University of Natural Resources
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USE OF MODIS TIME SERIES FOR DETERMINING PHENOLOGICAL INDICATORS AND COMPARISON WITH NETWORK OBSERVATIONS

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Master's thesis
submitted in partial fulfilment of the requirements for the academic degree of
Diplomingenieurin

2019

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

Acknowledgements

I would first like to thank my thesis advisors Dr. Anja Klisch and Prof. Clement Atzberger. They always made time for me whenever I had questions or uncertainties related to my research.

I also say thank you to the members of the IVFL Institute and to my master colleges for making the work environment so pleasant. Last but not least I would like to thank my friends and my family for supporting me.

Affidavits

I hereby declare that I am the sole author of this work. No assistance other than that which is permitted has been used. Ideas and quotes taken directly or indirectly from other sources are identified as such. This written work has not yet been submitted in any part.

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ABSTRACT

Phenology is the study of periodic events in plant and animal life cycles and has been widely studied for many decades (White et al., 2009). Currently, studies are being carried out from two fundamentally different perspectives, ground observed phenology (GP) and satellite-based phenology (LSP).
This study focuses on the phenological parameter start-of-season (SOS) and investigates the relationship between GP and LSP for deciduous tree species, in a study area covering Austria, Germany and Switzerland, for the time-frame 2002-2015. For that purpose, two geospatial databases are pre-processed, computed, compared and statistically analysed. The first database consists of PEP725 stations (Pan European Phenological Database) observing the phenological parameters leaf unfolding (LU) and first flowering (FF) and was used to derive a GP-SOS time-series. The second database consists of LSP-SOS and was computed using MODIS NDVI. The deciduous tree species covered in PEP725 have been aggregated into two groups with European Beech (Fagus sylvatica) and Common Hazel (Corylus avellana) as representatives. The research questions addressed in this thesis are:

1. Does the LSP parameter start-of season, derived from MODIS NDVI time-series, show a good agreement with the GP parameters leaf unfolding and first flowering date? Does the GP of specific deciduous tree species show a better agreement with the LSP?
2. Which percentage of the seasonal amplitude is better suited for calculating the LSP-SOS?
3. Do the GP and LSP indicate an earlier onset of spring phenology?
4. Do the environmental variables altitude and geographical position have an influence on the GP-SOS?

In order to tackle these questions several statistical analysis have been conducted on the data for European Beech and Common Hazel: correlation analysis, evaluation of the model and exploratory data analysis.

For European Beech, the research shows a good agreement between GP and LSP-SOS, with 79.5% of the PEP-stations showing significant positive correlations, when computing LSP-SOS with a threshold of 70.0% of the seasonal amplitude. For the same threshold, RMSE shows a difference between simulated observations (LSP) and actual observations (GP) of 10.9 days per year and 10.3 days per station. For Common Hazel, the research shows a poorer agreement, with 45.6% of the stations correlating significantly, when using a threshold of 10.0% of the seasonal amplitude. In this case, the RMSE shows a difference between LSP and GP of 33.7 days per year and 28.2 days per station. The results obtained in the course of the exploratory data analysis indicate an earlier onset of spring for both species, meaning that spring phenology tended to occur earlier every year in the time-frame analysed. The influence of the environmental variables altitude and geographical position on the GP-SOS could not be demonstrated on account of the PEP-stations analysed.

ZUSAMMENFASSUNG

Die Phänologie befasst sich mit den im Jahresablauf periodisch wiederkehrenden Entwicklungserscheinungen in der Natur (White et al., 2009). Phänologische Studien werden aus zwei grundsätzlich unterschiedlichen Perspektiven durchgeführt: Bodenbeobachtungen (GP) und Satellitenbeobachtungen (LSP).
Diese Masterarbeit untersucht den Zusammenhang zwischen GP und LSP für Laubbaumarten und konzentriert sich auf dem phänologischen Parameter Saisonstart (SOS). Das Untersuchungsgebiet fasst Österreich, Deutschland und der Schweiz um in den Zeitraum 2002-2015. In Rahmen dieser Arbeit werden zwei Geodatenbanken vorbereitet, verglichen und statistisch ausgewertet. Die erste Datenbank besteht aus PEP725-Stationen (Pan European Phenological Database), die die phänologischen Parameter Blattentfaltung (LU) und Erstblüte (FF) beobachten und zur Ableitung einer GP-SOS-Zeitreihe herangezogen wurden. Die zweite Datenbank besteht aus LSP-SOS und wurde mit MODIS NDVI berechnet. Die in PEP725 behandelten Laubbaumarten wurden in zwei Gruppen mit Rotbuche (Fagus sylvatica) und Hasel (Corylus avellana) als Vertreter zusammengefasst.
Die Forschungsfragen dieser Masterarbeit lauten:

1. Stimmt der aus den MODIS NDVI-Zeitreihen abgeleiteten LSP-SOS mit den GP-Parametern LU und FF überein? Zeigt der GP bestimmter Laubbaumarten eine bessere Übereinstimmung mit dem LSP?
2. Welcher Prozentsatz der saisonalen Amplitude eignet sich besser für die Berechnung des LSP-SOS?
3. Zeigen GP und LSP einen früheren Beginn der Frühlingsphänologie an?
4. Beeinflussen die Umgebungsvariablen Höhe und geographische Position der GP-SOS?

Um diese Fragen zu beantworten, wurden für Rotbuche und Hasel verschiedene statistische Analysen durchgeführt: Korrelationsanalyse, Bewertung des Modells und explorative Datenanalyse.

Für Rotbuche wurde eine gute Übereinstimmung zwischen GP und LSP-SOS gefunden. 79,5% der PEP-Stationen zeigten signifikante positive Korrelationen, wenn LSP-SOS mit einem Schwellenwert von 70,0% der saisonalen Amplitude berechnet wurde. RMSE zeigt einen Unterschied zwischen simulierten (LSP) und tatsächlichen Beobachtungen (GP) von 10,9 Tagen pro Jahr und 10,3 Tagen pro Station. Für Hasel zeigt die Studie eine schlechtere Übereinstimmung: 45,6% der Stationen korrelieren signifikant, wenn einen Schwellenwert von 10,0% der saisonalen Amplitude verwendet wird. In diesem Fall zeigt der RMSE einen Unterschied zwischen LSP und GP von 33,7 Tagen pro Jahr und 28,2 Tagen pro Station. Die im Zuge der explorativen Datenanalyse erzielten Ergebnisse deuten auf einen früheren Frühlingsbeginn für beide Arten hin, was bedeutet, dass die Frühlingsphänologie jedes Jahr im untersuchten Zeitraum früher auftrat. Der Einfluss der Umgebungsvariablen Höhe und geografische Position auf die GP-SOS konnte aufgrund der untersuchten PEP-Stationen nicht nachgewiesen werden.

1. Introduction

Phenology is the science of periodic events in plant and animal life cycles and has been widely studied for many decades. It has been used throughout history as a proxy for climate and weather, with important applications in agriculture and forestry. It is an emerging field of climate change studies since phenological events are being regarded as climate change indicators (White et al., 2009). Studies of plant phenology are currently being carried out from two fundamentally different perspectives: ground observed phenology (GP) and satellite-based phenology (land surface phenology, LSP).

GP has the advantage of long temporal coverage with many records going back to the early 1900. Currently, several phenological observation networks such as the Pan European Phenological Network (PEP725) and United States of America National Phenology Network (USA-NPN) provide observations covering several terrestrial ecosystems (Hamunyela et al., 2013). However, GP also entails a series of shortcomings: gathering records is time-consuming and impossible to be done at a global scale, unifying records across plant species and phenological events is difficult and the phenological events observed are representative at species level, and less so at community level (Rodriguez-Galiano et al., 2015).

LSP can be defined as the seasonal pattern of variation in vegetated land surfaces as observed by satellite sensors (Usanpn.org, 2018). During recent decades, a variety of methods has been used to derive metrics of LSP from time-series of earth observations (EO). Although LSP metrics do facilitate large-scale assessments of seasonal vegetation dynamics, they are different from the GP and represent the timing of reflectance changes that are driven by the aggregate activity of vegetation within the areal unit measured by satellite sensors. The satellite sensors most commonly used to derive LSP are the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Remote sensing indices characterizing vegetation conditions form the basis for deriving LSP metrics. Such indices are: the normalized difference vegetation index (NDVI), the enhanced vegetation index (EVI), the leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (FPAR). The most ubiquitous algorithm is NDVI, which utilizes chlorophyll and leaf structure-induced reflectance contrast between red and near-infrared spectral bands from live vegetation (Hanes et al., 2013).

LSP overcomes some of the GP shortcomings and most importantly it can be used at a regional and global scale. Unfortunately, this method is not exempted from uncertainty; estimates might include signals from multiple sources, such as noise in the satellite sensor or errors in the processing methods, and the signals can be mixed on account of multiple land-covers (Rodriguez-Galiano et al., 2015).

Multiple studies concerning phenology in Europe have been published, both from the GP and from the LSP perspective. However, not many attempts to compare LSP with GP have been documented, and few of them have managed to temporarily match GP with LSP (Misra et al, 2016). Most of these studies focus on deciduous tree species, and the most common phenological parameters for the GP data are leaf unfolding (LU) (Hamuyela et al. 2013;

Verger et al. 2016; Rodriguez-Galiano et al. 2015; Yongshuo et al. 2014), first leaves separated (Hamuyela et al. 2013; Verger et al. 2016) and first flowering date (FF) (Yongshuo et al. 2014). These parameters are most commonly compared with LSP start-of-season (SOS). Various methods of calculating the LSP SOS have been explored in the past two decades, with the most frequent one being thresholds of the seasonal amplitude, which is the difference between the maximum and the minimum of vegetation in a season (Misra et al., 2016). The impact of different datasets and filtering techniques on LSP has been researched and proven very significant. Atzberger et. al 2013 compares two LSP datasets derived from MODIS and GIMMS NDVI, finding only a moderately good agreement between them and highlighting the importance of cross-sensor inter-calibration. Atkinson et. al 2012 compares four models for smoothing satellite sensor time-series, concluding that different models lead to different LSP outcomes.

The main aim of this master thesis is to investigate the relationship between GP-SOS and LSP-SOS for deciduous tree species in a study area covering Austria, Germany and Switzerland. For this purpose, the PEP725 database has been pre-processed and the observations have been filtered to consist exclusively of broadleaf species situated within broadleaf forests, with LU and FF as phenological parameters. A corresponding LSP-SOS database has been created, and efforts have been made for calibrating the LSP to the GP.

The following research questions have been addressed within the aims and scope of this research:

1. Does the LSP parameter start-of-season, derived from MODIS NDVI time series, show a good agreement with the GP parameters leaf unfolding and first flowering date? Does the GP of specific deciduous tree species show a better agreement with the LSP?
2. Which percentage of the seasonal amplitude is better suited for calculating the LSP-SOS?
3. Do the GP and LSP indicate an earlier onset of spring phenology?
4. Do the environmental variables altitude and geographical position have an influence on the GP-SOS?

The research is organized as follows: First, a theoretical background regarding remote sensing and phenology is provided. Then, the materials and methods used to pre-process the GP database, to model the LSP database and to statistically analyse the relationships between them are described in detail. After that, the results are presented with their affiliated graphs. Finally, the results and their implications are discussed, and a conclusion is formulated.

2. Theoretical background

2.1. Remote Sensing

Remote sensing refers to technologies for recording electromagnetic energy that emanates from areas or objects on (or in) the Earth’s land surface, oceans, or atmosphere

(Short 2010). The properties of these objects or areas, in terms of their associated levels of electromagnetic energy, are essential to provide a way to identify, delineate, and distinguish between them. The electromagnetic properties of these features are commonly collected by instruments mounted on aircraft or Earth-orbiting spacecraft, thus remote sensing provides scientists the opportunity to capture large geographic areas with a single observation, or scene (Khorram, 2012).

Electromagnetic radiation (EMR) is defined as all energy that moves with the velocity of light in a harmonic wave pattern. The categories of EMR are visible light, radio waves, infrared, and gamma rays. All these types together comprise the electromagnetic spectrum. The different forms of EMR differ in both wavelength[1] and frequency[2] (Khorram, 2012). As can be observed in *Figure 1*, the visible light represents only a small portion of the electromagnetic spectrum ranges in wavelength from about 3.9 x 10^{-7} (violet) to 7.5 x 10^{-7} m (red), and has corresponding frequencies that range from 7.9 x 10^{14} to 4 x10^{14} Hz (Khorram, 2012).

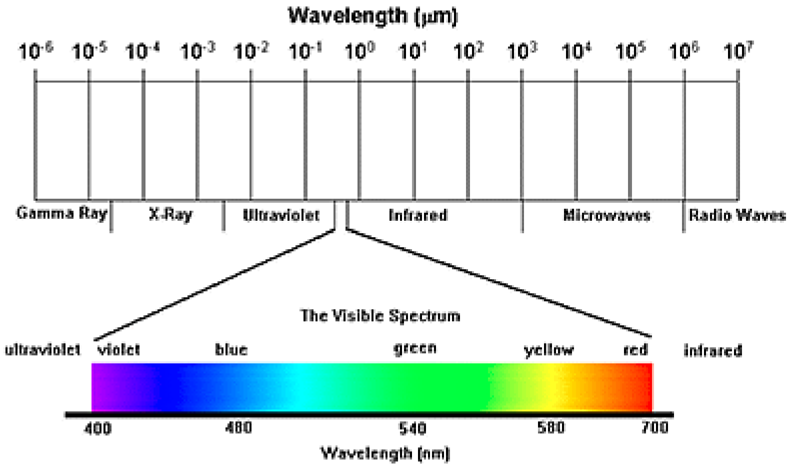

Figure 1: The electromagnetic spectrum (Crisp.nus.edu.sg, 2018).

When EMR comes in contact with matter, the following interactions are possible: absorption, reflection, scattering or emission of EMR by the matter, or transmission of EMR through the matter. Remote sensing is primarily based on detecting and recording EMR. Each object or material has particular emission and reflectance properties, known as spectral signature, which distinguishes it from other objects or materials (Khorram, 2012).

Remotely sensed vegetation indices (VIs), derived from satellite image data, have become one of the primary information sources used for monitoring vegetation conditions (Teillet, 1997). The Normalized Difference Vegetation Index (NDVI), is one of the most widely used VIs in ecosystems monitoring and it quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs) (Land.copernicus.eu, 2018). The NDVI can be calculated with the formula depicted

[1] Wavelength - is the distance between one position in a wave cycle to the same position in the next wave (Khorram, 2012).
[2] Frequency - in the context of the EMR, is the number of wave cycles passing the same point in a given time period (1 cycle per s = 1 Hertz, or Hz) (Khorram, 2012).

in *Figure 2*, ρ_{nir} and ρ_{r} stand for the spectral reflectance measurements acquired in the red (visible) and near-infrared regions, respectively (Anyamba and Tucker, 2005).

$$NDVI = (\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})/(\rho_{\mathrm{nir}} + \rho_{\mathrm{r}})$$

Figure 2: The formula of NDVI (Anyamba and Tucker, 2005).

2.2. Phenology

Phenology is the study of recurring plant and animal life cycle stages, especially their timing and relationships with weather and climate. Sprouting and flowering of plants in the spring, colour changes of leaves in the fall, bird migration and nesting, insect hatching, and animal hibernation are all examples of phenological events. Seasonality is a closely related non-biological term, which describes the recurrence of phenological events (Schwartz, 2013).

Phenology has been used through history as a proxy for climate and weather, with important applications in agriculture and forestry. It is an emerging field of climate change studies, phenological events being regard as climate change indicators. Thus, phenology can provide an independent measure on how ecosystems respond to climate change (Schwartz, 2013). Decadal trends and inter-annual variability, which can both be outlined with phenological data, are important because they affect carbon, water and energy exchange between vegetation and atmosphere (White et al., 2009).

Knowledge and activities related with what we now call phenology are very old and closely related with the beginning of plant cultivation. Phenology began to emerge as an environmental science by the mid-1900s, when continuous and continental-scale observation networks have been established (Schwartz, 2013).

Studies of plant phenology are currently being carried out from two fundamentally different perspectives: ground observed phenology (GP) and satellite-based phenology (land surface phenology, LSP).

Europe has a broad tradition of GP. Many countries have long-term data, spreading over decades, thus Europe is a particularly suitable region for analysing phenological changes or providing “ground truth” to satellite data. However, these data sets do not follow unique phenological guidelines, but instead almost each country follows their own tradition of observation and the observations are gathered mostly by volunteers and not by specialists (Schwartz, 2013). Recently, new initiatives such as COST725[3], which resulted in the PEP725 European Phenological database, offer structured, broad data sets following the same guidelines and thus using the same phenological measurement units (Templ et al., 2018).

[3] COST725 - running from 2004 to 2005, aimed at and succeeded in establishing a European phenological data base, classifying the data according to one common system (Koch et al., 2009). It is the precursor of PEP725 (Templ et al., 2018).

LSP may be defined as the seasonal pattern of variation in vegetated land surfaces as observed by satellite sensors. LSP reflects the response of the vegetated surfaces of the earth to seasonal and annual changes in the climate and hydrologic cycle. (Usanpn.org, 2018). *Figure 3* shoes the LSP over Europe as computed in Atzberger et al. 2013 by using GIMMS and MODIS NDVI.

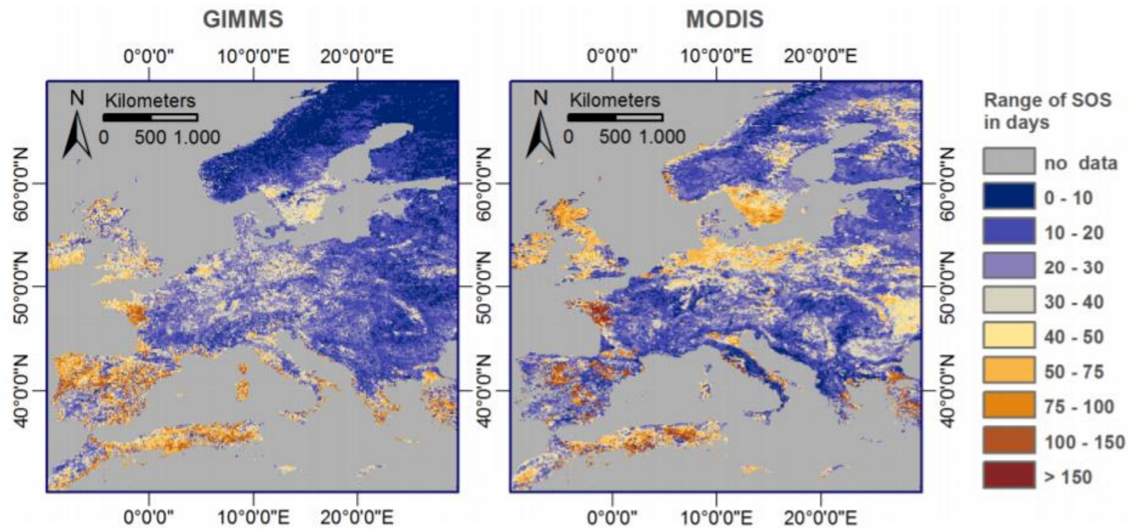

Figure 3: LSP SOS of Europe as computed with GIMMS (left) and MODIS (right) NDVI (Atzberger et al. 2013).

As outlined by Rodriguez-Galiano et al. 2015, both GP and LSP have advantages and disadvantages.

