP Forests program, the forest condition in Europe is monitored periodically in a harmonized monitoring approach at two levels of detail. For the purpose of damage assessment Level I monitoring consists of a general inventory of crown condition based on more than 5000 plots, 100000 trees on a 16 x 16 km grid across Europe according to the ICP Forests Manual (Eichhorn et al., 2010). Level II, named as "Program for Intensive and Continuous Motoring of Forest Ecosystems", was established in 1994 and consists of more detailed observations on around 500 plots aimed to clarify cause and effect of defoliation in addition to the large scale Level I monitoring (www.icp-forests.net). The plots of ICP Forests cover a wide and representative part of European forests. This well developed monitoring system is suitable for providing information on several indicators for sustainable forest management.

Level II sites are large enough, placed in well-designed homogeneous forest areas without a predefined shape and with a minimum size of 0.25 ha. However, plots within the Level II sites are areas of defined shape and surrounded by a buffer zone. The buffer zone ensures the plot is not influenced by paths, roads and other human activities. Therefore, it must be large enough to fulfill this goal. Different from the plots, buffer zones do not have a predefined shape and size.

Its establishment depends on local conditions. Level II plot and buffer zone together have constituted the Level II site (ICP Forests Manual Part II).

Since 30 years ago, the ICP Forests project has monitored tree crown defoliation monitoring due to a lack of information of foliage loss linked to the heavy atmosphere pollution and its deposition. Annually, the trees in more than 5000 Level I plots and 500 Level II plots are monitored and assessed to evaluate their condition. A concept that tree crowns are reflecting overall tree health and may thus predict the ability of trees to survive and grow (Tkacz et al., 2013) is the base of this monitoring. The observation to the tree is by optical ways from the ground in order not to be destructive to the tree itself. Defoliation is visually assessed in steps of 5% (Table 1) relative to what the canopy condition would be of a healthy tree in that site. This is the only available format of defoliation recording in ICP Forests monitoring reports. A tree with >95% and <100% defoliation is coded as 99%. Defoliation values were estimated by comparing to a reference photo of a standard fully-foliated reference tree by the forest investigation officers (Ferretti et al., 1999). Then defoliation values are categorized into 5 levels to evaluate the health state of the forests in the plots (Table 2). All raw data from field will be checked by participating countries before the online submission to ICP Forests.

Table 1. Defoliation code

Defoliation code	Needle/leaf loss
0	0
5	>0~5%
10	>5~10%
…	…
95	>90~95%
99	>95~<100%
100	100%

Table 2. Defoliation levels

Defoliation level	Needle/leaf loss	Degree of defoliation
0	Up to 10%	None
1	>10%~25%	Slight (warning stage)
2	>25%~60%	Moderate
3	>60%~<100%	Severe
4	100%	Dead

The field data in this study comes from ICP Forests. ICP Forests provides the Level II inventory results every year with a proper statistical way. All the measurements of the trees are done inside the boundaries of the plots. The defoliation data from 2009 to 2015 is used in this study. Every sampling plot contains around 40 trees on average. During the Level II inventory, annual tree related data is reported by tree, including its ID, plot information (country and plot number), location of the plot (longitude and latitude), altitude, species code, defoliation code, identified damage causes and date of observation besides defoliation. An example record is presented in Table 3:

Table 3. A typical record in field inventory sheet

survey_year	code_country*	code_plot	Latitude**	longitude	code_altitude***	tree_number	code_tree_species****	code_defoliation
2009	11	25	383111	-3753	16	1	125	20

*: Member state in which the plot is assessed

**:Latitude and longitude are recorded in [degrees, minutes, seconds], WGS-84

***:Elevation above sea level is measured in 50 m steps

****:Species of the observed tree

From 2009 to 2015, 183235 inventory records in Level II plots were investigated to formulate the defoliation data set.

2. 1. 2. Preprocess of defoliation data

A. Calculation of mean defoliation

Mean defoliation of all the trees in a plot of the same year was calculated, giving and estimated annual forest defoliation level by plot. The result of this calculation is recorded in the following table.

Table 4. Mean plot defoliation

Plot ID	2009	2010	2011	2012	2013	2014	2015
1							
2							
…							
593							

B. Grouping

a) Altitude

The 593 plots are distributed from sea level to an elevation of 2050m. Four groups of altitude are formulated to address the research question "will the correlation (if there has) between average diurnal range of LST in summertime (July and August) and defoliation be stronger in low altitude forests than high altitude forests" (Table 5). More than 95% of the plots are distributed in low altitude zones lower than 1500m, while only 21 plots are distributed in higher altitude zones.

Table 5. Grouping of plots by altitude

Altitude(m)	Number of Plots	Percentage
0-500	378	63.74%
500-1000	142	23.95%
1000-1500	52	8.77%
1500-2050	21	3.54%
Total	593	100%

b) Latitude

The 593 plots ranged from 28.13°N to 69.58°N among the whole Europe. Four groups of latitude are formulated to solve the research question "will the correlation (if there has) between average diurnal range of LST in summertime (July and August) and defoliation be stronger in Southern forests than Northern forests" (Table 6). More than 90% of the plots are distributed in mid latitude zones from 40°N to 60°N, while only 51 plots are to the south of 40°N or to the north of 60°N.

Table 6. Grouping of plots by latitude

Latitude	Number of Plots	Percentage
~40°N	25	4.22%
40°N~50°N	294	49.58%
50°N~60°N	248	41.82%
60°N~	26	4.38%
Total	593	100%

c) Forest stand

There are 79 species of trees growing in these 593 plots. Forest were categorized as broad-leave, conifer and mixed forests based on the dominance of the tree species in the forests to solve the research question of "will the correlation (if there has) between average diurnal range of LST in summertime (July and August) and defoliation be stronger in conifer forests than broad-leave forests". A threshold of 80% was used. When more than 80% of the trees in a plot was conifer, it would be considered as a conifers forest, and when more than 80% was broad-leave, it would be considered as broad-leaves forest, and all other plots were categorized as mixed forests. Because of the data ICP Forests has provided, broad-leave forests are sued as deciduous forests while conifer forests are sued as evergreen forests. Broad-leave forests take 36.59% and conifer forests take 59.70% of all the inventory plots. 22 plots are mixed forests (Table 7).

Table 7. Grouping of plots by forest stand

Species	Number of Plots	Percentage
Broad-leaves	217	36.59%
Conifers	354	59.70%
Mixed	22	3.71%
Total	593	100%

2. 2. Location

The study area is located in 593 Level II plots in Europe (between latitudes 28°7'32" N and 69°34'59" N, longitudes 17°17'58" W and 33°3' E) where have a consistence records of forest inventory by ICP Forests of 6 years (2009 to 2015). The distribution of the Level II plots is shown in the map below.

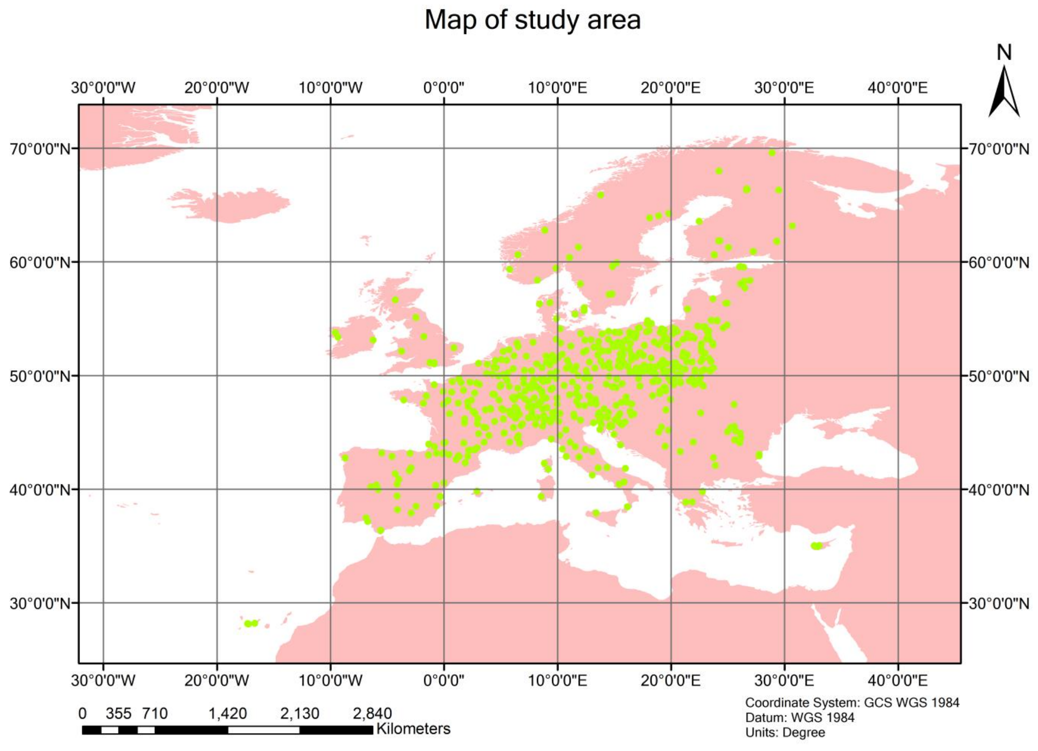


Figure 1. Study area

Mean defoliation, mean LST and mean LST diurnal range are shown in Figure 2 and Table 8, 9 and 10. It can be observed from Table 8 and Figure 2 that most of the plots is suffering slight and moderate defoliation. Very few plots are suffering severe defoliation. Table 9 and Figure 2 indicate that mean LST of most of the plots is around 10°C to 30°C during July and August. Very few plots have hot summers with a mean LST of more than 30°C. Table 10 and Figure 2 shows that the average diurnal range of LST. The same as mean LST, the LST diurnal ranges in most of the plots are around 10°C to 30°C, and very few plots can be over 30°C.

Table 8. Summary of mean plot defoliation

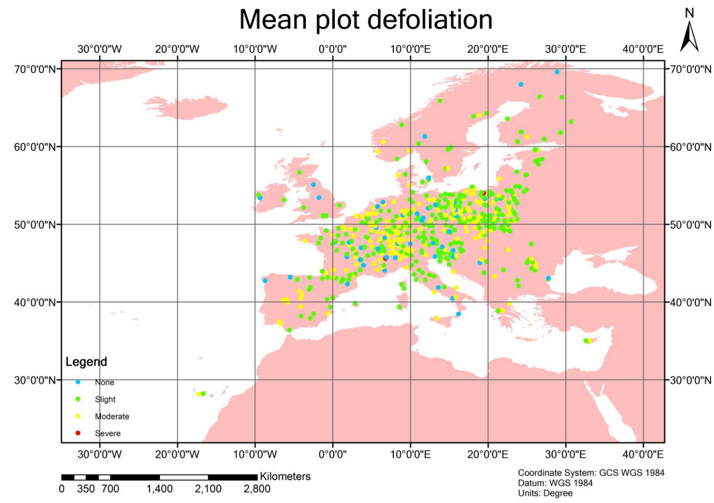
Degree of defoliation	Number of plots	Percentage
None	50	8.43%
Slight	339	57.17%
Moderate	202	34.06%
Severe	2	0.34%
Total	593	100%

Table 9. Summary of mean plot LST

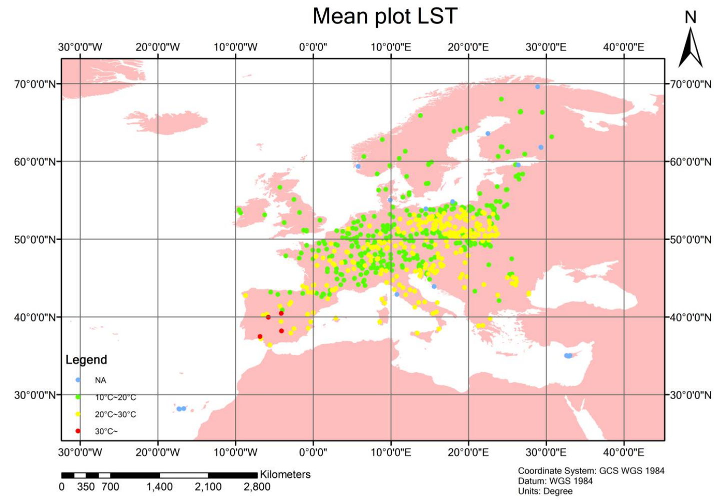
Temperature (°C)	Number of Plots	Percentage
NA	19	3.20%
10~20	322	54.30%
20~30	248	41.82%
30~	4	0.67%
Total	593	100%

Table 10. Summary of mean plot LST diurnal range

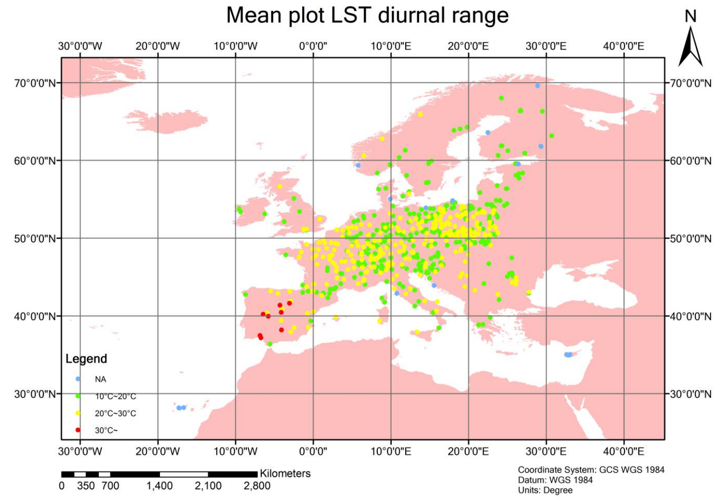
Temperature (°C)	Number of Plots	Percentage
NA	19	3.20%
10~20	299	50.42%
20~30	267	45.03%
30~	8	1.35%
Total	593	100%



a)



b)



c)

Figure 2. Mean plot defoliation, LST and LST diurnal range of the study area

2. 3. Remote Sensing Data Source

2. 3. 1. Meteosat second generation (MSG)

To combine with the defoliation data investigated in Level II plots by ICP Forests, geo-stationary satellites have higher temporal resolution because it keeps relatively static to the earth, which means it can provide continuous time series of LST diurnal range in pixels. Although compared with other satellite based sensors which has a high spatial resolution, including Moderate Resolution Imaging Spectro-radiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), Advanced Along Track Scanning Radiometer (ASTER) and other sensors, geo-stationary sensors provided the best frequency of the LST diurnal range data. In this study, Meteosat Second Generation (MSG) operated by European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) under the Meteosat Transition Program (MTP) were chosen to be the data sources to get time series of LST diurnal range because it can provide LST in high temporal resolution of near real-time (http://www.eumetsat.int). The MSG project is contained by 4 satellites (MSG-8, MSG-9, MSG-10, MSG-11). The operation of MSG was started on January 2004. It was aimed to the requirement of providing numerical weather information also a prediction of extreme dangerous weather phenomena of Europe, Africa and parts of the Atlantic and Indian Ocean every 15 minutes, which has guaranteed a high temporal resolution of remote sensing data. As a geo-stationary satellite locating at an altitude of 36000 km, MSG can scan the whole Europe in 5 minutes. Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensor is the main instrument in MSG satellites. It was applied to provide visible and infrared images of the Earth's surface and atmosphere in 12 channels. Also focusing on climate studies, Geostationary Earth Radiation Budget (GERB) is the new instrument carried by MSG. It measures Earth heat radiation originating from the Sun. It helps the studies of assessment that if the Earth is warming up at present. The nadir spatial resolution for high resolution visible channels are 1 km and for infrared channels are 3 km. More information of channels in MSG is provided in Table 11. MSG will service until 2019 or later.