GP has the advantage of long temporal coverage with many records going back to the early 1900. Even in LSP based studies, GP is essential because it provides "ground-truth", for supporting and interpreting satellite estimates (Rodriguez-Galiano et al., 2015). Monitoring phenology at a ground level for individual species presents also a series of shortcomings such as:

- Unifying records across plant species and phenological events is difficult,
- Gathering records is time-consuming, making change detection at regional and global scales very difficult,
- Relating field data with observations of climatic variables which have a very coarse spatial resolution is difficult,
- The phenological events observed are representative at species level, and less at community level (Rodriguez-Galiano et al., 2015).

LSP overcomes some of the GP shortcomings and most importantly it can be used at a regional and global scale. However, it is not exempt from uncertainty:

- Estimates might include signals from multiple sources, such as noise in the satellite sensor or errors in the processing methods,
- Mixed phenological signals from multiple land covers (Rodriguez-Galiano et al., 2015).
- Different sensors yield different outputs (Atzberger et al., 2013)
- Different pre-processing (smoothing) methods yield different outputs (Atkinson et al., 2012)

- No generally accepted rules for calculating LSP (Misra et al., 2016)

Multiple studies concerning phenology in Europe have been published, both from the GP and from the LSP perspective. However, attempts to compare LSP and GP are not so many, although benefits are twofold. First, GP can provide a means of validating the satellite derived data. Secondly, LSP data are necessary in some situations to upscale GP (Rodriguez-Galiano et al., 2015).

Table 1: Summary of research papers with the GP and LSP datasets and conclusions.

Article	Authors	GP	LSP	Conclusion
Trends in spring phenology of western European deciduous forests	Hamuyela et al. 2013	PEP 725 -Leaf unfolding (11) -First leaves separates (10)	MODIS NDVI -SOS	Earlier onset of spring for both GP and LSP.
Vegetation baseline phenology from kilometric global LAI	Verger et al. 2016	PEP 725, USA National Phenology Network -Leaf unfolding (11) -First leaves separates (10)	GEOCLIM LAI, MODIS EVI -SOS	RMSE of 7 days for SOS of European Birch.
Intercomparison of satellite sensor land surface phenology and ground phenology in Europe	Rodriguez-Galiano et al. 2015	PEP 725 -Leaf unfolding (11)	MERIS MTCI -SOS	90% of the correlations between GP and LSP were significant.
Recent spring phenology shifts in western Central Europe based on multiscale observations	Yongshuo et al. 2014	PEP 725 -Leaf unfolding (11) -First flowering date (60)	GIMMS NDVI3g -SOS	Discrepancies between GP and LSP have been found. According to LSP spring stopped advancing after year 2000.
Phenology estimation from Meteosat second generation data	Sobrino et al. 2013	PEP 725 -Beginning of sprouting (7)	MSG-SEVIRI NDVI, MODIS NDVI -SOS	Green-up dates show on average a one and a half month difference.

The studies which have been the most useful in the course of this research are presented in the table above. The GP dataset along with the phenological parameters analysed, the satellite sensors used, as well as the LSP parameter derived and the conclusions are summarized.

3. Materials and Methods

3.1. Study Area

The study area, depicted in *Figure 4*, is situated in the Northern Hemisphere between 5°E and 15°E longitude and 45°N and 56°N latitude. This area covers the territories of Germany, Switzerland and Austria and has approximately 482 330 km^2.

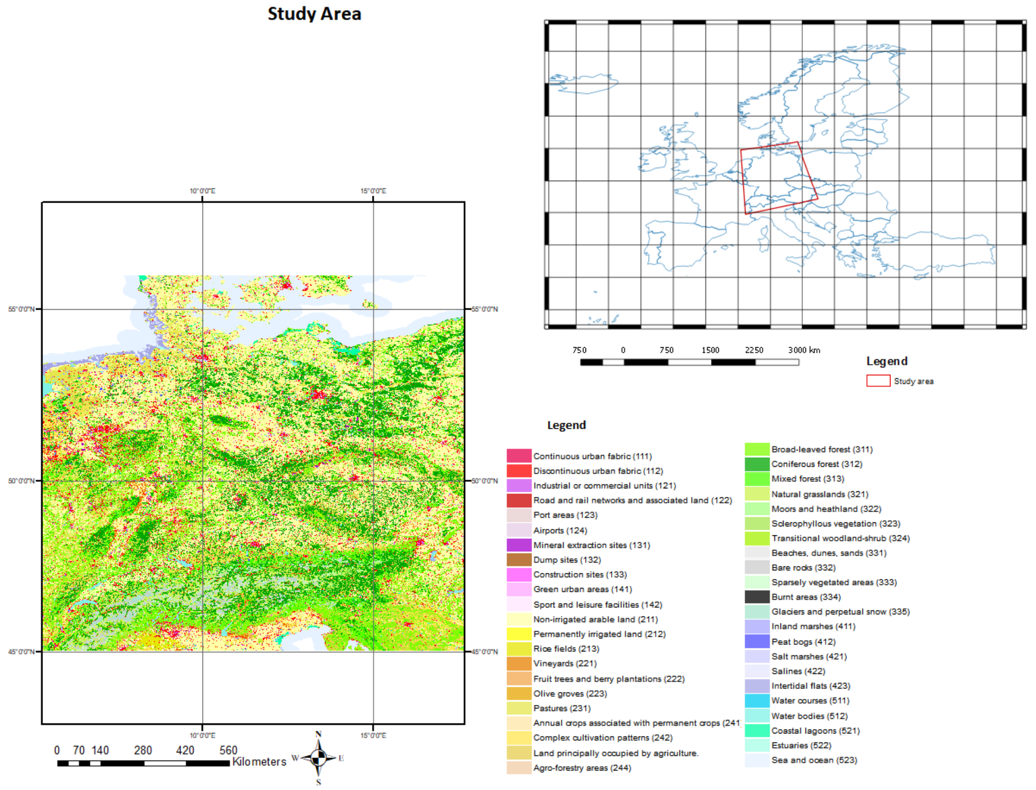

Figure 4: Study area and its land cover. Upper right: the position of the study area in Central Europe (red rectangle). Left: the land cover of the study area created using the CORINE land cover map 2012. Source: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012 (3.08.2018).

The left part of *Figure 4* illustrates the large variability of land covers that can be found in the study area. These consist of artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands and water bodies.

The focus of this research are the broadleaf forests in the study area. *Figure 5* illustrates the forests according to the CORINE land cover. The study area consists of approximately 156.096 km^2 of broadleaf forests, 236.026.5 km^2 of coniferous forests and 98.660 km^2 of mixed forests. According to Olson et al. (2001), the study area belongs to the temperate broadleaf and mixed forests ecoregion, with species such as oak (Quercus spp.), beech (Fagus spp.), birch (Betupa spp.), and maple (Acer spp.) being most common for this region.

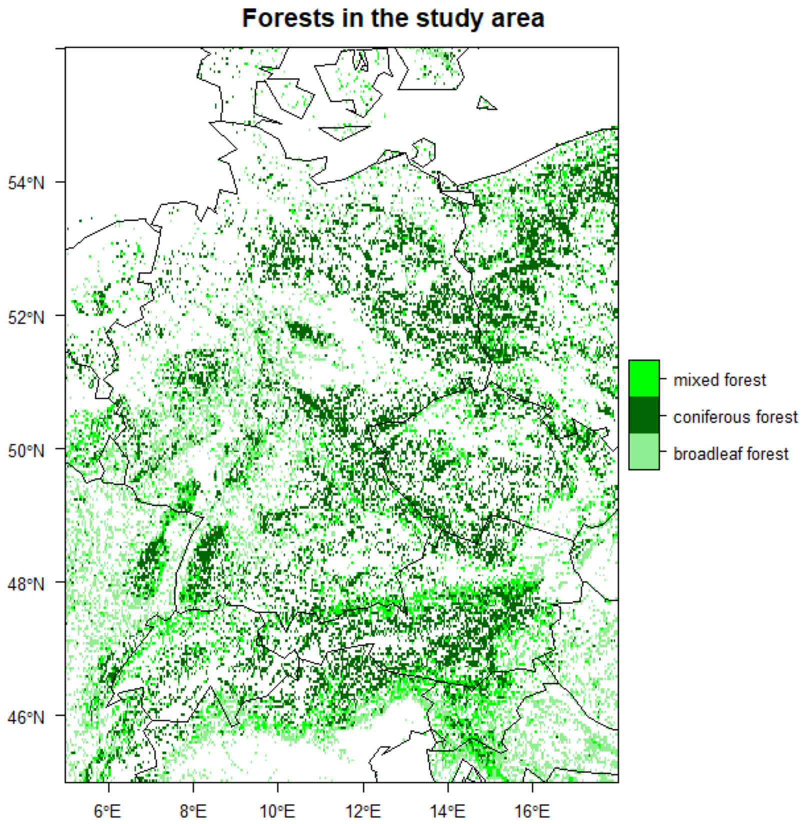

Figure 5: Forests in the study area as depicted by CORINE land cover 2012. Source: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012 (03.08.2018).

Figure 6 illustrates, in the upper part, the typical vegetation growth for a winter month (January) and a summer month (July) by assessing the mean NDVI. The existence of growing seasons is made visible by the contrast between winter, with very low NDVI values, and summer, with very high NDVI values. This indicates that the study area is suitable for the analysis of the periodic plant life cycles, and thus, suitable for phenological analysis. The lower part of this figure depicts typical NDVI profiles for broadleaf forest, which is the main focus of this study. The profiles have been computed for the years 2002 to 2017, and outline very good the seasonality of broadleaf species, the growing seasons being very visible.

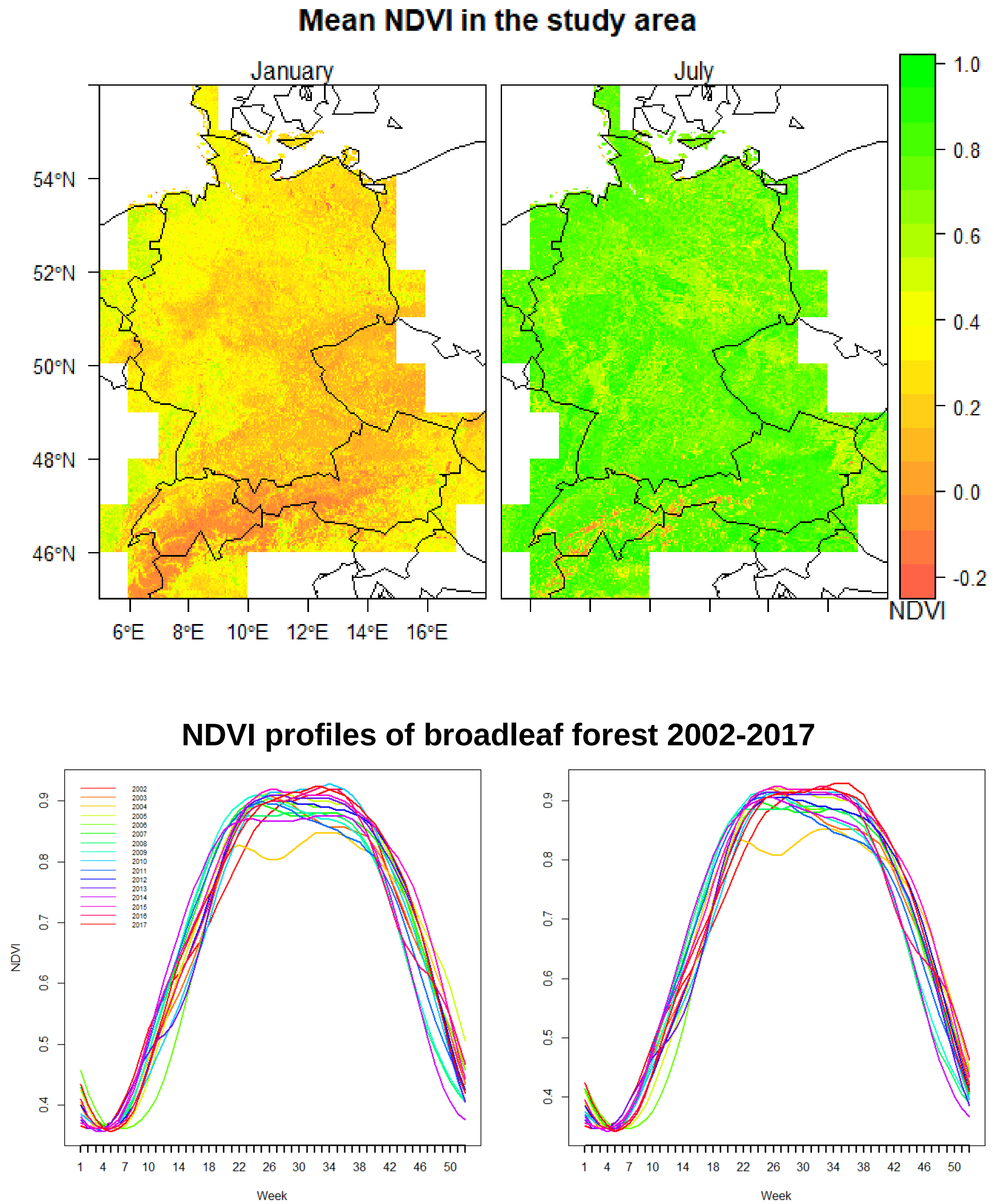

Figure 6:Mean NDVI in the study area (2002-2017). Upper left: mean NDVI in January. Upper right: mean NDVI in July. Lower images: NDVI profiles of two broadleaf forest pixels (coordinates lower left pixel: 11.93 LON , 49.01 LAT, coordinates lower right pixel: 11.56 LON, 48,96 LAT).

Climate, altitude, air temperature and land cover are some of the environmental variables important in phenological studies, which have been analysed in the study area for the purpose of this study. These variables demonstrate relatively diverse spatial variability and climatic conditions.

Figure 7 illustrates the climate types according to the Koeppen classification (left) and the elevation (right). In order to avoid any yearly fluctuations and thus eliminating outliers, climate data covering 25 years has been used (Rubel et al., 2017). The digital elevation model in the picture on the right side of *Figure 7* is a product of the Copernicus programme, available on its website (https://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem).

The study area shows large variability when it comes to climate. According to the Koeppen climate classification[4], Germany has a warm temperate climate with large amounts of precipitation and warm summers (Cfb). Austria shows a warm temperate climate with large amounts of precipitation and warm summers in the eastern and northern part of the country (Cfb), in the southern and eastern parts, the climate is mostly warm humid continental with large amounts of snow (Dfb). In the mountains, even subarctic climate (Dfc) and polar tundra (ET) can be found. In Switzerland the same types of climate are present, but with polar tundra (ET) and subarctic climate (Dfc) covering bigger areas (Kottek et al., 2006). The elevation of the study area varies between 0 and 4634 m (Dufourspitze, Switzerland).

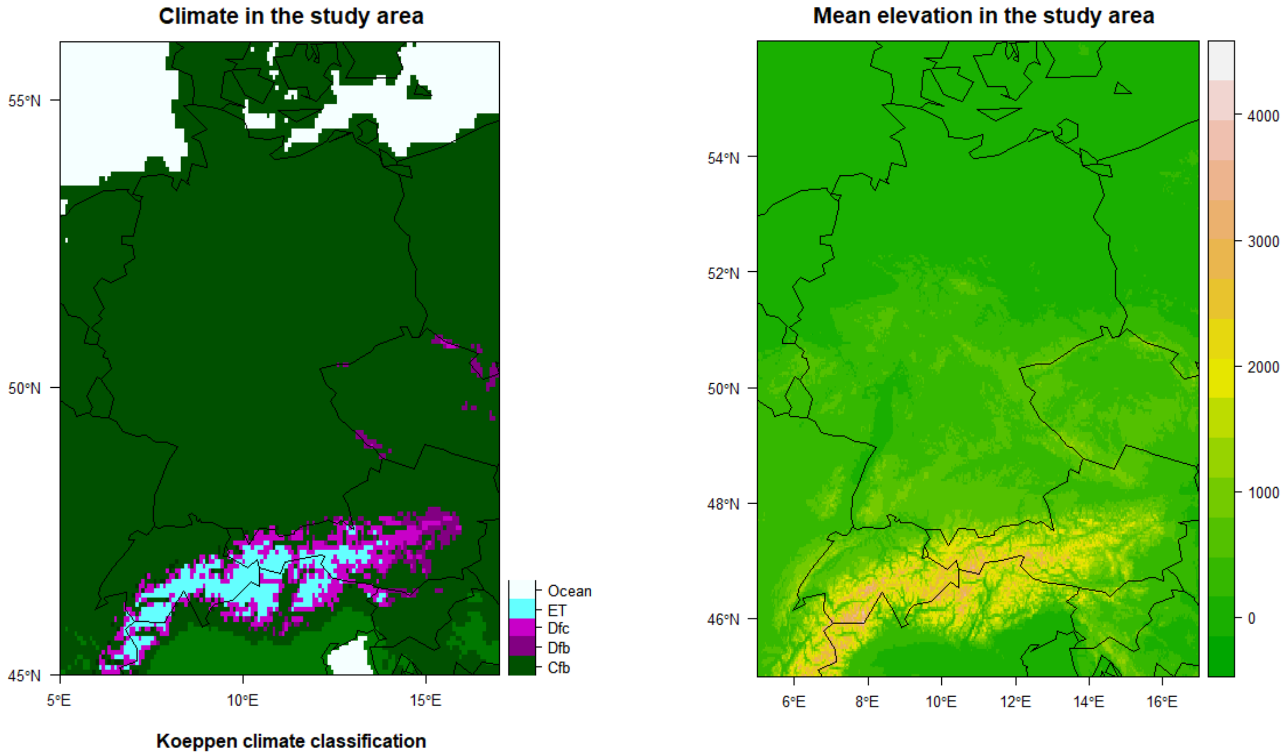

Figure 7: Climate classification according to Koeppen (left) (Rubel et al., 2017), mean elevation in the study area (right). Source: https://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem (03.08.2018).

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[4] Koeppen climate classification - widely used, vegetation-based, empirical climate classification system developed by German botanist-climatologist Wladimir Köppen. is based on a subdivision of terrestrial climates into five major types, which are represented by the capital letters A, B, C, D, and E. Each of these climate types except for B is defined by temperature criteria. Type B designates climates in which the controlling factor on vegetation is dryness (rather than coldness) (Encyclopaedia Britannica, 2018).