Table 11. MSG Channels SEVERI

Channel No.	Channel Wavelength (10^{-6}m)	Channel Type		Nadir spatial resolution (km)	Description
1	0.6	Solar		3 by 3	Cloud detection and tracking
2	0.8				Recognition of surface structure
3	1.6				Discriminate between ice and water clouds, cloud over snow and ice
4	3.9	Infrared	Sun and Earth radiation		Detection of low cloud and fog detection, forest fires, cloud phases and cirrus clouds at day and night
					Sea and land surface temperature, urban heat island at night
					Cloud up structures and sunlight at daytime
5	6.2		Thermal Earth radiation		Water vapor channels
6	7.3				Identification of high level of WV and dry areas
7	8.7				Indicative for thin cirrus clouds
					Supports discrimination between ice and water clouds
8	9.7				O_3
9	10.8				Split-window channels
10	12.0				Sea, land surface and cloud-top temperatures
11	13.4				CO_2
12	0.3-0.7	High resolution visible		1 by 1	Optical remote sensing

2. 3. 2. Preprocess of LST data

The extraction of the remote sensing data is done with the "MSG Toolbox" developed by VITO NV as contribution to the LSA-SAF. It has integrated a set of functions to help with the processing and analysis of Earth Observation products that are operationally produced and disseminated by LSA-SAF, as part of the EUMETSAT SAF network. Its main functions include daily and n-day temporal composition, spatial subsetting and remapping while combining LSA SAF regions and filtering on provided product quality layers.

To project the LST raw raster images, WGS-84 coordinate system was added to those images first to ensure the harmony with defoliation data. Then in MSG Toolbox, Euro was selected to be the region where the extraction of time series of LST is done. The longitude and latitude mentioned in study area part was applied to customize the study area.

Since the aim of this study is to detect correlation between average diurnal range of LST and defoliation then test if that correlation would be stronger in stable forests than less stable forests in their temperature regime, the observations of LST being collected every 15 minutes must be converted into diurnal ranges in order that we can analyze the diurnal characteristics of LST (maximum, minimum and range). Also, there are missing data in LST data set, a sensitivity analysis of determining how much data within a day would be allowed to still be regarded as a valid data set should be done. Several scenarios concentrating on "how large the gap is allowed to be" and "how many valid observations remain for each year" were established while determining the maximum consecutive gaps.

Scenario A: Maximum consecutive gap=13% (maximum consecutive gap=3 hours)
Scenario B: Maximum consecutive gap=8% (maximum consecutive gap=2 hours)
Scenario C: Maximum consecutive gap=4% (maximum consecutive gap=1 hour)

2. 4. Method

2. 4. 1. Regression analysis

Regression analysis is an empirical approach to analyze and model the relationship between dependent and independent continuous variables (Cohen et al., 2003). It has been commonly used in defoliation studies (Nevalainen & Tokola, 2002). In this study, linear regression is used to calculate the correlation coefficients between defoliation values and LST diurnal range values of the 593 plots in 7 years (from 2009 to 2015). P-value is used to evaluate whether the correlation is significantly different from H0 and coefficient of determination (R^2) is utilized to evaluate the significance of linear models. The strength and direction between defoliation values and LST diurnal range values are defined by correlation coefficient. R^2 is expected to indicate the proportion of the LST diurnal range values that is predictable from the defoliation values. With the defoliation and LST diurnal range model, the defoliation values are expected to be predicted from the average LST diurnal range values.

2. 4. 2. Analysis strategies

Two methods are followed to discover the relations of LST diurnal range and defoliation and to analyze whether these relations are significant. The first method (called method A) consisted of correlating the defoliation values and LST diurnal range values plot by plot. So method A resulted in 593 records of correlation results theoretically. The second method (called method B) combine all pairs of the defoliation values and LST diurnal range values as independent observations into one big data set. Then a regression analysis between these two variables in that data set was analyzed. Different from method A, method B resulted in one correlation result. After the overall correlation result were calculated and evaluated, several subsets based on the grouping of altitude, latitude and forest stand of defoliation values and LST diurnal range were made to relate with each other to prove the hypotheses. For all models above, R^2 were used to indicate the percentage of defoliation that can be explained from LST diurnal range observations.

3. RESULT

This chapter is structured in three sections. Firstly, the characteristics of the spatial and field data and results of the processing steps are presented. The results of the processing steps shape the selection of the second section where the data is grouped in classes by different attributes. Lastly, the regression analysis results for these different groups are presented.

3. 1. Data Collection

3. 1. 1. LST diurnal range data extraction result

a) Summary of LST image data

A summary of LST data was done after its extraction. The results from Table 12 shows that the amount of satellite images is enough to guarantee the following study. Few images are lost because of the sensor problem.

b) Scenario determination

In Section 2.3.2 the scenarios to determine the maximum consecutive gaps were introduced. In this study scenario A of 13% maximum consecutive gap (also 3 hours) in LST was selected to apply the extraction because this scenario can keep the most amount of LST images than the other two scenarios without too much concern of data consistency compared to 4 and more hours and more maximum consecutive gaps, which is a balance between data amount and data consistency. Then the LST maximum and LST minimum were extracted in R statistics. A subtracting between maximum and minimum of diurnal LST was done to develop the LST diurnal range. Finally a data set of LST diurnal range of 593 plots in 7 years is established. The data loss in Scenario 3 is presented in Table 12. Only in few plots LST records are not extracted because of consecutive cloud problems there.

c) Summary of diurnal LST range data

Although the images and the available plots are enough, only around 26% of the diurnal range of LST data is available because of serious accidental cloud problems (Table 12).

Table 12. LST diurnal range extraction result

Year	**Days**	**Image amount**	**Available image amount**	**Image loss**	**Image loss rate**	**Available plot amount**	**Plot loss**	**Plot amount**	**Plot loss rate**	**Data amount**	**Available data amount**	**Data loss**	**Available Data rate**
2009	62	5952	5838	114	1.92%	572	21	593	3.54%	36766	9462	27304	25.74%
2010	62	5952	5832	120	2.02%	574	19	593	3.20%	36766	9324	27442	25.36%
2011	62	5952	5816	136	2.28%	568	25	593	4.21%	36766	8630	28136	23.47%
2012	62	5952	5657	295	4.96%	574	19	593	3.20%	36766	11201	25565	30.47%
2013	62	5952	5909	43	0.72%	570	23	593	3.88%	36766	11594	25172	31.53%
2014	62	5952	5939	13	0.22%	568	25	593	4.21%	36766	5773	30993	15.70%
2015	62	5952	5904	48	0.81%	569	24	593	4.05%	36766	10963	25803	29.82%
Total	434	41664	40895	769	1.85%	3988	163	4151	3.93%	257362	66947	190415	26.01%

3. 1. 2. General data collection and summary

Forest inventory data from ICP Forests and LST data from MSG satellite are acquired from data collection part. The number of plots that are reported on for Level II plots each year varies in the ICP Forests database (Table 13), causing that not for all plots in the database a complete time series is available. The reason some plots are missing comes from a difference in forest inventory policies among countries and between years. After a union calculation to those plots, 593 plots were chosen to the next step of LST extraction. Then in general, the mean defoliation is increasing from around 20% to nearly 30% in 7 years.