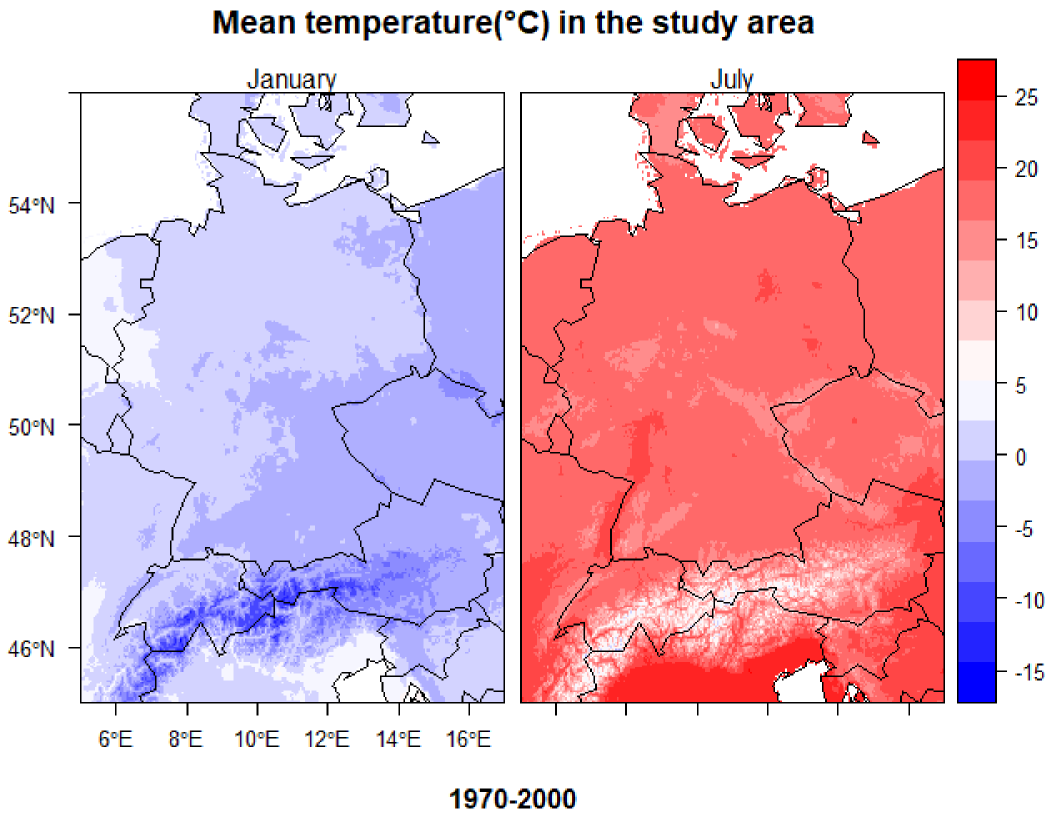

Figure 8: Mean temperature calculated for the years 1970-2000 for the months of January (left) and July (right) (Fick and Hijmans, 2017).

Temperature is another important environmental variable, which is depicted in *Figure 8*. The difference in air temperature between winter and summer is put into contrast in the images showing the mean air temperature in January and July. The mean temperature in January varies between 5°C and -15°C, with the lowest temperature in the mountain regions and the highest in the eastern and north-eastern part. The mean temperature in July varies between 25°C and -5°C with the lowest temperatures in the mountain regions and the highest temperatures in the southern part of the study area. The difference in temperature between July and January, being on average between 15°C and -10°C is consistent for cold winters and warm summers – the perfect variability for observing phenological events.

3.2. Data and program flow

Figure 9 illustrates the flow diagram of the process for determining phenological parameters from MODIS NDVI data and comparison with network observations, developed in the R statistical programming environment for the current work. The diagram contains every step of the process, from raw data to the statistical evaluation, which contains different types of quantitative analysis.

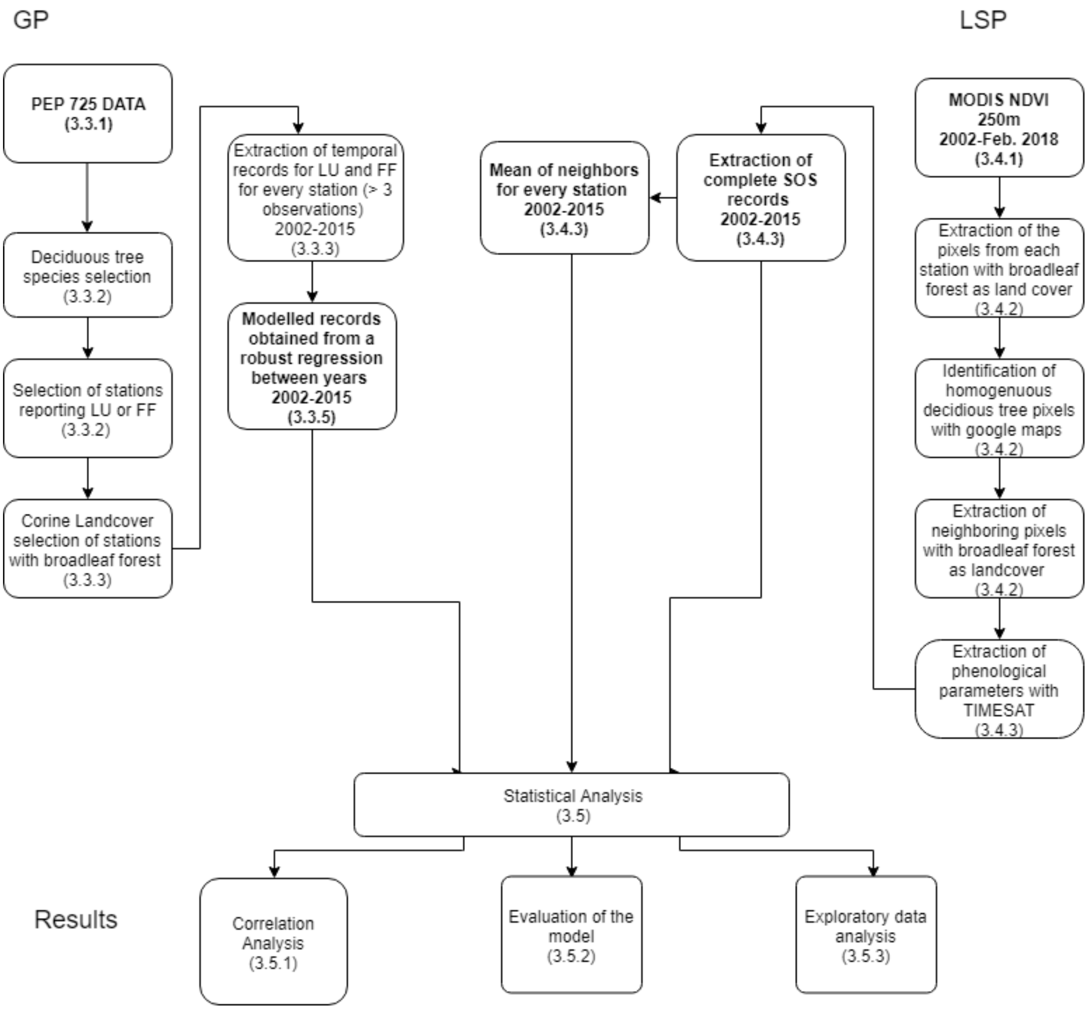

Figure 9: Flow diagram of the process for determining phenological parameters from MODIS NDVI data and comparison with network observations.

The development process draws from two different sets of raw data, which are pre-processed in parallel—namely, that of the ground data (left) and that of the satellite data (right). The data obtained after this preparation is used in a statistical analysis designed to answer the research questions mentioned in the first chapter of this thesis (section 1).

RStudio with R-Script version 3.4.3 and 3.5.0, ArcGIS version 10.6.1 and TIMESAT version 3.2 were the software tools used in the process.

The data used in this research, as well as the development process will be explained in greater detail in the following subchapters.

3.3. Ground Phenology

3.3.1. PEP725 Data

For the purpose of this research the database of the Pan European Phenology Project PEP725 was used as ground data (GP). The database is available online on the PEP website (www.pep725.eu).

PEP725 was founded in 2011 by the Central Institute of Meteorology and Geodynamics in Austria, the Austrian Ministry of Science and Research, the network of European meteorological services (EUMETNET), and partnering national and regional institutions in Europe. The main objective of the project is to promote and assist the progress of phenological research by maintaining a database with a single point of access covering Europe entirely. PEP725 is an open database with unrestricted data access for educational and research purposes. The project has currently 32 European partners regularly submitting phenological data (Templ et al., 2018).

The earliest datasets start in 1868, but generally there are only a few observations available until 1950. In August 2017 it was reported that 12 million records were already included in the database covering 46 growing stages related to 121 wild plants and 144 cultivars from about 20000 different locations across Europe. These locations, as well as the number of observations per location are visible in *Figure 10* (Templ et al., 2018).

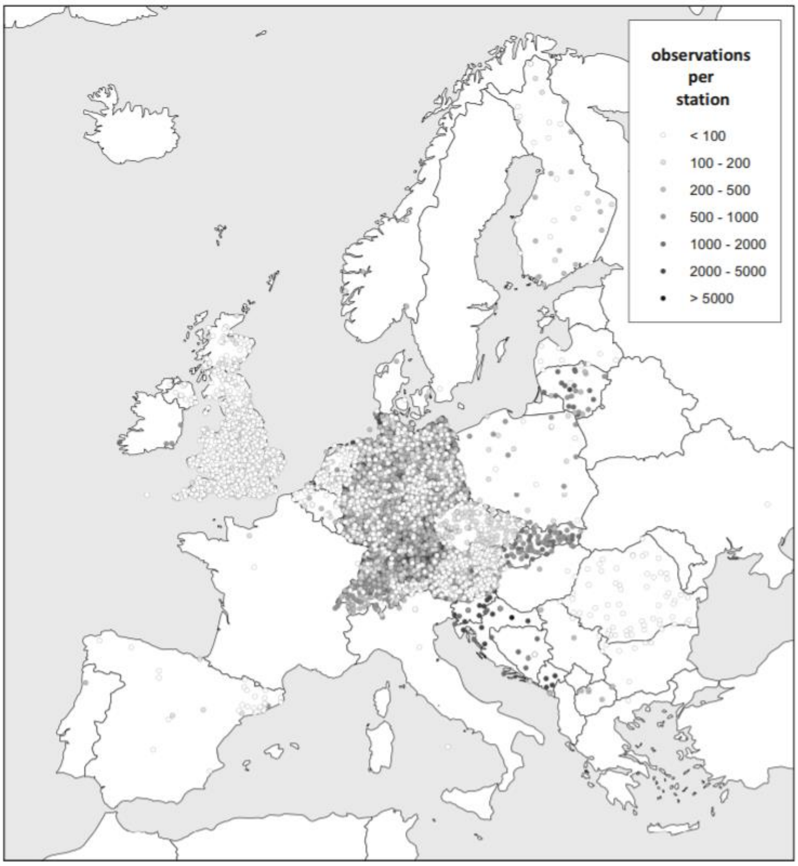

Figure 10: Distribution of PEP 725 stations across Europe with the number of observations per station (Temple et al. 2018).

The phenological networks taking part in the project use either the COST 725 final guideline for phenological observations or a country-specific version of it (Templ et al., 2018). Since the most important precondition to get homogenous comparable data which can be used for further research is the exact definition of the phases (Koch et. al 2009), some additional preparation of the data is being carried out by the regional/national partners of the project before the submission to the database. Dates are converted to day-of-the year values and phenophase codes translated to the BBCH scale.[5] The quality of the data is ensured by a multi stage control process which is still in development (Templ et al., 2018).

The growing stages which are most frequently reported to the PEP725 are beginning of flowering, fruits ripe for picking, leaf unfolding, and first leaves separated.

The web application for download allows for data selection by plant species and country. After download, the user receives an archive containing 3 files:

- A file with the description of all the phenophase BBCH codes
- A file containing metadata information of all the stations of the country (PEP_ID for location, altitude, coordinates, county, national ID)
- A file containing the phenological records including species name, year, day of the year, PEP_ID for location, and BBCH codes for phenophases

3.3.2. Deciduous tree species selection and PEP-stations selection

The PEP 725 dataset contains records for a number of 14 deciduous tree species in the study area, which are listed in *Table 2*. For each species and country, the year of the first and the last observation as well as the number of records are listed before download.

It is noteworthy that, the records between the first and last observation are not complete in all cases, meaning that one does not get phenological parameters for each year from the database. For the purpose of this research every station with more than 3 observations for the time frame 2002- 2017 has been used. This time frame has been chosen in accordance to the time frame of the satellite observations. However, because of missing observations newer than 2015 for Germany, the time frame of this research has been limited to 2002-2015.

Table 2: Species from PEP725 which can be found in the study area with number of records, year of first observation and year of last observation per country.

Name (binomial name)	No. of records/ year of first observation/ year of last observation **AT**	No. of records/ year of first observation/ year of last observation **CH**	No. of records/ year of first observation/ year of last observation **DE**
Norway Maple (Acer platanoides)	2971 / 1946 / 1997	97456 / 1951 / 2015	

[5] BBCH scale – is a system for a uniform coding of phenologically similar growth stages of all mono- and dicotyledonous plant species. It results from the teamwork between German Federal Biological Research Centre for Agricultural Forestry (BBA), the German Federal Office of Plant Varieties (BSA), the German Agrochemical Association (IVA) and the Institute of Vegetables and Ornamentals in Grossbeeren/Erfurt, Germany (Meier, 1997).

Sycamore Maple (Acer pseudoplatanus)	4841 / 1949 / 2016		2493 / 1996 / 2015
Horse-chestnut (Aesculus hippocastanum)	30296 / 1926 / 2016	584356 / 1951 / 2015	19758 / 1951 / 2015
Alder (Alnus)		173270 / 1951 / 2015	
Birch (Betula pendula)	11729 / 1943 / 2016	302991 / 1951 / 2015	6367 / 1996 / 2015
Common Hazel (Corylus avellana)	12625 / 1926 / 2016	115159 / 1951 / 2015	8104 / 1951 / 2015
European Beech (Fagus sylvatica)	19164 / 1926 / 2016	323325 / 1951 / 2015	10966 / 1951 / 2015
European Ash (Fraxinus excelsior)	18 / 1926 / 1927	163127 / 1951 / 2015	
Blackthorn (Prunus spinosa)	3968 / 1926 / 2016	110549 / 1951 / 2015	
Common Oak (Quercus robur)	9776 / 1926 / 2016	376292 / 1951 / 2015	
Common Locust (Robinia pseudoacacia)	5713 / 1929 / 2016	138368 / 1951 / 2015	3707 / 1996 / 2015
Willow (Salix caprea)	6616 / 1946 / 2016	139628 / 1951 / 2015	
Elder (Sambucus)	20401 / 1926 / 2016	270084 / 1951 / 2015	7686 / 1951 / 2015
Mountain-Ash (Sorbus Aucuparia)	13375 / 1926 / 2016	291525 / 1951 / 2015	5684 / 1996 / 2015

Table 3 shows the number of stations with more than 3 observations per species and country. One species (the Sycamore Maple) has been dropped from the research because of the small number of observations available, thus records of 13 species have been analysed in this research. The BBCH phenophase stages available for each specie and country can also be found in this table.

Table 3: Number of stations with more than 3 observations and BBCH phenophase stage by specie and country.

Species	AT > 3	BBCH AT	DE > 3	BBCH DE	CH > 3	BBCH CH	Stations Total
Norway Maple			1380	60			1380

Chestnut	102	11	1557	11	111	13	1770
Alder			1385	11			1385
Birch	112	11	1582	11	133	11	1827
Common Hazel	101	11	1559	60	137	60	1797
European Beech	89	11	1476	11	129	13	1694
European Ash			1348	60			1348
Blackthorn	68	60	1468	60			1536
Common Oak	77	11	1505	11			1582
Common Locust	85	60	1281	60	62	13	1428
Willow	85	60	1500	60			1585
Elder	125	60	1560	60	134	65	1819
Mountain Ash	85	11	1505	11	128	60	1718

The most common BBCH phenophase stages observed are:

- 11 - Leaf unfolding (first visible leaf stak) (LU),
- 60 - Beginning of flowering (FF),
- 13 - Leaf unfolding (50%), and
- 65 - Full flowering,

whereas the BBCH stages 13 and 65 can only be observed in the records from Switzerland. Thus, because of the small number of stations reporting these stages, they have not been further considered in this research.

Figure 11 illustrates the distribution of the PEP- stations from *Table 2* in the study area. It is visible that Germany (black rectangles) has the densest network of all the 3 countries being analysed.

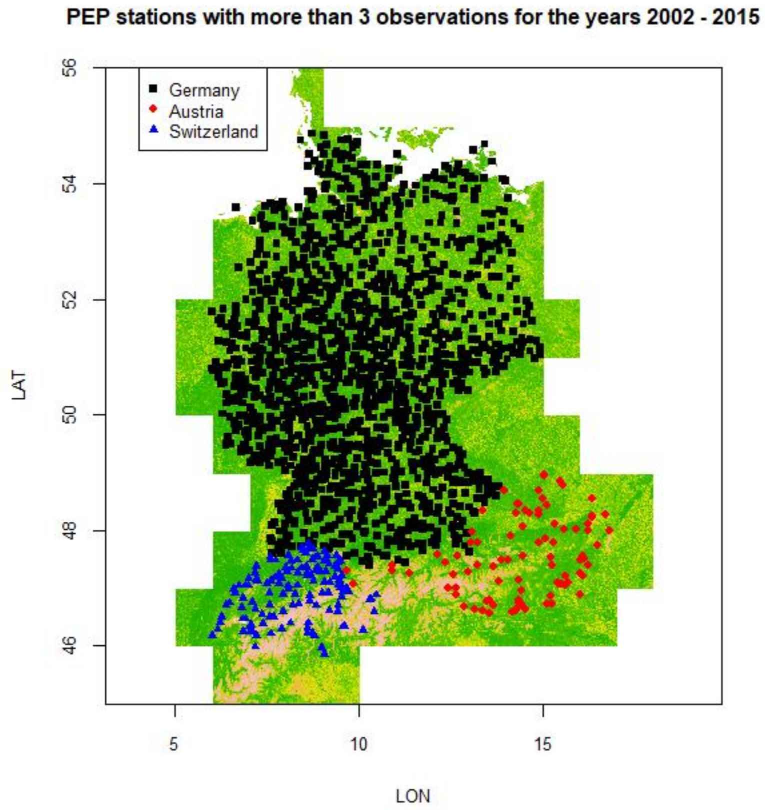

Figure 11: Stations with more than 3 observations for the years 2002 - 2015 in the study area.

Throughout the literature regarding phenology, the most common BBCH phenophase stages, which have been compared to satellite derived phenology indicators, are leaf unfolding (11) and first flowering date (60). We therefore use records of leaf unfolding and first flowering date in our research. These indicators are analysed separately.

3.3.3. CORINE land cover selection of the stations with broadleaf forest as land cover

CORINE land cover (CLC), which is a product of the Copernicus Programme, provides information on the biophysical characteristics of the Earth's surface. It consists of an inventory of land cover divided in 44 classes, with the minimum mapping unit being 25 hectares (European Environmental Agency, 2017). In this research the 2012 version of the map has been used, in the ESRI Geodatabase [6] format. The projected coordinate reference system of the map ETRS89 / LAEA Europe[7]. The map is available free of charge on the official website (Land.copernicus.eu, 2018)

The tool used in this step of the process is R-Script, with the libraries *raster*, *rgdal* and *rgeos.* For better visualisation ArcGIS has also been used.

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[6] ESRI Geodatabase - is the native data storage format for ArcGIS (Esri.com, 2018).
[7] ETRS89/LAEA Europe - Pan-European mapping standard, based on the ETRS89 Lambert Azimuthal Equal-Area projection coordinate reference system. Created for having a single coordinate reference system for Europe (Epsg.io, 2018).

The CLC map has been cut to the spatial extent of the MODIS images used in this research. The polygon obtained has been converted to a raster, with the same resolution as the MODIS images (250 meters), and the same geographic coordinate system (WGS 1984[8]). In this step, a raster,[9] having LC codes as values, with the exact same spatial extent and resolution of the MODIS images, has been obtained.