Table 13. Summary of field data and satellite data

Year	2009	2010	2011	2012	2013	2014	2015
Number of Level II Plots	555	424	381	496	508	499	143*
Mean defoliation (%)	20.9	21.21	22.78	23.51	23.35	23.19	28.03
Standard deviation of defoliation (%)	9.82	10.84	10.7	9.83	9.63	9.04	7.49
Mean LST range (°C)	19.81	19.93	19.79	20.83	19.32	18.76	21.22
Standard deviation of LST range (°C)	3.27	2.82	3.12	3.21	2.83	2.85	3.4
Minimum of LST range (°C)	10.25	9.84	9.21	9.5	10.42	11.24	11.14
Maximum of LST range (°C)	36.31	33.44	33.71	35.95	33.98	34.28	34.93

*: ICP Forests changes Level II inventory plots from 2015. 143 plots are remained in the forest inventory of next years.

3. 2. Grouping Strategies

Observations were grouped to altitude, latitude or forest stand characteristics, and then analyzed accordingly. The group sizes and general characteristics are also described shortly in this section.

3. 2. 1. Altitude

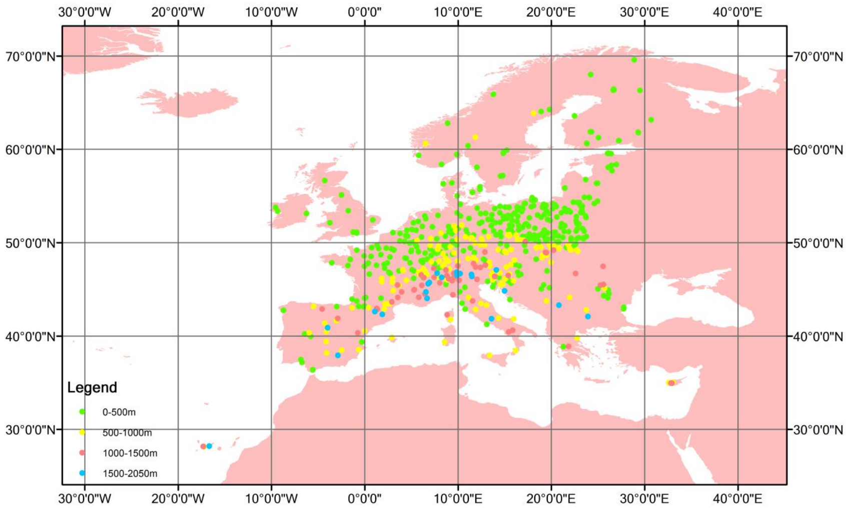
A forest altitude map (Figure 3.a) is made to show the distribution of different altitude of ICP Forests Level II plots. Most of the plots (more than 75%) fell in the range of 0-1000 m, although ether were a number of plots that were at altitudes above 1500m.

3. 2. 2. Latitude

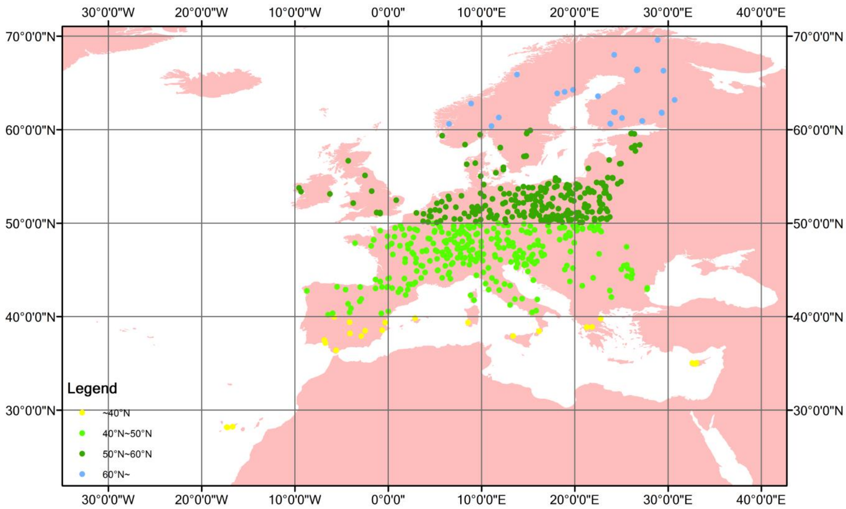
A forest latitude map (Figure 3.b) is made to show the distribution of different latitude of ICP Forests Level II plots. Most of the plots are distributed in an area from 40°N to 60°N. Although 8.6% of the plots lie in the northern (more than 60°N) or southern (less than 40°N) areas.

3. 2. 3. Forest stand

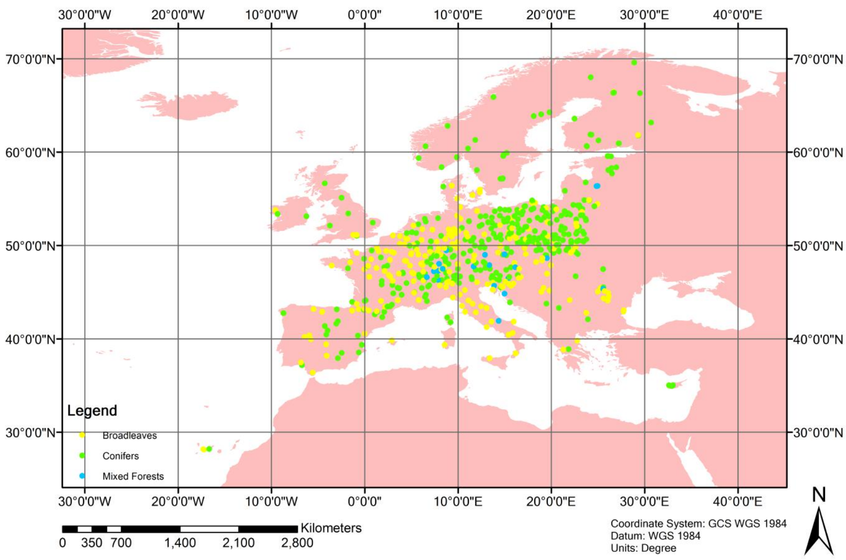
A forest stand map (Figure 3.c) is made to show the distribution of different kinds of forests. Broad-leave forests are mainly distributed in western Europe while conifers take the domain in eastern Europe. Most of the mixed forest are among the borders of broad-leave and conifer forests.



a) Forest altitude distribution



b) Forest latitude distribution



c)Forest stand distribution

Figure 3. Grouping of the forests

3. 3. Regression analysis and result

To compare defoliation and LST diurnal range, regression test was used to test if there were statistically significant correlations in defoliation and LST diurnal range by different grouping strategies. Two ways of regression analysis are conducted in this study as introduced in the last chapter.

3. 3. 1. Method A

Firstly, the relation was analyzed plot by plot. Figure 4 shows the p-value distribution and Figure 6 shows the amount of available plots whose p-value are smaller than 0.05 of method A. Figure 5. a, b and c have shown scatter plots between p-values and the three proxies to reveal how the significance of fitted correlations can not be explained by the factors we thought which can determine the stability of the temperature regime of an ecosystem. For example, according to the hypotheses, a positive correlation between latitude and p-value would be expected because in more constant temperature environments (southern plots), a better correlation will be expected.

For 85 plots no correlation (and consequently a p-value) could be calculated because of their consecutive gaps (two or larger than two missing values in seven) of sequence time series defoliation or LST diurnal range. Finally, the defoliation values and average LST diurnal range values can be significantly correlated only in 24 plots from 508 plots where have at least three effective combinations of average LST diurnal range-defoliation in 7 pairs rather than all 593 Level II plots in method A. Because we can not prove the research hypotheses from the distribution of those 24 plots where the average diurnal range and defoliation are significantly correlated, there is no need to do the rest regression analysis in plot level.

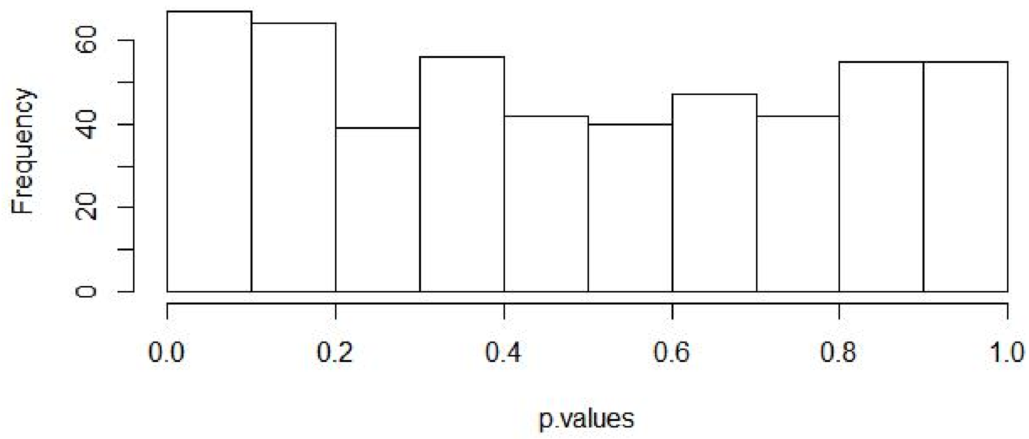
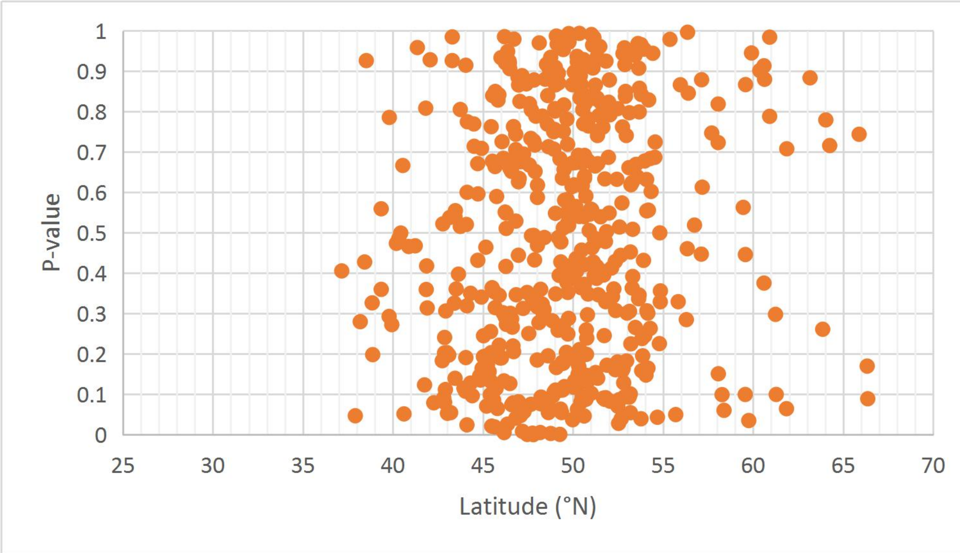
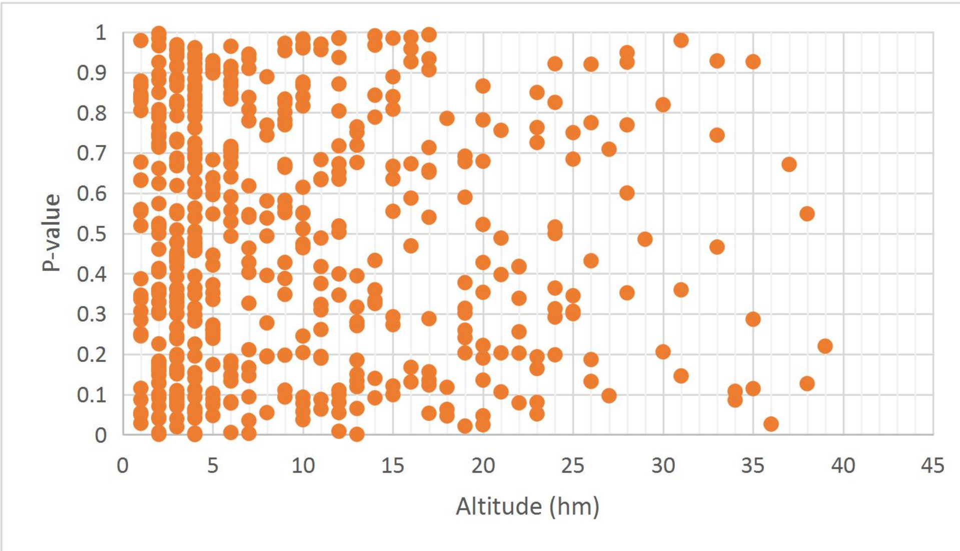


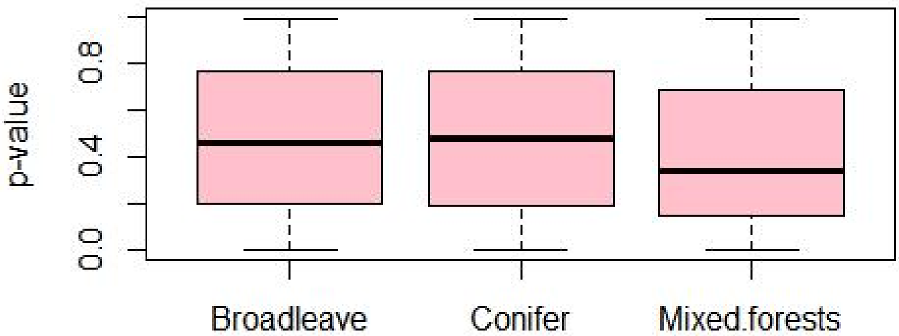
Figure 4. P-value distribution histogram, method A.



a) P-value-latitude scatter plot



b) P-value-altitude scatter plot



c) P-value-forest stand box plot

Figure 5. P-values and proxies

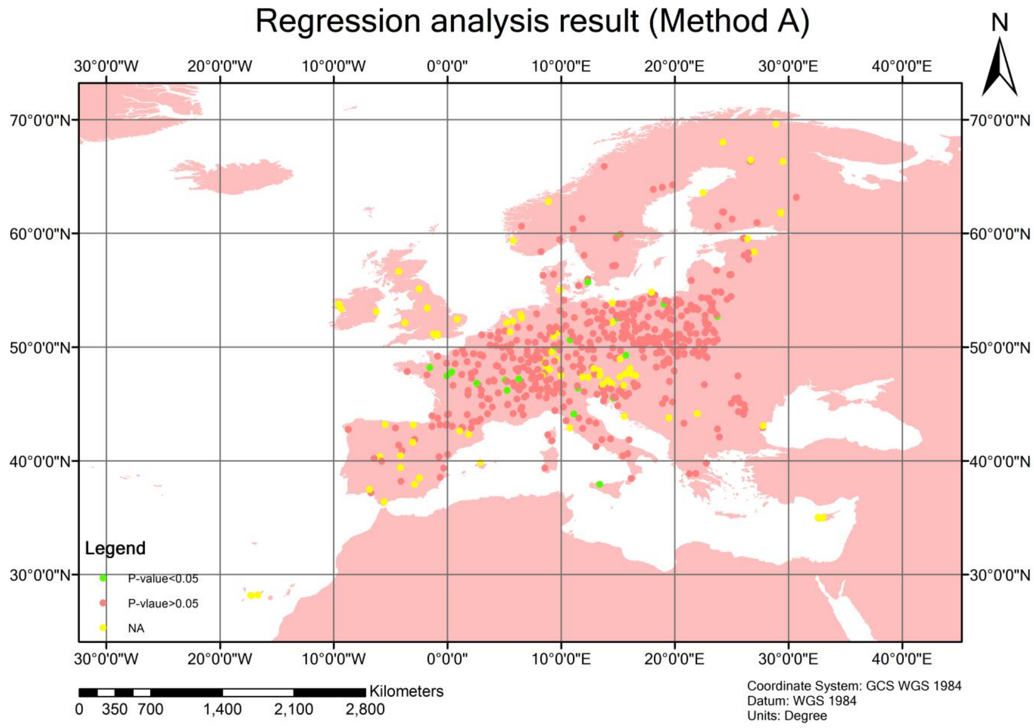
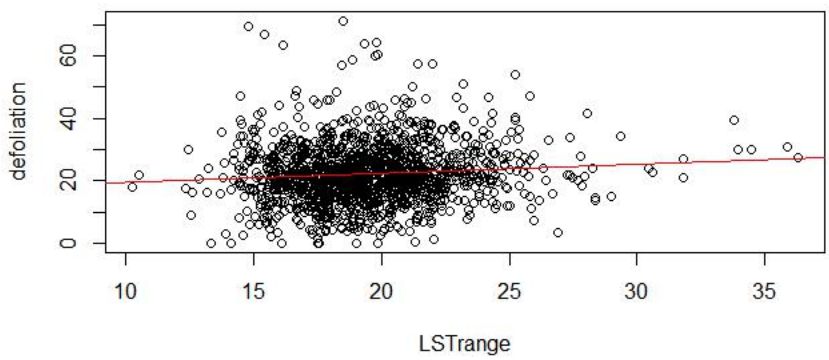