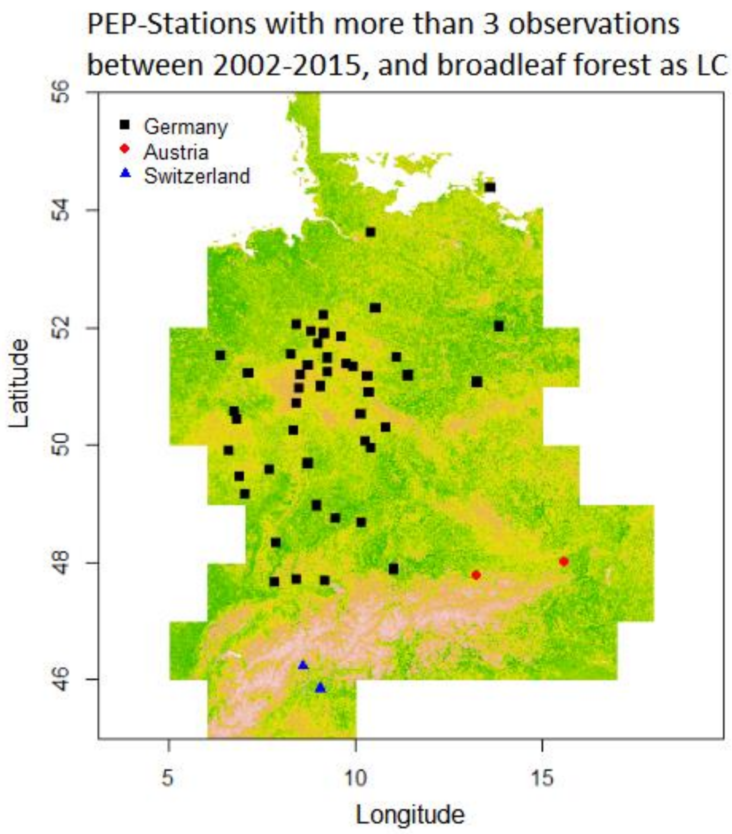


Figure 12: PEP-Stations with more than 3 observations between 2002 and 2015 and broadleaf forest as LC.

Using the raster described above, the land cover of each PEP-station with more than 3 observations between 2002 and 2015 has been extracted. Following the extraction, only the stations with broadleaf forest as LC have been used in the next steps of the process.

The PEP-stations with broadleaf forest as LC are depicted in *Figure 12*. As a result of this LC selection we are left with 47 PEP-stations in Germany, 2 PEP-stations in Austria, and 2 PEP-stations in Switzerland. The majority of the stations from Table 2 has land covers belonging to the categories artificial surfaces, agricultural areas.

Every PEP-station observes a wide range of species. The number of stations per species is shown in *Table 4*.

[8] WGS 1984 - World Geodetic System 1984, uses a global ellipsoid model. Is used in GPS (Epsg.io, 2018).

[9] Raster data - consists of a matrix of cells (or pixels) organized into rows and columns (or a grid) where each cell contains a value representing information, such as temperature. Rasters are digital aerial photographs, imagery from satellites, digital pictures, or even scanned maps (Desktop.arcgis.com, 2018).

Table 4: Stations with more than 3 observations and broadleaf forest as LC, for every specie and country.

Specie	AT	DE	CH	Stations Total
Norway Maple		37		37
Chestnut	2	44	2	48
Alder		37		27
Birch	2	44	2	48
Common Hazel	2	44	2	48
European Beech	2	42	2	46
European Ash		36		36
Blackthorn	2	36		38
Common Oak	2	43		45
Common Locust	2	34	2	38
Willow	2	40		42
Elder	2	43	2	47
Mountain Ash	2	41	2	45

Next, for each specie mentioned in *Table 4*, a file containing a time series per station has been created. This has been accomplished by using R-Script. The time series have a periodicity of one observation per year, covering the time frame between 2002 and 2015, with records representing the day-of-the-year of LU or FF. For each species, a single phenological parameter is being analysed, either LU or FF, as can be seen in *Table 2*. Given the fact that Germany has the most available records, the phenological parameter reported by Germany for a given specie is to be analysed for that specie regardless of what the other countries in the study area report. Therefore, stations from Austria and Switzerland which do not record the same phenological parameter(s) as Germany for a specie, are dropped from the analysis.

3.3.4. Grouping of tree species

Next, a grouping of tree species by LU and FF dates has been conducted. The purpose of this process is to avoid redundancies in the data. By grouping the tree species which have similar LU or FF dates, it is possible to further analyse only one specie from each group.

Consequently, for every species, the yearly mean for all the PEP-Stations has been calculated. After that, the R^2 between species[10] has been determined using the mean values per year. The values obtained can be observed in the heat map from *Figure 13*. This process revealed two groups of species. The first group consists of Hazel and the species, which show high positive correlations with it: Blackthorn and Willow (the minimum R^2 between the species in this group 0.71). The second group consists of European Beech and the species, which show high positive correlations with it: Alder, Norway Maple, Chestnut, Birch, Mountain Ash, European Ash, Elder and Common Oak (the minimum R^2 between the species in this group is 0.44).

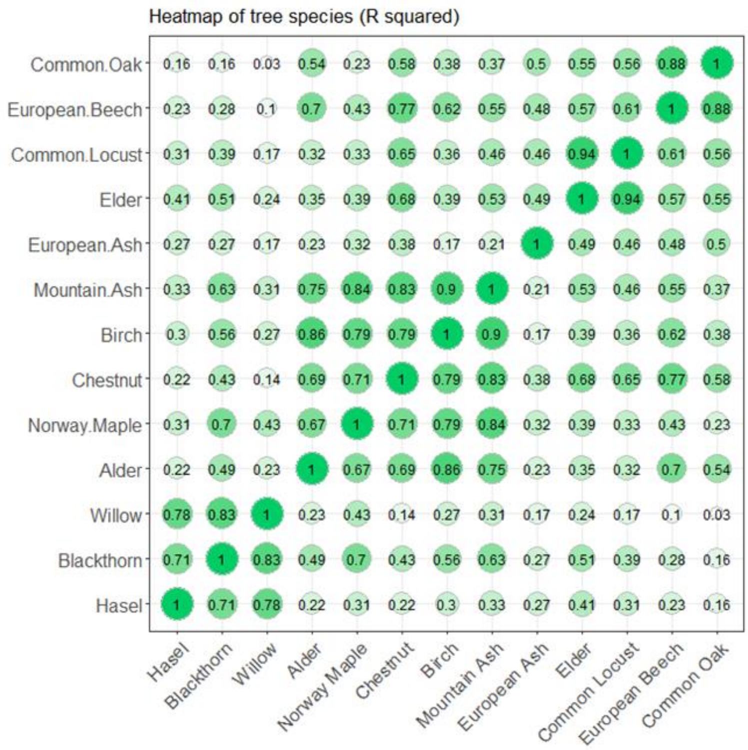


Figure 13: Heat map illustrating the correlation analysis between species. The values represent R^2.

In the Common Hazel group, the phenological parameter observed is FF. In the European Beech group, the phenological parameters observed are:

- LU for Chestnut, Alder, Birch, European Beech, Common Oak and Mountain Ash
- FF for Norway Maple, Common Locust, European Ash and Elder.

The next steps of the process have been conducted on Common Hazel and European Beech.

3.3.5. Gap filling

As stated in the previous subchapters, the time series for each species consists of at least three observations. Before proceeding to the analysis of the GP, a gap filling has been

[10] R^2 - the coefficient of determination, is the proportion of the variance in the dependent variable that is predictable from the independent variable(s) (En.wikipedia.org, 2018).

conducted in order increase the number of observations. This has been accomplished by means of a robust regression, with the MASS package, in R-Script, done separately for Hazel and European beech.

First, a correlation between years has been computed. The heat maps shown in *Figure 14* show the Pearson correlation coefficients between years.

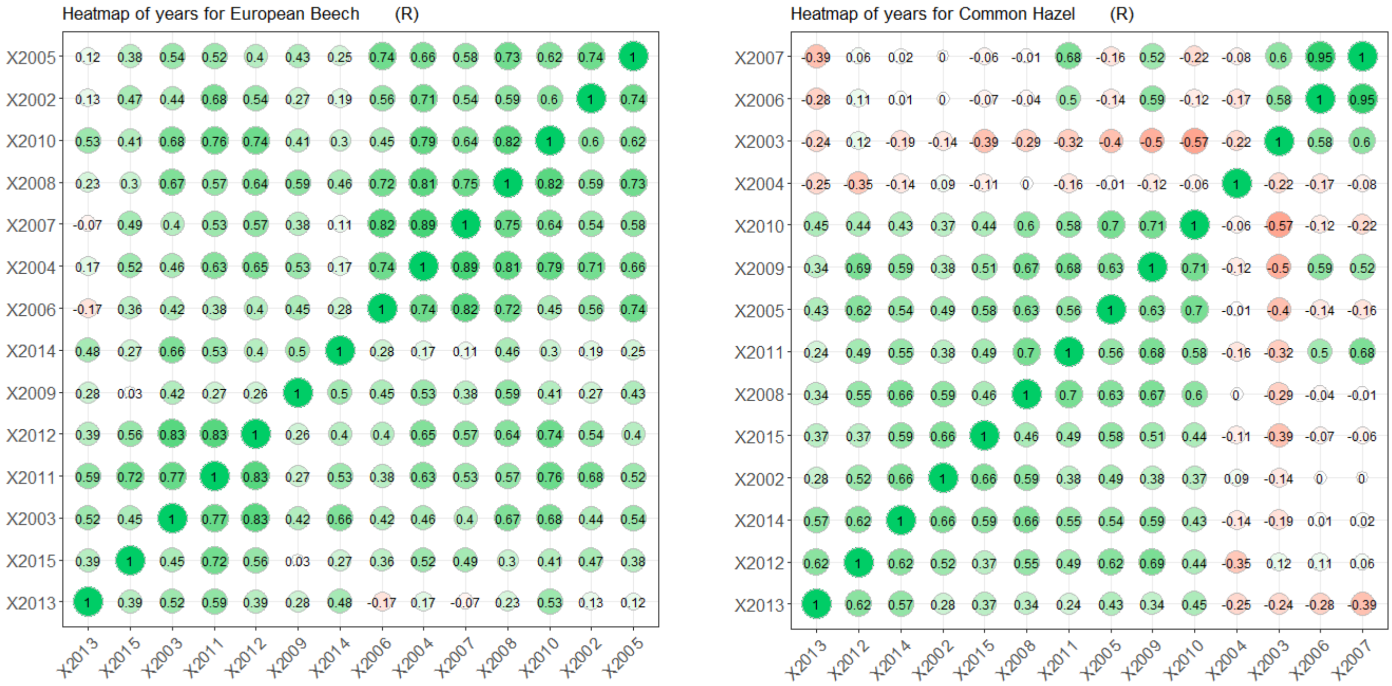


Figure 14: Heat map depicting the correlation between years, per species. The values represent the Pearson correlation coefficient. Left: common hazel. Right: European beech.

Second, within another iteration, the missing values have been filled by means of a robust regression between the current year and the years having high Pearson correlation coefficient values, starting with the year with the highest value and stopping at the lowest value higher than 0.5. More precise, the missing value of a station for a year, is replaced with the “synthetic” value calculated by regression, using a value of the same station from the available year which correlates best with the year of the missing observation.

Using this modelling technique, the number of observations has been significantly increased. Before gap filling, the European Beech data had 138 (24.7% of the total observations) and the Common Hazel had 186 (30.0% of the total observations) missing observations. After gap filling, the European Beech data were left with 16 (2.7%) and the Common Hazel with 55 (8.9%) missing observations.

3.4. Satellite Data

3.4.1. MODIS NDVI

In this study, the extraction of LSP parameters is based on MODIS data. MODIS is a imaging sensor, launched into Earth's orbit by NASA in 1999 on board the Terra (originally known as EOS AM-1) satellite, and in 2002 on board the Aqua (originally known as EOS PM-1) satellite. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. The Terra and Aqua satellites can view the entire Earth’s surface in 1 to 2 days, acquiring data in 36 spectral bands, ranging in wavelength from 0.4 µm to 14.4 µm. Two of the spectral bands offer data at a spatial resolution of 250 m, five bands at 500 m and the remaining 29 at a resolution of 1 km (Modis.gsfc.nasa.gov, 2018).

Two vegetation indices are derived from atmospherically-corrected reflectance in the red, near-infrared, and blue wavebands; the normalized difference vegetation index (NDVI), which provides continuity with NOAA's AVHRR NDVI time series record for historical and climate applications; and the enhanced vegetation index (EVI), which minimizes canopy-soil variations and improves sensitivity over dense vegetation conditions (Modis.gsfc.nasa.gov, 2018).

The data of both satellites is processed in a phased production providing a global NDVI with an improved temporal frequency of 8 days (Terra 16-days starting Day 001, Aqua 16-days period starting Day 009) (Solano et al., 2010).

In this study, collection 6 MOD13Q1 and MYD13Q1 products of the Terra and Aqua MODIS sensors from January 2002 to February 2018 has been used. The vegetation index used is NDVI. The data have been pre-processed, smoothed and interpolated by the BOKU IVFL Institute. First, the winter period (31.12 to 28.02) was excluded from the time-series, which was replaced by the 10^{th} percentile of NDVI values of each pixel. After that, the data was smoothed and interpolated with the Whittaker smoother (Eilers, 2003), providing a temporal resolution of one picture per day. Only every 7th image is saved representing each Monday, which results in a 7-day time series with 52 images per year and 840 images in total. The spatial resolution of this images is 250 m in sinusoidal projection. The images have been re-projected to the geographic coordinate system WGS84. The NDVI values have been scaled with 8 bits, meaning that 0 represents the lowest value and 250 the highest value, while 255 stands for missing data.

3.4.2. Extraction of PEP- station pixels

As mentioned before, the PEP725 database, provides coordinates for every station. Thus, in this step of the process, the MODIS NDVI pixels, where the PEP-stations obtained as a result of the LC selection (described in chapter 3.3.3.) are being located by using their coordinates, and their values are being saved for the whole time series of images. This has been accomplished in R-Script by saving the cell numbers of the images, where PEP-stations can be located, and then by extracting the values from this cell numbers from the whole stack of satellite images for the period January 2002 to February 2018. Additionally, for each station, also the 8 neighbouring pixels of each station are being checked for land cover, and the ones which are situated in broadleaf forest are being extracted from the stack of satellite images.

As a result, we get a comma-separated-values (CSV) file with time series of NDVI values for every PEP-station analysed in this research, and a CSV with time series of neighbouring pixels. Since we have 840 MODIS NDVI images, each time series consists of 840 values.

3.4.3. Extraction of SOS for each PEP-Station

The extraction of SOS has been done using TIMESAT version 3.2. TIMESAT is a software package for analysing time-series of satellite sensor data. It is a tool which enables the investigation of the seasonality of satellite time series, and the relationship of these time series with vegetation properties such as phenology (Web.nateko.lu.se, 2018). Some of the main features of the TIMESAT software as listed in the manual for the version 3.2 (Eklundh. and Jönsson, 2015) are:

- Several smoothing algorithms for time-series data
- Several methods for detecting outliers
- Weighting of data using quality information
- Fitting the upper envelope of the data
- Methods of defining start and end of season
- 11 seasonality parameters

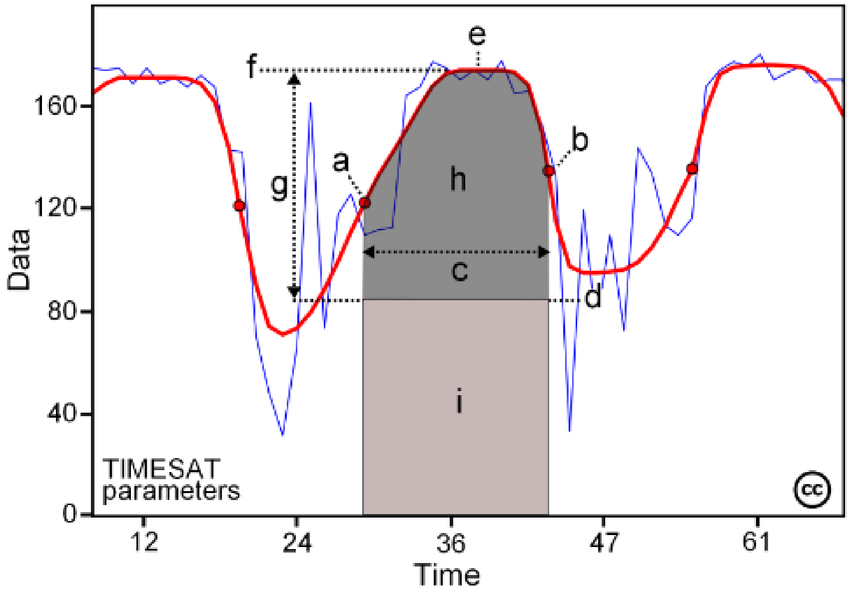


Figure 15: Figure 13: Some of the seasonality parameters generated in TIMESAT: (a) beginning of season, (b) end of season, (c) length of season, (d) base value, (e) time of middle of season, (f) maximum value, (g) amplitude, (h) small integrated value, (h+i) large integrated value (Eklundh and Jönsson, 2015)

Figure 15 depicts the phenological parameters, that can be calculated with TIMESAT, from a time-series of satellite data. The parameter of interest in this research, SOS, is labelled in the figure by (a). The SOS is the time for which the left edge has increased to a user defined level (often a certain fraction of the seasonal amplitude) measured from the left minimum level. The seasonal amplitude is the difference between the maximum value(f) and the base level (d).

3.4.3.1. TIMESAT Inputs

In order to be able to use our CSV-file with time-series obtained after extracting the pixel values of the PEP-stations (chapter 3.4.2), in TIMESAT, one needs to convert it to ASCII. The first row of this file has to contain the number of years in the time-series, followed by the number of data values per year, and the number of time-series in the file. The number of data values per year must be equal throughout the period. Because of the variation in days per year (365-366 days), for the years 2007 and 2012 we have 53 pictures instead of 52. For the purpose of having 52 values for every year in the time-series, the last value in December for 2007 and respectively, 2012 have been erased. Since for the year 2018 we had just 6 images, the values obtained from these have been erased. To sum this up, the ASCII file for TIMESAT, consists of 16 years of data (2002-2017), with 52 values per year. The number of time-series in the file, meaning the number of PEP-stations regarded in the analysis, depends upon the tree species which is being analysed—44 for European Beech and 46 for Common Hazel.

After loading the ASCII file with time-series, TIMESAT allows some settings, which define how the phenological parameters will be calculated. First, some additional filtering of the time-series can be done, using either Savitzki-Golay, Logistic or Gaussian fitting. After deciding upon a fitting method or no fitting, so called common settings can be adjusted. The *data range* can be set up by specifying the lower and upper data range. Data outside that range will be ignored. An *amplitude value* can be chosen between 0 and 39. This threshold value can be used to remove pixels with very weak seasonality from the processing, e.g. desert areas. The next available setting in this category is the *Spike method*. By selecting method 1, the single values that deviate more than a specific distance from the running median will be removed. A value of 2 denotes that spikes larger than two standard deviations from the running median will be removed. The value can be decreased to remove smaller spikes or increased to allow larger spikes (Eklundh. and Jönsson, 2015).

In this research the following common settings have been used:
- Data range: 0 to 250
- Amplitude value 0, because we want to include all pixels in the analysis,
- No spike method as there has been already applied a smoothing procedure.

Next, some class specific settings are available. The first class-specific setting is the *Seasonal parameter*. This can be set to 1, if we assume a single growing season per year, or to 0 if we assume dual seasons per year. Further, the *No. of envelope iterations* can be adjusted. When it is set to 1 no envelope adaptation is carried out, and when set to 3 maximum adaptation is done. This can be further fine-tuned using *Adaptation strength*. Minimum strength is 1 and maximum is 10. The *Force minimum setting* can be used to set minimum values to a certain value. Some very important settings for the outcome of the SOS are available in this section: *start/end of the season method* and percentage for *season start (*called threshold*)*. For the start/end of season method, we can choose between two options: start and end where fitted curve reaches a proportion of the seasonal amplitude measured from the left/right minimum value and start and end where fitted curve crosses a threshold value (Eklundh. and Jönsson, 2015).