Figure 6. Regression analysis result, method A.

3. 3. 2. Method B

Secondly, the relationship was analyzed by combining all observations as individual records onto one data set. The regression result of method B is shown in Figure 7.



P-value=0.0027, R^2=0.0060, Correlation=0.0776, Slope=0.0026

Figure 7. Regression result between LST diurnal range and defoliation, method B.

From this result we can find that although there shows a positive correlation while p-value is smaller than 0.05, which means there exists a significant correlation between LST diurnal range and defoliation, however, this only indicates only 0.6% of the variance of defoliation can be explained by LST diurnal range.

a) Altitude

Table 14, Figure 8 and 9 shows the result of regression analysis grouped by altitude. The result shows only little percentage of the variance of defoliation can be explained by LST diurnal range by grouping with altitude. There were significant correlations found among three groups. In the plots that are below an altitude of 500m elevation and over the altitude of 1500m elevation, the LST diurnal range has a positive correlation with defoliation ($p<0.05$), but plots between the altitude of 500m and 1500m elevation, the LST diurnal range may not have a correlation with defoliation ($p>0.05$). Based on this result, we conclude that "there is a significant positive correlation between average LST diurnal range and defoliation at higher altitude plots (1500-2050m) than lower altitude plots (0-500m)", which is contrary to the hypotheses, as higher altitudes are expected to be less stable in terms of temperature regime. So here we would actually expect weaker correlations.

Table 14 Result of regression analysis, grouped by altitude, method B.

Altitude (m)	P-value	Slope	Correlation	R^2
0-500	0.0001	0.4175	0.1211	0.0147
500-1000	0.9705	0.0050	0.0019	0.0000
1000-1500	0.0509	0.4803	0.1576	0.0248
1500-2050	0.0040	1.5937	0.3696	0.1366

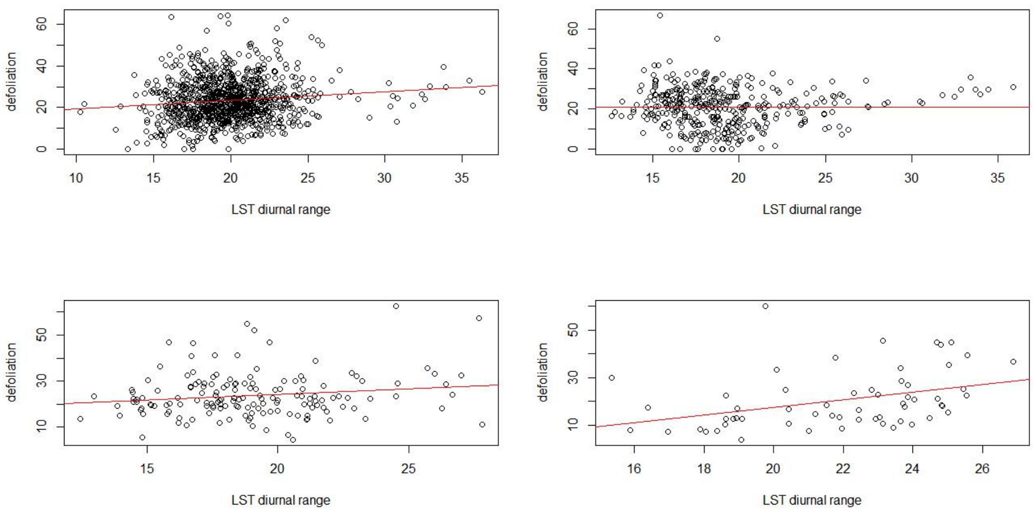


Figure 8. Scatter plot of regression analysis, grouped by altitude, method B (Top left=0-500m, top right =500-1000m, below left=1000-1500m, below right=1500-2050m).

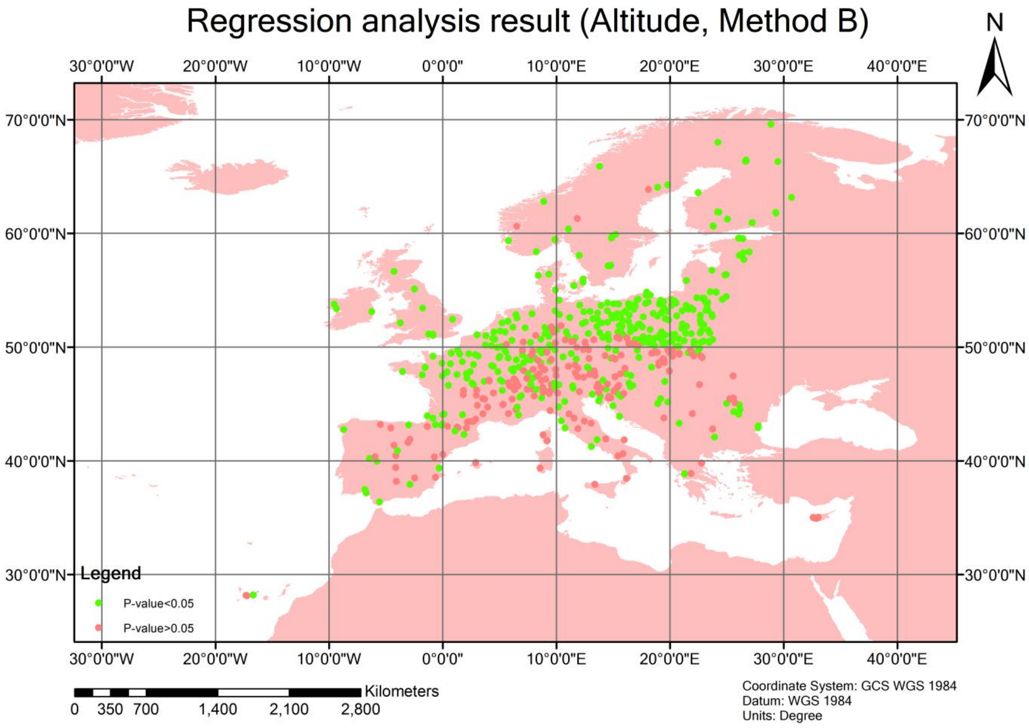


Figure 9. Map of regression analysis, grouped by altitude, method B.

b) Latitude

Table 15, Figure 10 and 11 shows the result of regression analysis grouped by latitude. The result shows only a little percentage of the variance of defoliation can be explained by LST diurnal range by grouping with latitude. There were significant correlations found among four groups. In the plots where are to the south of 40°N line and between 50°N line and 60°N line, the LST diurnal range has a positive correlation with defoliation ($p<0.05$), when comes to the plots which are to the north of 60°N line and between 40°N line and 50°N line, the LST diurnal range may not have a correlation with defoliation ($p>0.05$). Based on this result, we conclude that "there is a significant positive correlation between average LST diurnal range and defoliation at lower latitude plots (to the south of 40°N) than higher latitude plots (50°N~60°N)", which is the same as the hypotheses.