In this research the following class-specific settings have been used:

- Seasonal parameter 1, because we have one growing season per year,
- No. of envelope iterations: 1, meaning that no envelope adaptation has been carried out,
- Force minimum has not been used.
- Start of season method: proportion of the seasonal amplitude.
- The percentage for the season start has been customized for each group of species, in order to get more accurate results. The exact percentages (thresholds) used will be discussed in the chapter *Results*

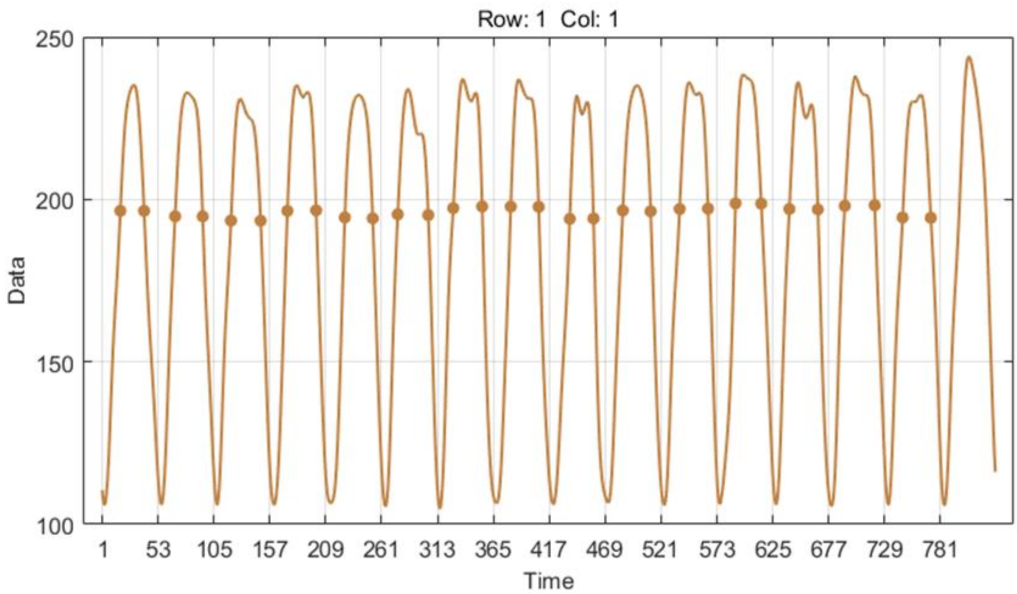


Figure 16: Time-series of the first PEP-station in the ASCI file, used as input in TIMESAT.

Figure 16 has been extracted from TIMESAT and shows how a PEP-station time-series is visualised, after all the settings have been inputted. On the y-axes the scaled NDVI-values are represented, while on the x-axes the time in weeks is shown. The dots mark the SOS and EOS for every year. This figure makes the seasonality very evident.

After inputting these settings, the ASCII data can be processed by using the *TSF_process* program of TIMESAT. The program will process the data row by row and will create two files: one with the *.tts* extension, which contains the time-series, and one with the .tpa extension, which contains the seasonality data.

Following the processing of the ASCII data, the seasonality information can be extracted by using the TIMESAT program *TSM_printseasons.* This program uses the .tpa file with seasonality data created with TSF_process, as input.

3.4.3.2. TIMESAT Output

The output of the TIMESAT program *TSM_printseasons* is a text file, containing seasonality parameters expressed in weeks. In TIMESAT, a time-series spanning n years will give seasonality parameters for n-1 years. In our case, the time-series inputted has 16 years, meaning that the output contains seasonality parameters for 15 years. Since we have output data for 15 years, the week number can vary between 1 and 780 (15*52).

Since the GP contains records expressed in day-of-year, the week-in-time-series number in the output of TIMESAT has been transformed to day-of-year by using R. Every seasonality parameter besides SOS has been dropped from the output file, since this one is the only one of interest in this research.
Next, the output has been transformed to a csv file, in which each row contains the SOS time-series of a PEP-station analysed in this research.

The result pro processing session in TIMESAT is a csv-file, with the exact same structure as the one obtained in the GP processing, but with LSP-SOS instead of GP-LU or GP-FF, as time-series elements. For every threshold used, we compute a csv-file of time-series. So, to sum this up, for the LSP we created several distinct sets of data.

3.5. Statistical Analysis

3.5.1. Correlation analysis

The first statistical analysis conducted for the purpose of this research has been the correlation analysis. This has been done at a station level, for each of the representative species of the species groups, separately. The correlation between the time-series of LSP and the time-series of GP of each PEP-station has been calculated using the Pearson r correlation coefficient and meaningful plots have been created by using the R *ggplot* library.

The Pearson r correlation coefficient is defined as the ratio of the covariance of two variables representing a set of numerical data, normalised to the square root of their variances. The Pearson correlation coefficient measures the strength of a linear association between two variables, thus indicates how far away the data points are to the line of best fit (Statistics.laerd.com, 2018). The Pearson correlation coefficient can take values between -1 and 1, and Evans 1996 proposes the following interpretation for the absolute value of r:

- 0.00-.19 “very weak”,
- 0.20-.39 “weak”,
- 0.40-.59 “moderate”,
- 0.60-.79 “strong”,
- 0.80-1.0 “very strong”.

In the course of the statistical analysis, each distinct set of data, obtained in the TIMESAT processing by using several thresholds, has been used. The thresholds will be further discussed in the chapter *Results*.

3.5.2. Evaluation of the model

For the purpose of evaluating the model, RMSE and MAE, which are both indicators of model performance, have been employed (Chai and Draxler, 2014). They are used to determine how close the modelled LSP-SOS values are, to the GP.

The RMSE has been widely used to measure model performance in a large variety of fields, such as: meteorology, air quality, and climate research studies (Chai and Draxler, 2014).The formula to calculate RMSE can be observed in *Figure 17*, where y_j are the predicted values at the time j, $\hat{y}_j$ are the actual observed values (ground truth) at the time j and n represents the number of samples. Thus, RMSE is, therefore, a quadratic scoring rule that also measures the average magnitude of the error (Goodarzi, 2016).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(y_j - \hat{y}_j)^2}$$

Figure 17: Formula of the RMSE (Chai and Draxler, 2014).

The MAE has also been widely used in the geosciences (Chai and Draxler, 2014). The formula of this indicator can be observed in *Figure 18*, where y_j , $\hat{y}_j$, j and n remain the same as for RMSE. The MAE measures the average magnitude of the errors in a set of predictions, without considering their direction (Goodarzi, 2016).

$$\mathrm{MAE} = \frac{1}{n}\sum_{j=1}^{n}|y_j - \hat{y}_j|$$

Figure 18: Formula of the MAE (Chai and Draxler, 2014).

In our case, the y_j is represented by the LSP data, while the actual observed data $\hat{y}_j$ is represented by the GP.

While both RMSE and MAE have been extensively documented throughout geosciences literature, there is no consensus on which is the most suitable for measuring model performances (Chai and Draxler, 2014). Therefore, for the purpose of this research, both RMSE and MAE have been computed. This was achieved with the help of the R Script with the library *hydroGOF*.

RMSE and MAE have been calculated both at station and at year level. Detail on the outcomes will follow in the chapter *Results*.

3.5.3. Exploratory data analysis

The dependence of GP SOS on environmental variables such as altitude and geographical position has been investigated. The influence of altitude (metadata information of the stations) has been determined by doing a hierarchical cluster analysis. This has been achieved in R Script with the library *stats* by using Ward's method with the function *hclust*. The Euclidian distance between the As inputs for the cluster analysis, the Euclidean distances between the mean SOS per PEP-stations have been used. The dependence on the geographical position has been investigated by creating a map of the study area with the GP SOS, for each year. The GP values are plotted using a meaningful colour scale.

An inter-station variability analysis has been done in order to outline the difference between the onset of spring phenology between PEP stations. For this purpose, box plots for every station have been created in R Script, by using the time-series of GP SOS.

In order to analyse the difference between years regarding the SOS, an inter-annual variability analysis for each species group, has been done. For this purpose, the LSP and the GP have been analysed separately for each individual year. The main aims of this step are to detect the differences in SOS between years and to establish if a trend regarding the onset of spring phenology can be observed. In order to accomplish this, R Script has been used with the library *ggplot*, and meaningful figures in the form of box plots have been created for every species group. These figures contain also the regression line which is meant to outline the trend. The figures can be found in the chapter *Results*.

For a better understanding of the relationship between GP SOS and LSP SOS, a regression analysis has been done, for each one of the representative species, separately, by computing scatterplots. This has been executed for the whole datasets, containing each PEP station, and for each station separately.

4. Results

The results will be structured in two main chapters *Correlation analysis and evaluation of the model* and *Exploratory data analysis*.

4.1. Correlation analysis and evaluation of the model

The correlation analysis has been performed for both species groups, with their representatives European Beech and Common Hazel. For these species, the correlation between GP-SOS and LSP-SOS has been done per station. For this analysis, all versions of the LSP-SOS have been compared with the GP-SOS. For the European Beech the LSP-SOS has been computed with thresholds of 0.5, 0.7 and 0.8 of the seasonal amplitudes. For the Common Hazel the LSP-SOS has been computed with thresholds of 0.2 and 0.1.The motives behind choosing these thresholds will be presented in sections 4.1.1. and 4.2.2.. For the GP-SOS, the modelled version has been used (with gap filling using a robust regression).

The bar graphs (Fig. 17-23) which follow in support of this analysis are standardised, showing a bar per PEP-station, depicting the value of the correlation coefficient. The y-axis shows the values of the correlation coefficient, which can range between -1 and 1. The x-axis shows the PEP-ID of each station. The correlations which are significant (p value less than 0.05) are marked with green, and the correlations which are not significant (p greater than 0.05) are marked with red.

Each pair of GP-SOS and LSP-SOS has been evaluated by means of RMSE and MAE. This has been achieved at both year and station level.

4.1.1. European Beech

In the course of the inter-station variability analysis (see 4.2.2.), it was established that the mean GP-SOS per station of the European Beech, occurs around day 111—relatively late in comparison with the Common Hazel. Because of that, the LSP of the European Beech has been calculated at first with a threshold of 0.5 of the seasonal amplitude. *Figure 19* shows the correlation between GP-SOS and LSP-SOS per station, using a threshold of 0.5. For this threshold, 34% of the stations correlated positively, with 3 stations showing correlation coefficients of more than 0.8.

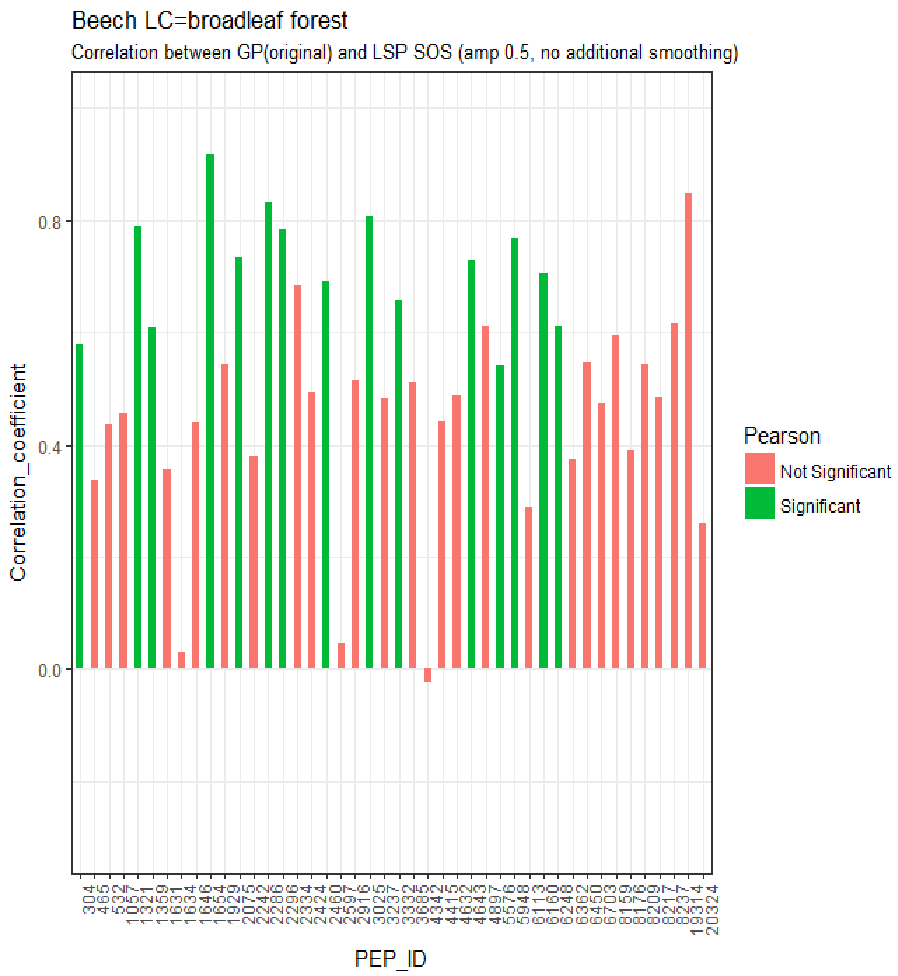


Figure 19: Correlation analysis between GP-SOS and LSP-SOS per station for the European Beech. Threshold used for the calculation of LSP-SOS: 0.5.

In the next step, a bigger threshold of 0.7 has been used. *Figure 20* shows the correlations per station using a threshold of 0.7. This threshold increases the number of positive correlations significantly, with 75% of the stations correlating positively and 6 stations showing correlation coefficients higher than 0.8. As depicted in the *Figure 21,* for a threshold of 0.8, 72% of the stations correlate positively. Thus, the LSP-SOS computed by using a threshold higher than 0.7, seem to deliver poorer results.

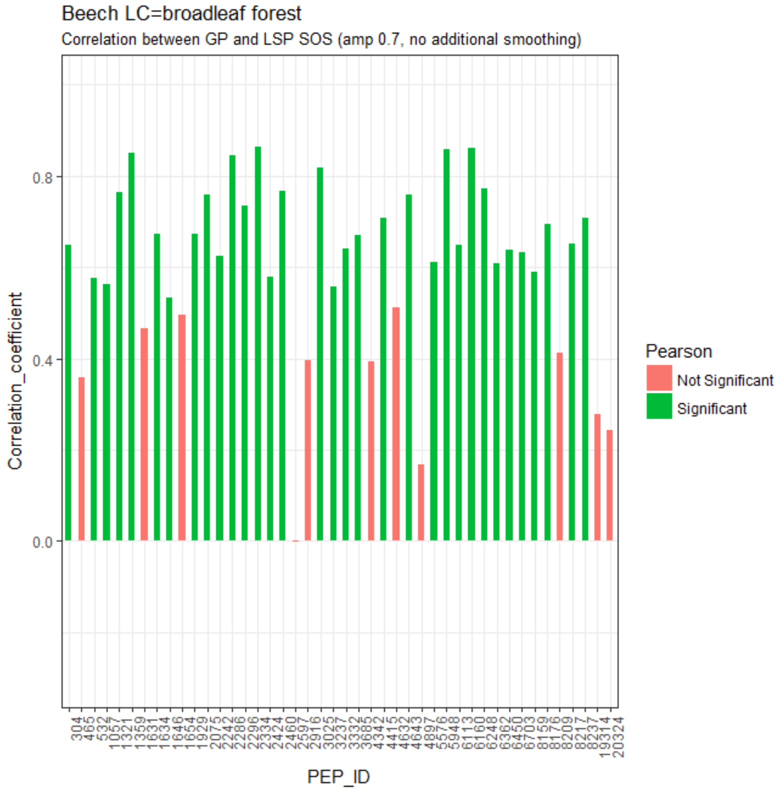


Figure 20:Correlation analysis between GP-SOS and LSP-SOS per station for the European Beech. Threshold used for the calculation of the LSP-SOS: 0.7.

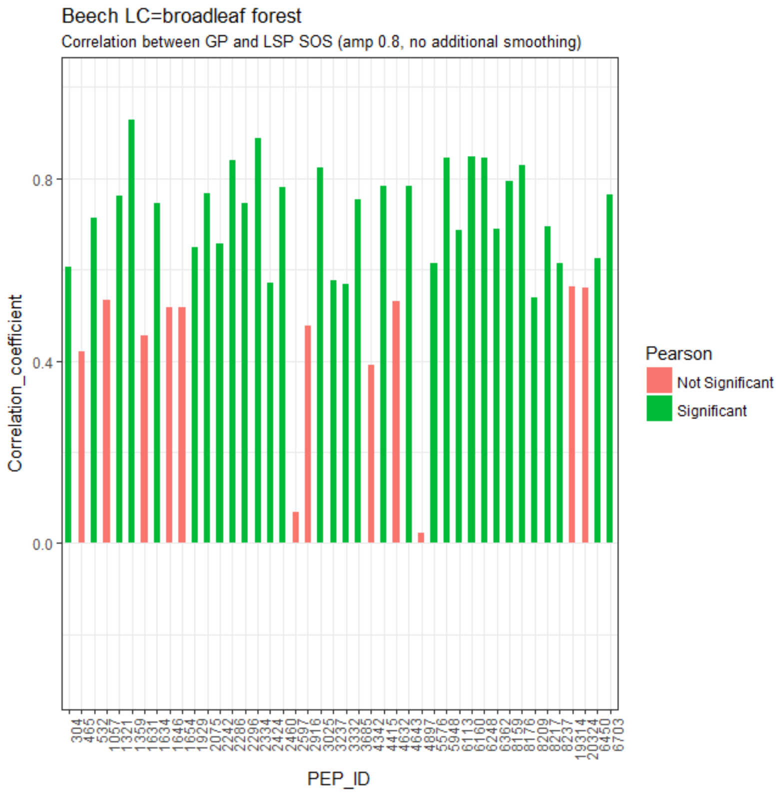


Figure 21: Correlation analysis between GP-SOS and LSP-SOS per station for the European Beech. Threshold used for the calculation of the LSP-SOS: 0.8.

Table 5 shows every threshold used for the European Beech with the percentage of significant correlations, and the evaluation of the model with its indices RMSE and MAE. The best results have been obtained for the threshold 0.7. The analysis shows a mean RMSE per year of 11.47 days and per station of 11.02 days. The mean MAE per year for this threshold is of 9.04 days and per station is of 9.17 days. This means that the simulated observation - LSP-SOS, occur later than the actual observations GP-SOS with 11.47 or 9.04 days when each year is compared and with 11.02 or 9.17 days when PEP-station is compared.

Table 5: Percent of positive correlations, RMSE and MAE for European Beech, for each version of LSP-SOS.