Table 15. Result of regression analysis, grouped by latitude, method B.

Latitude	P-value	Slope	Correlation	R^2
~40°N	0.00005483	0.6215	0.5292491	0.2801
40°N~50°N	0.6509	0.06041	0.01562614	0.0002442
50°N~60°N	0.00009846	0.6003	0.1595037	0.02544
60°N~	0.1880	-0.9576	-0.1912581	0.03658

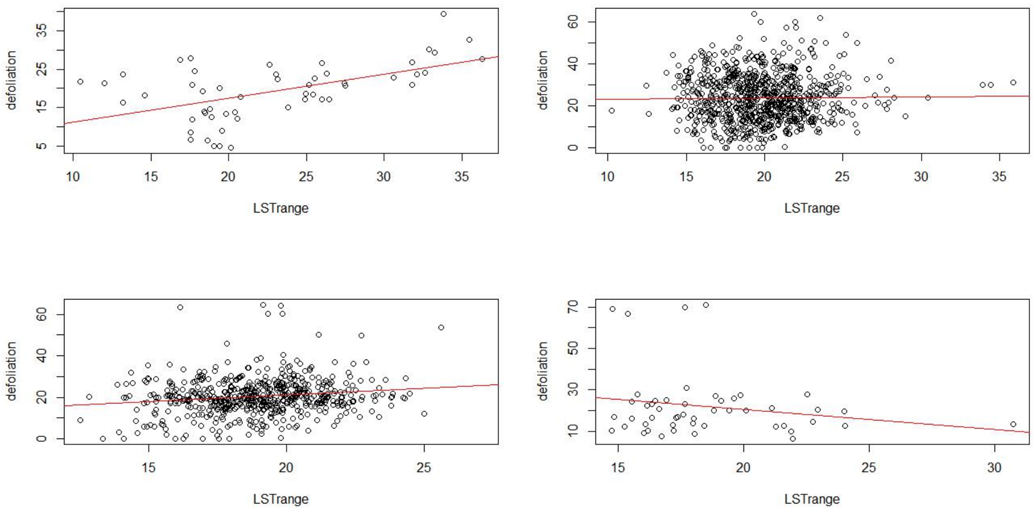


Figure 10. Scatter plot of regression analysis, grouped by latitude, method B (Top left=~40°N, top right =40°N~50°N, below left=50°N~60°N, below right=60°N~).

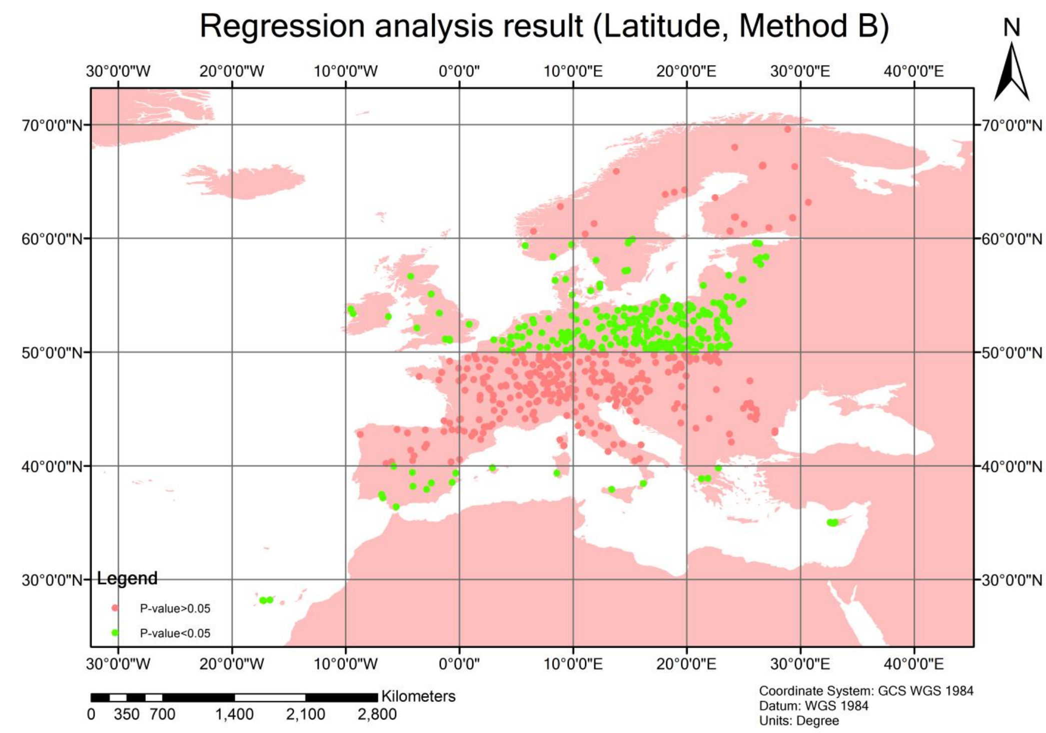


Figure 11. Map of regression analysis, grouped by latitude, method B.

c) Forest stand

Table 16 and Figure 12 shows the result of regression analysis grouped by forest stand. The result shows only a little percentage of the variance of defoliation can be explained by LST diurnal range by grouping with forest stand. There was no significant correlations found among three groups ($p>0.05$). This suggests that the forest stand may not be the main indicator for using diurnal range of LST to predict defoliation. The result doesn't provide evidence that a stronger correlation can be found in conifer forests than broad-leave forests.

Table 16. Result of regression analysis, grouped by forest stand, method B.

Forest stands	P-value	Slope	Correlation	R^2
Broad-leaves	0.4995	-0.1	-0.02812014	0.0007907
Conifers	0.9704	0.003957	0.001111513	0.000001235
Mixed	0.2087	0.6751	0.1605638	0.02578

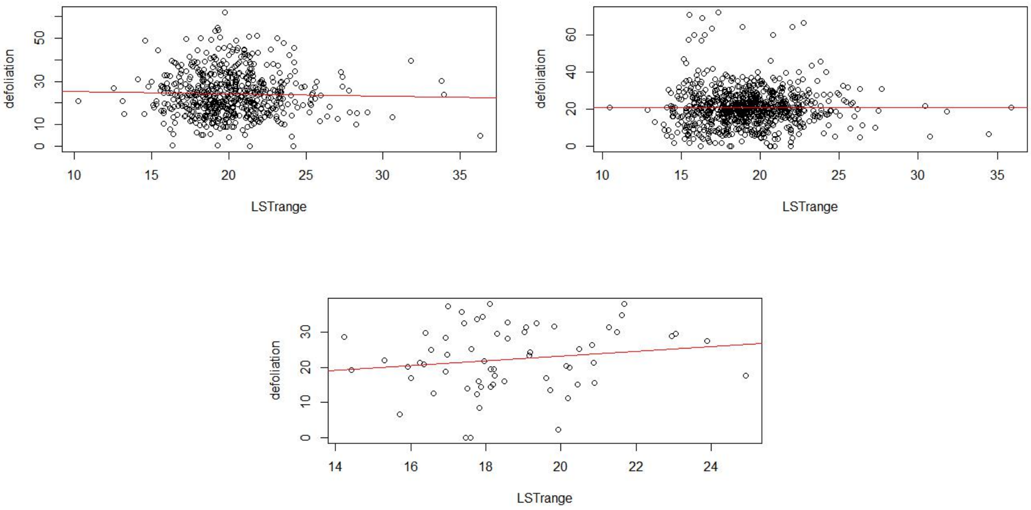


Figure 12. Scatter plot of regression analysis, grouped by forest stand, method B (Top left=Broad-leaves, top right =Conifers, below=Mixed forest).