European Beech LSP-SOS Threshold	**Positive correlations [%]**	**RMSE/Year [days]**	**RMSE/Station [days]**	**MAE/Year [days]**	**MAE/Station [days]**
0.5	34%	20.29	19.19	17.98	17.87
0.7	75%	11.47	11.02	9.04	9.17
0.8	72%	16.17	15.15	13.63	13.71

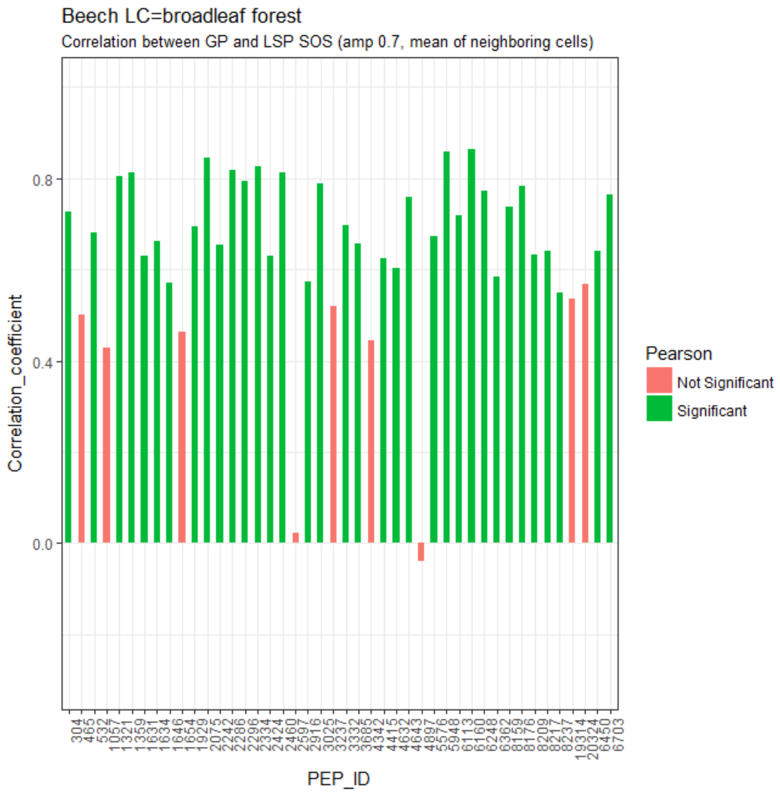


Figure 22: Correlation analysis between GP-SOS and LSP-SOS per station for the European Beech. Threshold used for the calculation of the LSP-SOS: 0.7. For each PEP-station, the mean of the neighboring pixels with broadleaf forest as land cover has been used.

Using the threshold of 0.7, which delivered the best results in the evaluation of the model, a LSP-SOS has been computed by calculating for each station the mean of the direct neighbouring pixels having broadleaf forest as land cover. The correlation between these data and GP-SOS has been analysed. The results are shown in *Figure 22.* 79.5% of the stations correlate positively, with 8 stations having a correlation coefficient of more than 0.8. The model has been evaluated once more with the results shown in *Table 6*. Both RMSE and MAE are improved when computed between years as well as between stations.

Table 6: Percent of positive correlations, RMSE and MAE for European Beech, for the threshold 0.7 and LSP.SOS for each PEP-station, calculated as mean of the neighbouring pixels.

European Beech LSP Threshold	Positive correlations [%]	RMSE/Year [days]	RMSE/Station [days]	MAE/Year [days]	MAE/Station [days]
0.7	79.5%	10.87	10.29	8.77	8.78

4.1.2. Common Hazel

In the course of the inter-station variability analysis (see 4.2.2.), it was established that the mean GP-SOS per station, for the Common Hazel, occurs around day 51, about 60 day earlier than that of the European Beech. For this reason, the thresholds used for the computation of the LSP-SOS have been lowered to 0.2 and 0.1. In order to ensure that LSP-SOS and GP-SOS do not correlate at a later point in time, an additional threshold of 0.5 has been tried out.

First, as shown in *Figure 23*, the correlation between GP-SOS and LSP-SOS has been computed using the LSP-SOS calculated with a threshold of 0.2. For this threshold, 43% of the stations correlate positively, while only 3 stations have a correlation coefficient of at least 0.8.

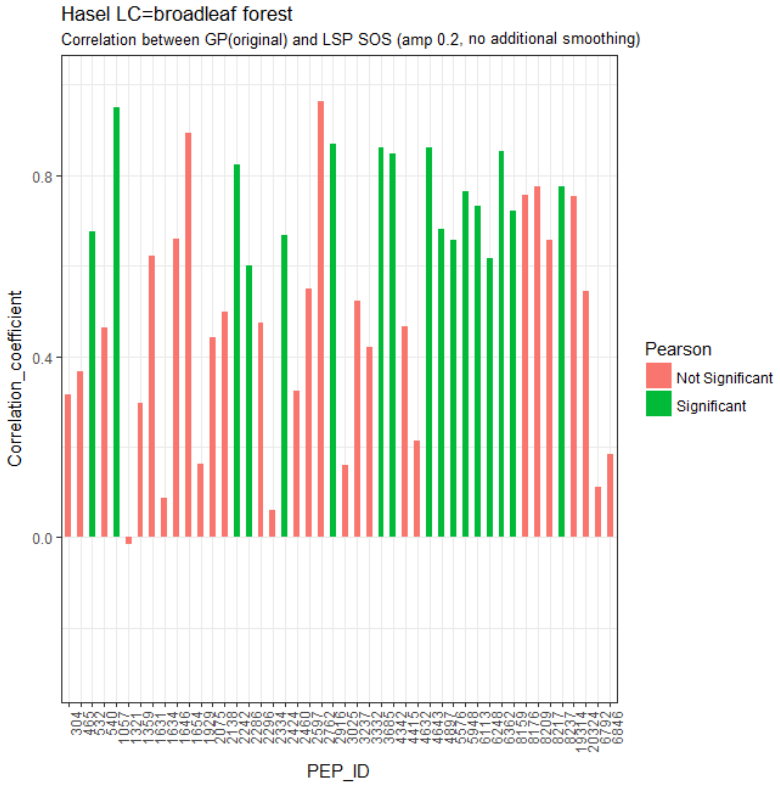


Figure 23: Correlation analysis between GP-SOS and LSP-SOS per station for the Common Hazel. Threshold used for the calculation of LSP-SOS: 0.2.

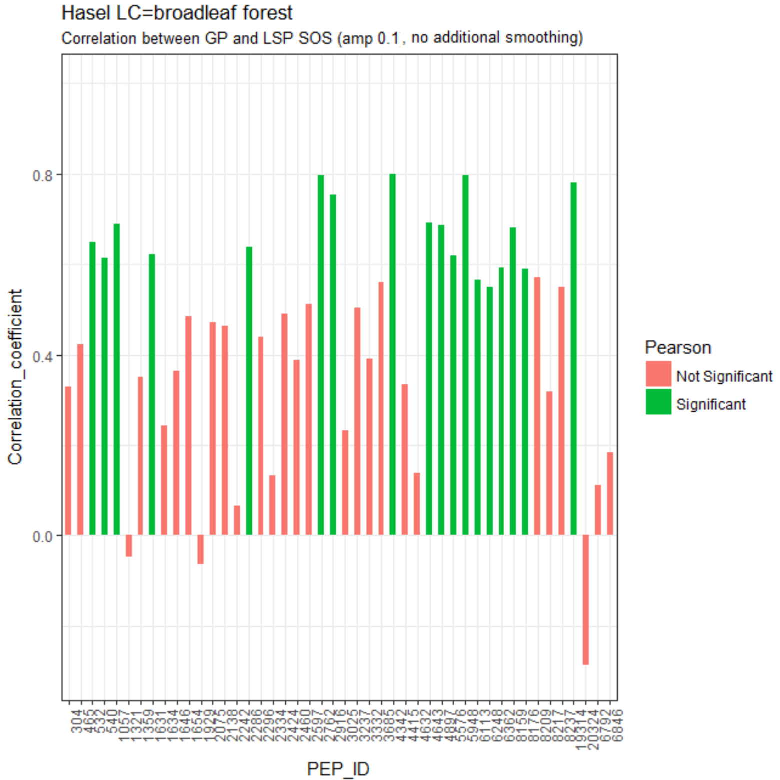


Figure 24: Correlation analysis between GP-SOS and LSP-SOS per station for the Common Hazel. Threshold used for the calculation of LSP-SOS: 0.1.

Second, as depicted in *Figure 24*, the correlation has been computed using the LSP-SOS calculated with a threshold of 0.1. For this threshold value, 39% of the PEP-stations correlate positively, with 3 having a correlation coefficient of at least 0.8.

In order to make sure that the GP-SOS, which in the case of the common Hazel is FF, does not correlate with LSP at a later point, a higher threshold of 0.5 has been computed as shown in *Figure 25*. In this case, 37% of the stations correlate positively, with no station having a higher correlation coefficient than 0.8.

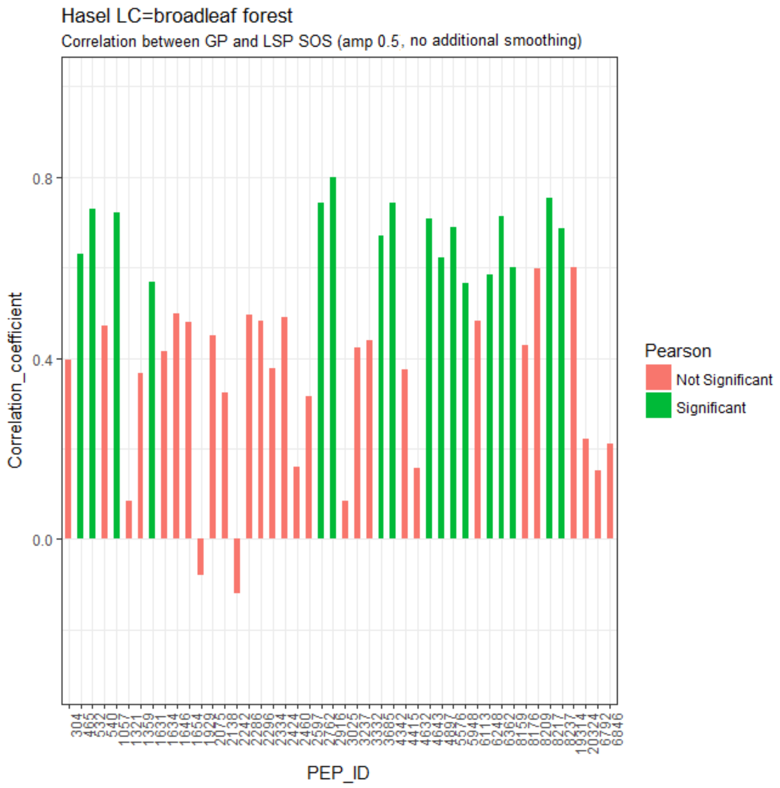


Figure 25: Correlation analysis between GP-SOS and LSP-SOS per station for the Common Hazel. Threshold used for the calculation of LSP-SOS: 0.5.

In *Table 7*, every threshold used for the Common Hazel is shown with the percentage of positive correlations and with the evaluation of the model, represented by RMSE and MAE. According to RMSE and MAE the threshold of 0.1 has delivered the best result. The computed RMSE per year is 33.36 days while the computed RMSE per station is 22.02. The MAE yields smaller differences between the models, with 22.89 days per year and 22.35 days per station. This means that the simulated observations - LSP-SOS, occur later than the actual GP-SOS with 33.36 or 22.89 days when years are compared and with 28.02 or 22.35 days when PEP-stations are compared.

Table 7: Percent of positive correlations, RMSE and MAE for Common Hazel, for each version of the LSP-SOS.

Common Hazel LSP-SOS Threshold	**Positive correlations [%]**	**RMSE/Year [days]**	**RMSE/Station [days]**	**MAE/Year [days]**	**MAE/Station [days]**
0.2	43%	37.32	32.56	27	26.67
0.1	39%	33.36	28.02	22.89	22.35
0.5	37%	56.69	53.16	49.67	49.20

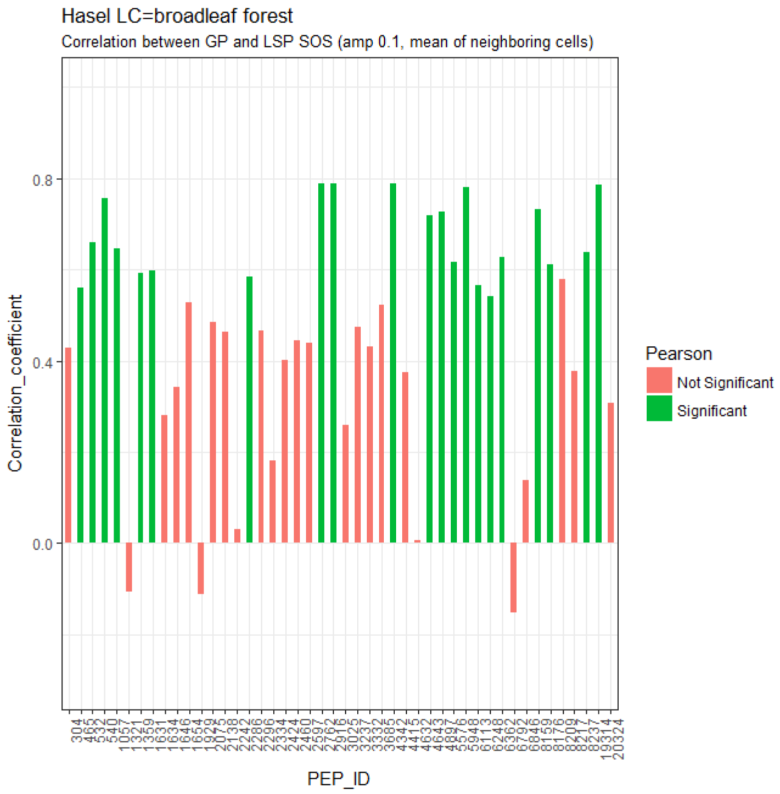


Figure 26: Correlation analysis between GP-SOS and LSP-SOS per station for the Common Hazel. Threshold used for the calculation of the LSP-SOS: 0.1. For each PEP-station, the mean of the neighboring pixels with broadleaf forest as land cover has been used.

For the threshold of 0.1, which delivered the best result upon the evaluation of the model, an LSP-SOS has been computed by calculating for each station the mean of the direct neighbouring pixels with broadleaf forest as land cover. The correlation between this data and the GP-SOS has been analysed. The results are depicted in the *Figure 26*. For this situation, 45,65% of the PEP-stations correlate positively. The evaluation of the model has been again computed and is shown in the *Table 8*. As can be observed, by computing the mean of the neighbouring pixels the percentage of positive correlations has been improved, but the values of RMSE and MAE have increased by 0.3 on average.

Table 8: Percent of positive correlations, RMSE and MAE for Common Hazel, for the threshold 0.1 and LSP.SOS for each PEP-station, calculated as mean of the neighboring pixels.

Common Hazel LSP Threshold	**Positive correlations [%]**	**RMSE/Year [days]**	**RMSE/Station [days]**	**MAE/Year [days]**	**MAE/Station [days]**
0.1	45,65%	33.67	28.16	22.96	22.43

4.2. Exploratory data analysis

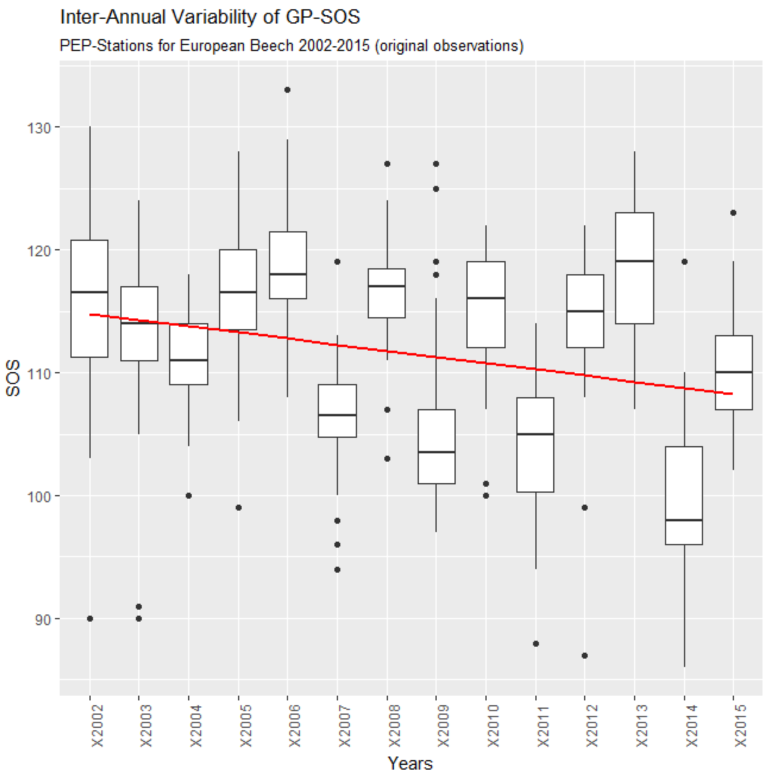
Following the correlation analysis, in order to be able to get a better sense of both the GP-SOS and LSP-SOS as well as their relationship with each other, an exploratory data analysis has been carried out. The results of this analysis will be structured around four main topics: inter-annual variability, inter-station variability, regression analysis and environmental variables. For the topics which analyse LSP, the data sets with the best results in the evaluation of the model have been used: LSP computed with a threshold of 0.7 for the European Beech, and LSP computed with a threshold of 0.1 for the Common Hazel.

4.2.1 Inter-annual variability

The results of the inter-annual variability analysis will be shown for both GP and LSP for the two species groups with European Beech and Common Hazel as representative species. The figures that follow in support of this analysis are standardised. The y-axes represent the SOS in days, while the x-axes represent the years composing our time-series: 2002 to 2015. Each boxplot represents the distribution of SOS in a year, with the black lines marking the median. The red line represents the regression line.

4.2.1.1 European Beech

Figure 27 shows the inter-annual variability of GP-SOS for the European Beech, using the original data (without gap filling) and the gap filled data (obtained by means of robust regression). The two figures are almost identical, the distributions and the regression line do not show any change, confirming the fact that the robust regressions serve only as gap filling and does not change the outcome of the analysis.



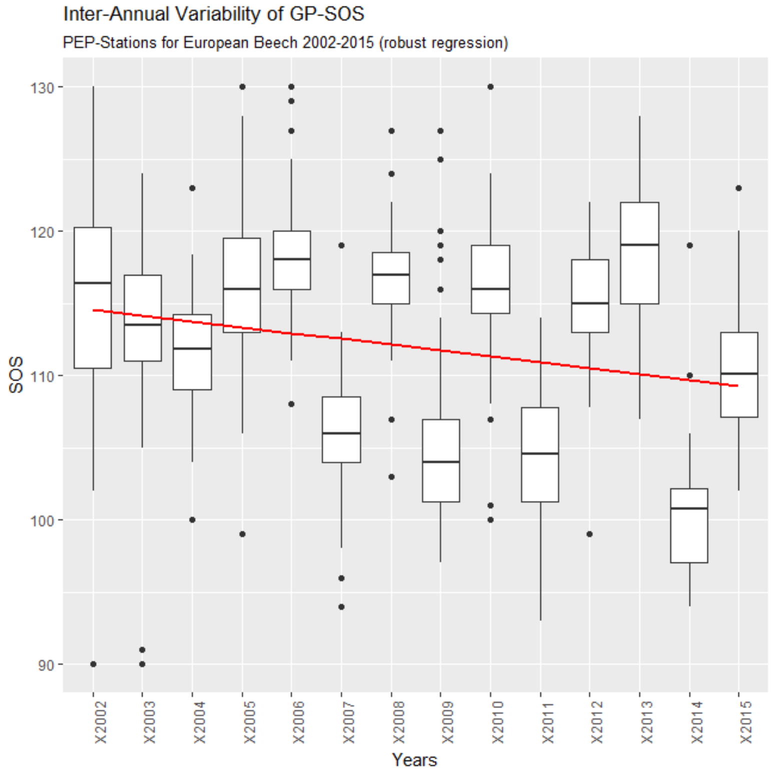


Figure 27: Inter-annual variability of GP-SOS for European Beech, with original values (upper image) and with gap filled data by means of robust regression (lower image).