4. DISCUSSION

In the following chapter, the consequences of the results obtained in this study are discussed. Sources of errors and implications of data quality improvement were also concluded.

4. 1. Factors influencing defoliation in the forest

In this study, several hypotheses related to how average LST diurnal range and average LST diurnal range grouped by different geographical and forestry factors will explain defoliation were analyzed and evaluated. The results of method A have shown that the defoliation values and average LST diurnal range values can be significantly correlated only in 24 plots from 593 Level II plots. The general result of method B have shown that only 0.6% of the variation in defoliation values can be predicted from LST diurnal range values. Above all, the phenomenon and results are not enough to conclude "defoliation can be correlated with LST diurnal range well" in this study. And also according to the correlation analysis results of LST diurnal range and defoliation by grouping of altitude, latitude and forest stand, it was found that the correlation between average diurnal range of LST in summertime (July and August) and defoliation is not stronger in forests that are more stable in their temperature regime than forests that are less stable in their temperature regime.

Although poor consistence of average LST diurnal range and the method how defoliation was assessed may have contributed to these non-significant results, furthermore, recorded in a relative term "defoliation", this study is based on a comparison of foliage condition of different individual trees at different time points, rather than a survey of absolute foliage volume among trees in a forest. Defoliation values can not reflect the reduction in the form of foliage volume (Solberg, 1999), which is an absolute numerical value which could be more representative of thermal inertia in the crown compared to a relative variable which focuses on the condition of individual trees. Based on the main research question of this study, it is reasonable to conclude that the same percentage of defoliation in a tree with more foliage would contribute to loss of thermal inertia more significantly rather than a tree with less foliage. So it is not hard to find that the volume of foliage may also be an indicator that would have an influence on the correlation between LST diurnal range and defoliation. Possibly, correcting for absolute volume of foliage might enhance the correlations found in this study.

4. 2. Defoliation-LST diurnal range model

A correlation coefficient of variables >0.7 or <-0.7 is considered to indicate a strong relationship (Clemens et al., 2008). P-value and correlation of defoliation (as dependent variables) and average

LST diurnal range (as independent variables) were analyzed in this study. Although some groups show significant correlation between LST diurnal range and defoliation, the R^2 only indicates a little percentage of the variance of defoliation that can be explained by LST diurnal range.

4. 3. Quality of remote sensing and ground data

LST data and processes of LST data are necessary to understand how thermal inertia works in the forest ecosystem and then to understand the reason of defoliation. In this study, daily maximum and minimum LST were extracted and then LST diurnal range is calculated by subtracting daily maximum and minimum LST. Consecutive gaps exists in LST diurnal range because of different reasons related to the constraints of LST. LST data can be only retrieved under cloud free conditions. In Europe, frequent cloudy condition was a challenge for LST data retrieving. The gaps of LST values due to cloud cover is very difficult to solve (Marques da silva et al., 2015). It is nearly impossible to extract LST from MSG while having consecutive days with cloud cover, especially some Level II plots in Northern Europe Boreal forests. However, abnormal phenomenon was found in Spain at the same time, which has shown a diurnal range of LST of more than 30 °C. In this study, although the available images are enough (only 1.85% of the images are missing, the available LST records are severely limited. Although a sensitivity analysis was applied to see which preprocessing steps keep most LST data, it doesn't solve the core problem of data gap. More techniques on MSG LST interpolation should be applied to fill the gaps in this data set. Lu et al. (2010) developed a new approach of temporal neighboring pixel to reconstruct diurnal range of LST by using channels derived from MSG. Missing records of diurnal range of LST due to the cloud effect in Kenya and Burkina Faso were extracted in that study. Having used a different method to extract LST, Duan et al. (2014) developed a method to estimate diurnal cycle of LST directly from MSG LST collected under clear-sky conditions without considering the relationships between LST and LSE (Land Surface Emissivity), and the results have shown that the accuracy of fitting is better than 1 K for most of the pixels. These approaches can be applied to this study if ground measured LST data is provided to accomplish the rectification.

Monitoring defoliation is needed in this study. Defoliation monitoring through remote sensing have difficulties. Problems of subjective field classification of defoliation, different forest characteristics and image qualities, cloudiness and image interpretation could be main sources of errors introduced in defoliation studies (Nevalainen & Tokola, 2002). So this study has chosen data collected in the field provided by ICP Forests as defoliation data source. However, assessments from the ground has limitations as well. Although the principle of ICP Forests is clear, there are systematic differences among observers from different countries of monitoring at practice level (Innes et al., 1993). Also, the accuracy of field assessment of defoliation can be affected by all the other reasons that would have an influence on the assessment by the observer, such as time available, weather, species, density (Nevalainen & Tokola, 2002). It would be possible that the result of assessment of defoliation in southern European forests was recorded higher than in Northern European forests because the plants looks unhealthy here, while actually this might be their normal state to cope with the climate conditions there. An experiment was done to examine the accuracy of assessment by four different observers. The result shows that only 65% of Scots pine and 41% of Norway spruce were estimated identically in 10% needle loss (Salemaa et al., 1991). So it could be questioned to what extent defoliation values reflect truly absolute health status on the ground, or whether they are more reflecting relative forest conditions. If that is true then only conclusions can be drawn based on trends in defoliation over time. While coming to this study, the analysis of method A would be the only solution because it analyzed the LST diurnal range and defoliation in pairs of all the plots by year. Therefore, the monitoring process itself may exist problems.

More than the problems found in the subjectivity of the assessment by observers, defoliation in ICP Forests data is assessed by comparing the real condition with a reference photo and stepped by 5%, which is not so reliable as some other indexes, such as NDVI (Normalized Difference Vegetation Index) and LAI (Leaf Area Index) to describe the crown condition in forests. To solve this problem, an average of defoliation across trees within a plot was calculated to enhance the data accuracy.

What's more, the definition of species by ICP Forests is broad-leave and conifer forests. The difference between broad-leave forests and conifer forests would be less clear than when it would have really been deciduous and evergreen, which would be better to reflect the differences in thermal inertia.

Additionally, one of the assumption this study based on is that there was no significant differences of LST in the same plot spatially. Since LST data was derived in Channel 9 and 10 of MSG, the nadir spatial resolution of LST diurnal range data is 3 by 3 kilometers, which is too big to represent all the temperatures in a plot whose size is usually smaller than 0.25 ha. So the enhancement of spatial resolution should be done by merging LST from MSG with LST from other sensors which has higher spatial resolution.

5. CONCLUSION AND RECOMMENDATION

5. 1. Conclusions of this study

This study had not demonstrated a successful approach using techniques of satellite derived diurnal range of LST in summertime (July and August) to indicate defoliation. No clear correlation was found between average LST diurnal range in summertime (July and August) and defoliation. What else, the intensity of their correlation has not been proved to have a relationship with forest stability in temperature regime.

5. 2. Recommendation

To develop the integrity and applicability of this approach, it is recommended to do the following improvements:

a) The quality of the data source can be improved. For the satellite derived LST data, an approach of the LST diurnal range data interpolation or retrieving LST in other approaches can be applied to guarantee the integrity and consistence of the data set. A LST data set of better spatial resolution can also be acquired by combining the observed results of various of sensors from satellite and ground measurement. For the defoliation data, it is better to analyze the species of the trees to study whether it is deciduous or evergreen. Such affirmation will be very useful while analyzing their thermal inertia.

b) The volume of foliage can be introduced into this study by a combination of defoliation data and indexes extracted from other optical remote sensing or ground based data sources, such as LAI measurements based on fish eye lens data provided by ICP Forests and satellite derived NDVI.

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