As can be seen in the figures above, the GP-SOS of the European Beech can be observed mostly between day 95 and day 125 (meaning early march to beginning of April), with only few exceptions. Cleary, some extreme years can be identified. The years 2007, 2009, 2011 and 2014 show lower SOS, suggesting that the onset of spring has been earlier in that years. Opposite from that, 2013, shows a higher median line than the other years, meaning that on average, the SOS occurred earlier. The regression lines show a decreasing trend, which indicates an earlier onset of spring.

Figure 28 shows the inter-annual variability of LSP-SOS for the European Beech. Upon a close comparison with the GP-SOS figures, both similarities and differences can be identified. The LSP- SOS ranges mostly between day 90 and day 130 (meaning early march to middle of April), with few exceptions. Therefore, it covers a larger time window than GP-SOS. A more obvious difference can be observed when comparing the years 2002-2005. LSP shows they have very close medians, meaning that, on average the SOS occurs roughly around the same date, while GP shows significant differences between them, with the SOS in 2004 occurring considerably earlier. The years 2007, 2009, 2011, 2014 and 2015 show earlier LSP-SOS. Except for 2015, the same has been observed for GP-SOS as well. On the other side, 2006 and 2010 show higher LSP-SOS than the other years—in the GP SOS figure they are closer to the average. Similarly, to GP-SOS, the regression line shows a decreasing trend.

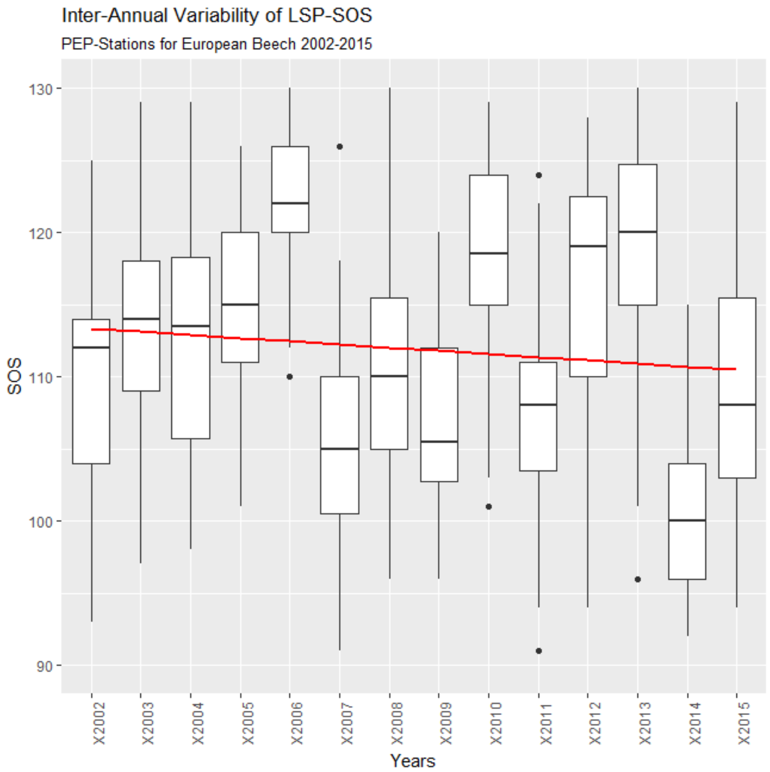
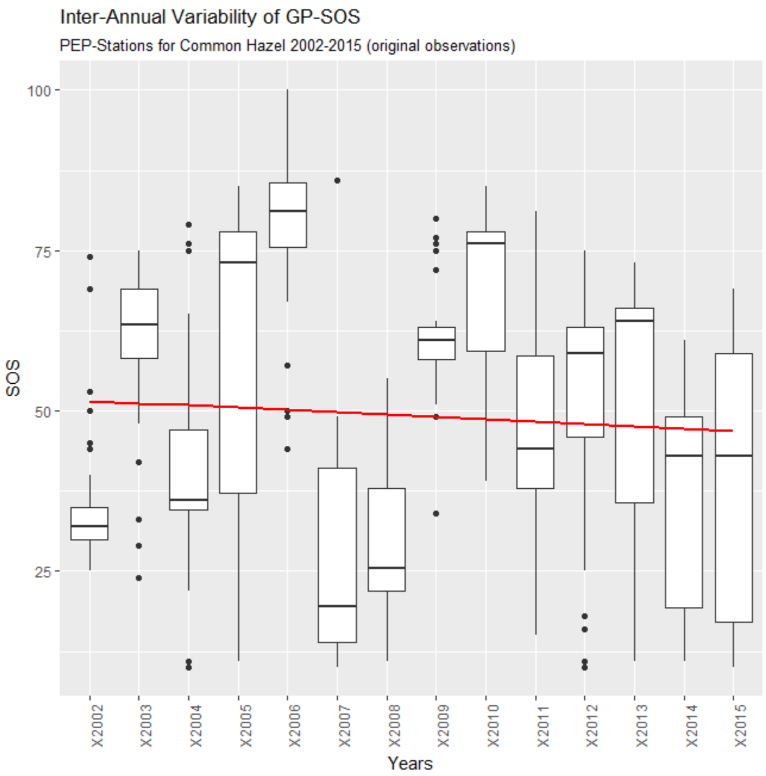


Figure 28: Inter-annual variability of LSP-SOS for European Beech

4.2.1.2. Common Hazel

Figure 29 shows the inter-annual variability of GP-SOS for Common Hazel, using the original data (without gap filling) and the gap filled data (by means of robust regression). Similarly, to the figures for the European Beech, the two figures are very similar, just for the years 2012 and 2014 some changes are visible, because the data contained very few observations for those years, so more values were filled in.



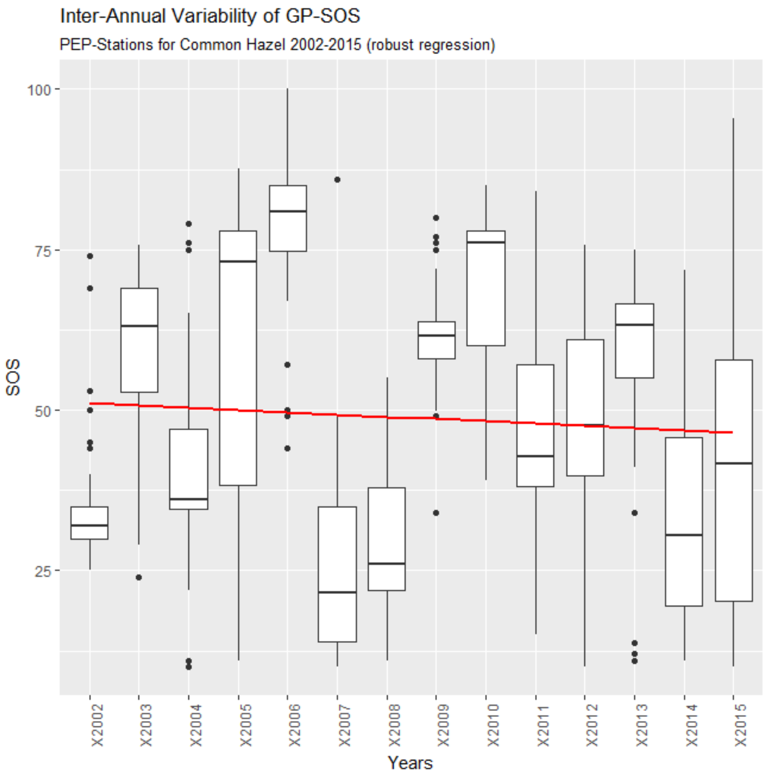


Figure 29: Figure 27: Inter-annual variability of GP-SOS for Common Hazel, for the original data, without gap filling (upper image) and with gap filling by means of a robust regression (lower image).

As can be observed from the figures, the GP-SOS of Common Hazel is spread approximately between day 15 and day 90 (middle January to early March), occurring considerably earlier and covering a broader time window than the SOS of European Beech.

Some extreme years can be identified. The GP-SOS of the years 2007 and 2008 occurred on average around day 25 or even earlier, meaning that the onset of spring for this species has taken place as early as January. At the other end, the GP-SOS of the year 2006 occurred on average around day 80, and that of year 2011 around day 75. Similarly, with the European Beech, the regression line shows a decreasing trend.

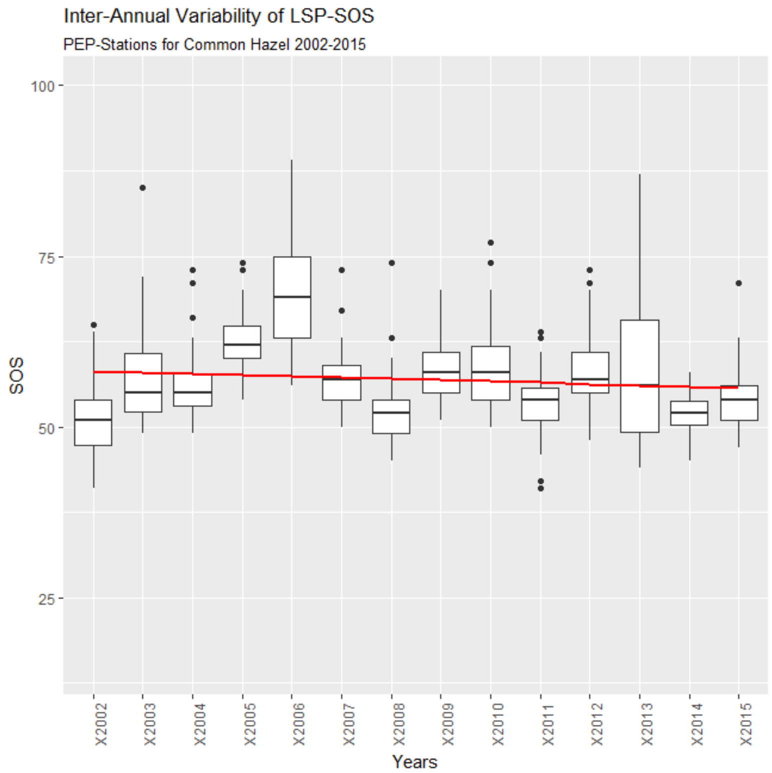


Figure 30: Inter-annual variability of the LSP-SOS for the Common Hazel.

Figure 30 shows the inter-annual variability of the LSP-SOS for the Common Hazel. Again, both similarities and differences between LSP and GP can be found. Firstly, the SOS spreads mostly between day 45 and day 80 (mid-February to mid-March), covering a smaller time window than the GP-SOS. Secondly, extreme years can be identified again. According to the LSP, the SOS of the year 2002 occurred earlier than in the other years, on average around day 50. At the opposite side, the SOS of the year 2006 occurred the latest, on average around day 70. The regression line has, again, a decreasing trend.

4.2.2. Inter-station variability

The results of the inter-station variability analysis will be shown for both GP and LSP for the two species groups with European Beech and Common Hazel as representative species. This analysis comes in support of the findings of the inter-annual analysis. The figures which will follow are standardised. The y-axis represents the SOS in days, and the x-axis represents the PEP-stations, labelled with the PEP-ID. Each boxplot represents the distribution of SOS for a PEP-station in the time frame 2002 to 2015. In order to make the figures more suitable for comparison, the y-axis has been limited to the same interval, day 0 to day 150.

4.2.2.1 European Beech

Figure 31 presents the inter-station variability of GP-SOS for the 44 PEP-stations with European Beech. The mean SOS occurs around day 111, which means mid-April. The mean standard deviation between stations is of 7.45 days. As can be observed from the figure, the distributions for each station are quite heterogeneous, having distinct medians and covering distinct time windows.

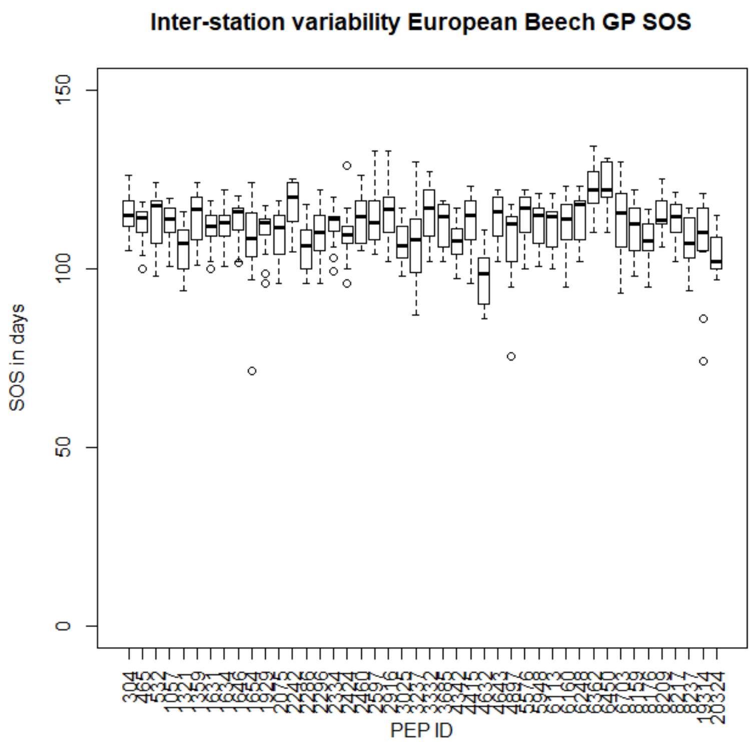


Figure 31: The inter-station variability of GP-SOS for the European Beech.

Figure 32 presents the inter-station variability of LSP-SOS for European Beech. The mean SOS occurs in mid-April, around day 112. The mean standard deviation between station is of 10.52 days, marginally higher than that of GP-SOS. The distributions of the stations seem to be more heterogeneous than those of GP-SOS.

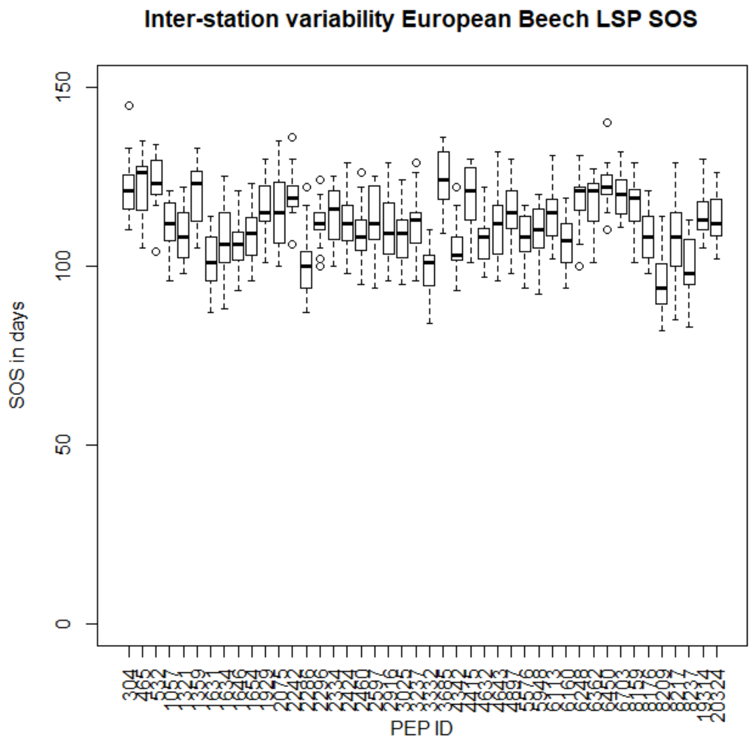


Figure 32: The inter-station variability of LSP-SOS for the European Beech.

4.2.2.2. Common Hazel

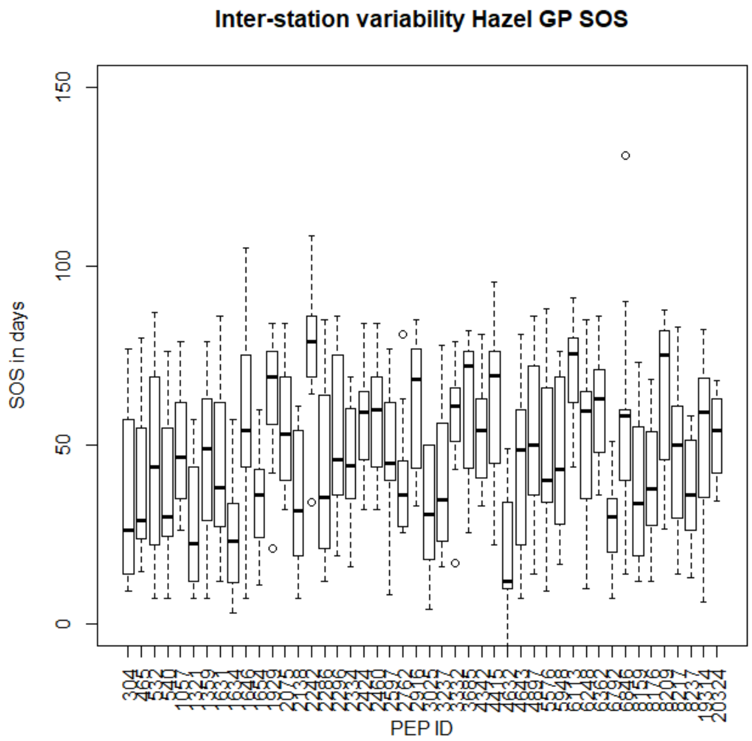


Figure 33: The inter-station variability of GP-SOS for the Common Hazel.

Figure 33 presents the inter-station variability of the GP-SOS for the 46 PEP-stations with Common Hazel. The mean SOS occurs in late February, at day 51. The mean standard deviation between stations is of 26 days. In comparison with the GP-SOS of the European Beech, the PEP-stations vary even more from each other and the time window for each station is considerably larger.

Figure 34 presents the inter-station variability of LSP-SOS for Common Hazel. The mean SOS occurs around day 58. The standard deviation is 8 days, considerably smaller than that of GP-SOS. Thus, the time window for the occurrence of LSP-SOS each year is considerably smaller. Similarly, the distribution of LSP-SOS is less heterogeneous.

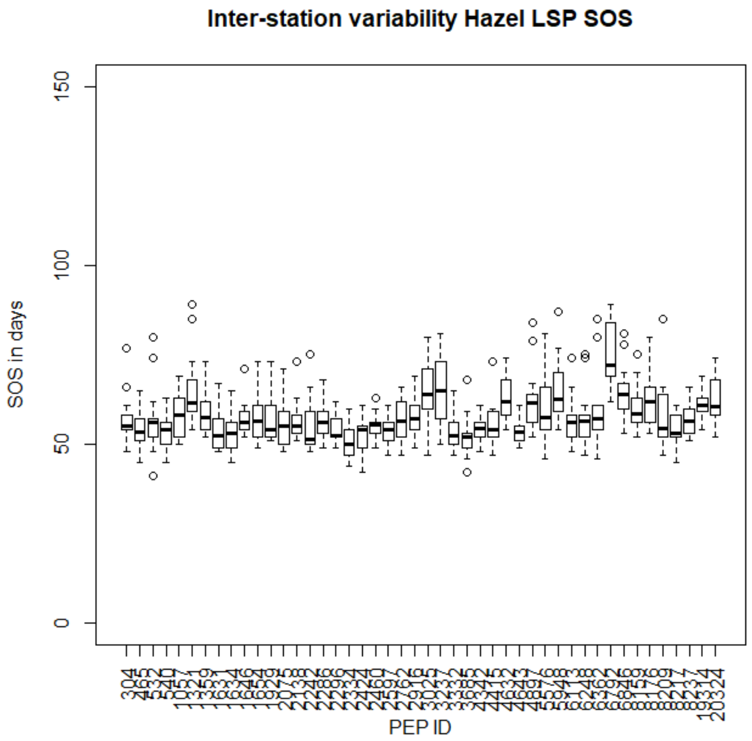


Figure 34: The inter-station variability of LSP-SOS for the Common Hazel.

4.2.3. Regression analysis

The regression analysis has been performed on the basis of scatter plots between GP-SOS and LSP-SOS. The analysis was performed for both species groups, with their representatives European Beech and Common Hazel, by using the LSP-SOS which has delivered the best results in the model evaluation; and for all stations together and then, separately. The stations considered were, on the one hand, those with high significant correlations and, on the other hand, those with very low, non-significant correlations. The scatter plots presented for European Beech and Common Hazel in the following two subchapters are standardised. The x-axis represents the GP-SOS, the y-axis represents the LSP-SOS, and the blue line depicts the regression line. The colour coding of the years is shown on the right side of every figure, while the species and the threshold used are mentioned in the lower right side.

4.2.3.1. European Beech

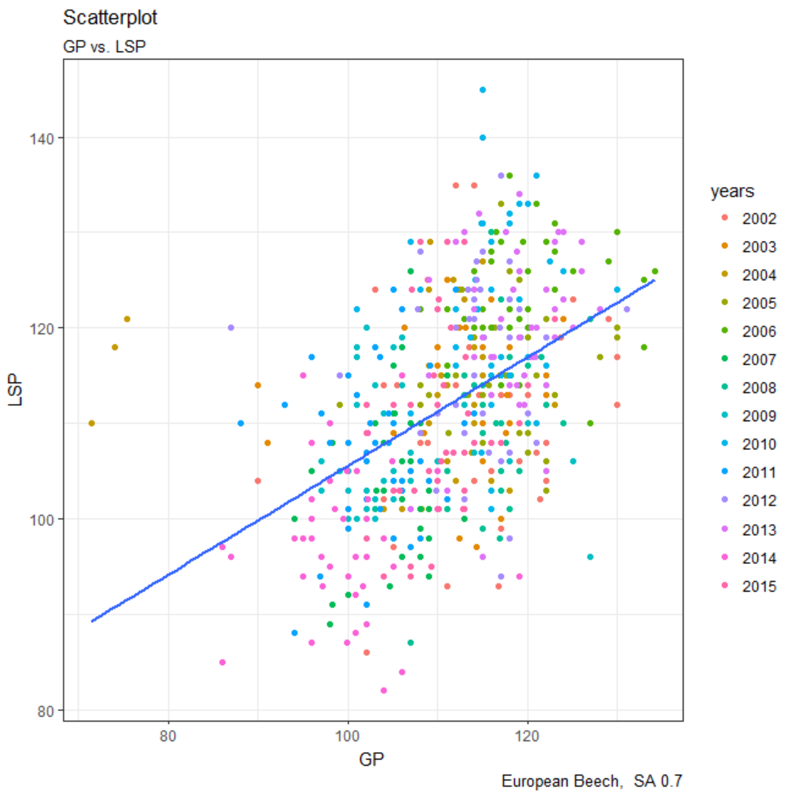


Figure 35: Scatterplot with the distribution and regression line between GP-SOS and LSP-SOS for the European Beech.

The scatter plot in *Figure 35* shows the relationship of GP-SOS with the LSP SOS computed with a threshold of 0.7 for the European Beech. As can be observed, the regression line shows a linear positive relationship between the two datasets. While some data points fit the regression line, most of them are scattered away from the regression line, suggesting that the relationship between datasets is week. Because of this finding, scatter plots for stations with high significant correlations and, on the opposite side, for stations with low, non-significant correlations have been generated.

The two upper images of *Figure 36* show PEP-stations for which LSP-SOS correlates significantly with GP-SOS. As can be observed, the data shows a linear positive relationship, and tends to align itself and be closer to the regression line. On the opposite site, in the lower two images of this figure, two examples of PEP-Stations which correlate poorly and not significantly are shown. The data in this images seems to have no relationship at all with the regression line.

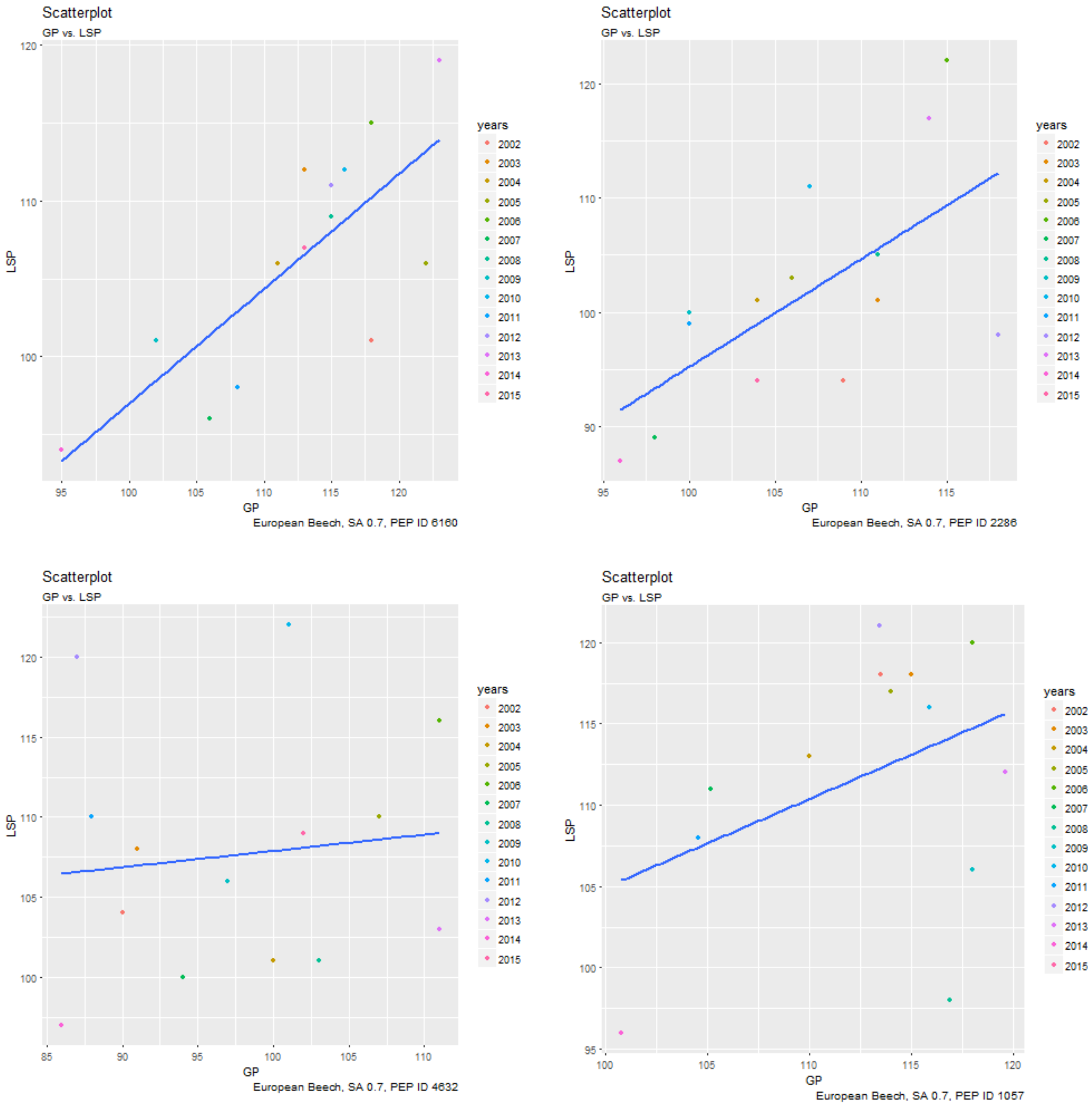


Figure 36: Scatter plots of single PEP-Stations between GP-SOS and LSP-SOS for European Beech. The upper images show examples of stations who correlate significantly, while the lower images are examples of stations who do not correlate significantly.

4.2.3.2. Common Hazel

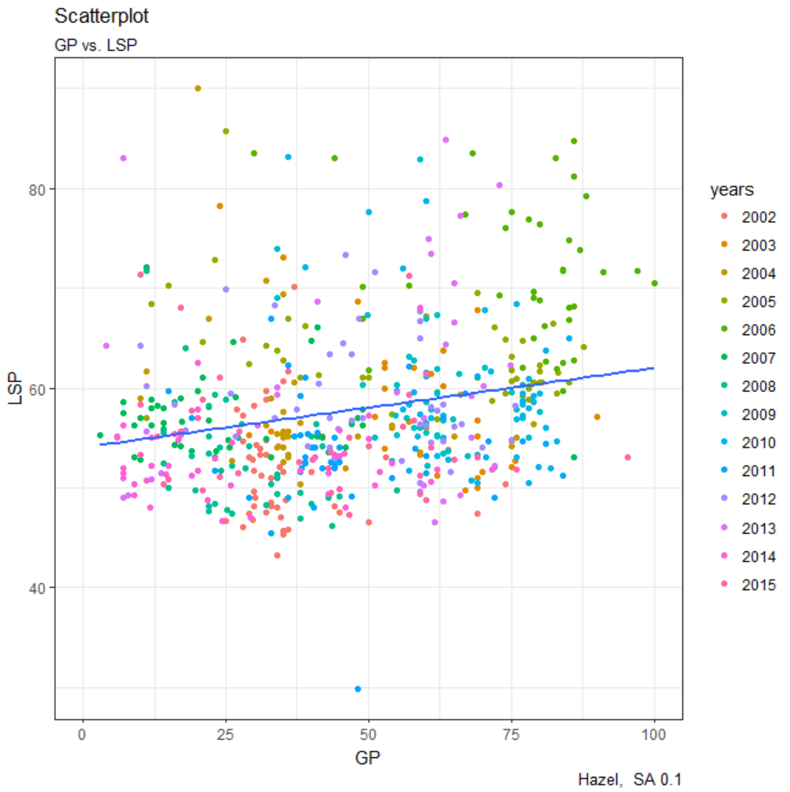


Figure 37: Scatterplot showing the distribution and regression line between GP-SOS and LSP-SOS for the Common Hazel.

The scatter plot in *Figure 37* shows the relationship of GP-SOS with the LSP-SOS, computed with a threshold of 0.1, for the Common Hazel. The regression line shows a positive relationship between the two datasets. However, the data is very scattered and seems to have no apparent relationship to the regression line.

In order to get a better sense of the data, again scatter plots for significant and not significant individual stations have been computed. These plots can be observed in *Figure 38*. The upper two images show PEP-stations with positive significant correlations, while the lower two images show PEP-stations with very poor not significant correlation. Similarly, with the findings for the European Beech, the data for the significant correlations shows linear positive relationship and a certain alignment with the regression line, while the data for the not significant correlations does not seem to have any relationship with the regression line. In the lower left image, the regression line shows even a negative linear relationship.

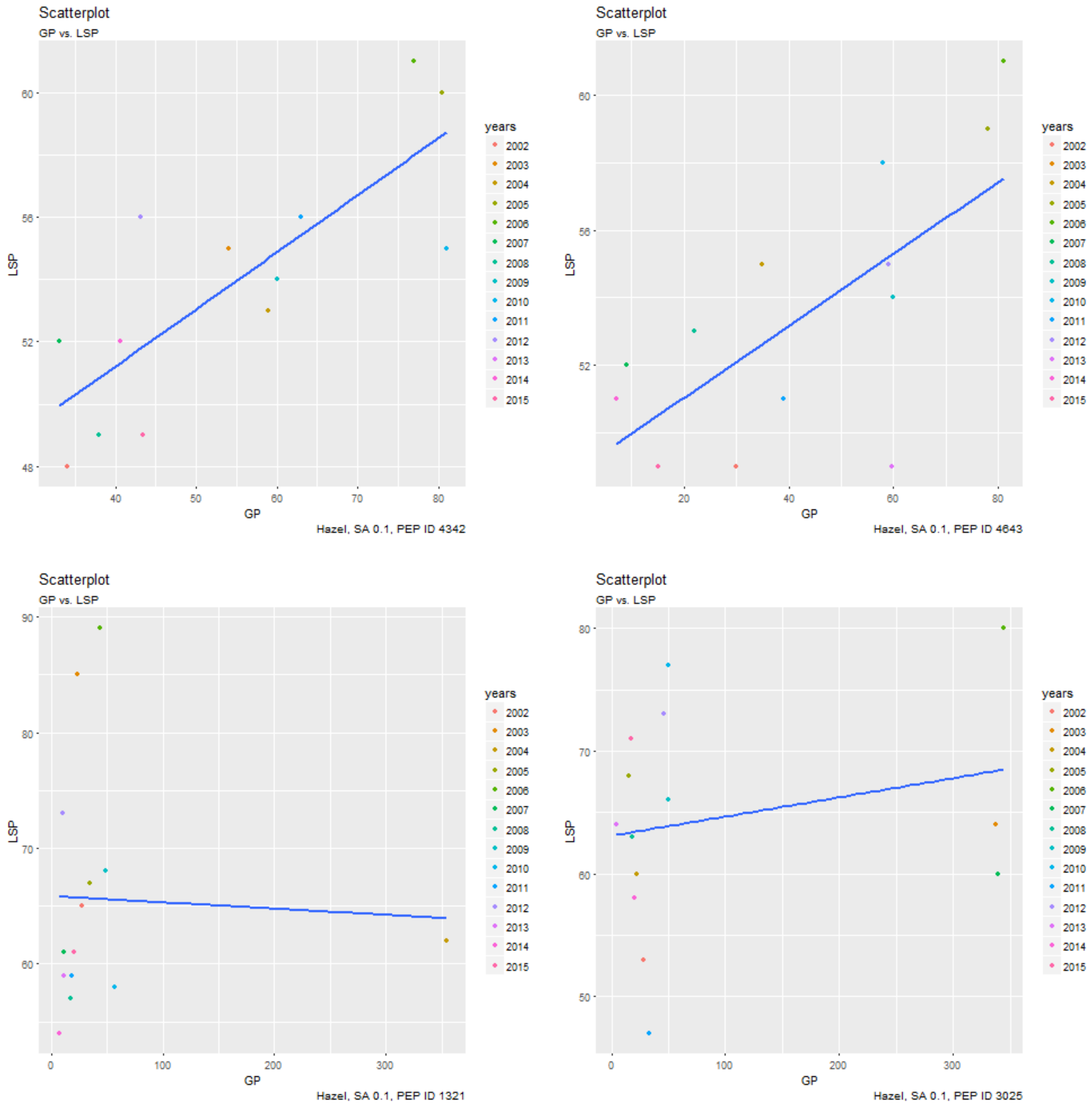


Figure 38: Scatter plots of single PEP-Stations between GP-SOS and LSP-SOS for Common Hazel The upper images show examples of stations who correlate significantly, while the lower images are examples of stations who do not correlate significantly.

4.2.4. Environmental variables

As mentioned in chapter *3.5.2.*, the influence of the *altitude* and *geographical position* environmental variables on GP has been analysed. The results of the analysis will be split in two parts: First, the influence of altitude will be investigated by means of a cluster analysis. Then, the geographical position will be investigated by analysing the distribution of GP-SOS for key years for the area map being investigated. Both parts of the analysis will be conducted for the representative species of both species' groups, European Beech and Common Hazel.

4.2.4.1. Altitude

The influence of altitude in the GP-SOS (or the lack thereof), has been investigated using a cluster analysis based on Ward's method. The following dendrograms[11] are standardised, with the y-axis representing the distance or dissimilarity between cluster, while the x-axis represents the PEP-stations and clusters. The red boxes show the proposed groups resulting from the clustering.

4.2.4.1.1. European Beech

The altitude of the PEP-stations with European Beech analysed in this research varies between 25 and 787 meters (above sea level).

The clustering of PEP-stations for the European Beech is visible in the dendrogram from *Figure 39*, wherein 5 distinct groups are visible. In this figure, the altitudes in meters (above sea level) of the PEP-stations has been used for labelling. It can be observed that the altitudes in the first 4 groups are heterogeneous with a difference between maximum and minimum ranging between 203 and 707 m. In the fifth group, which is the smallest and consists of just 2 elements, the altitude seems to be more homogenous with 30 m altitude difference. Because none of the groups, apart from the fifth and smallest one, show similarities regarding altitude, no apparent conclusion can be drawn regarding the influence of altitude on GP-SOS.

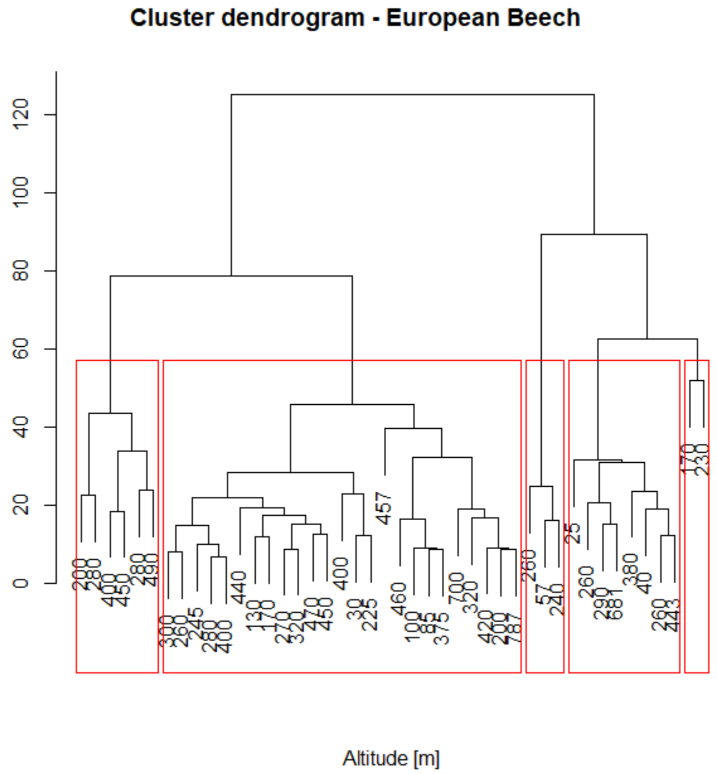


Figure 39: Dendrogram showing clusters of PEP-stations for the European Beech with altitude as labels for the PEP-stations.

[11] A dendrogram is a tree diagram used to illustrate the arrangement of the clusters produced by hierarchical clustering.

4.2.4.1.2. Common Hazel

The altitude of PEP-stations with Common Hazel, which are analysed in this research, varies between 30 and 1100 meters (above sea level).

The resulting clustering of the PEP-Stations for the Common Hazel is visible in the dendrogram from *Figure 40*, wherein 5 distinct clusters are visible. The first 3 ones are composed of a single station each, meaning they are outliers. Consequently, no conclusion can be drawn regarding the distribution of altitude within groups. The other 2 clusters seem to contain very heterogeneous altitudes. The altitude of the first cluster ranges between 130 and 1100 meters and the altitude of the second one ranges between 57 and 700 meters. Since the grouping seems to have no connection with the altitude, the influence of it on GP-SOS remains unclear.

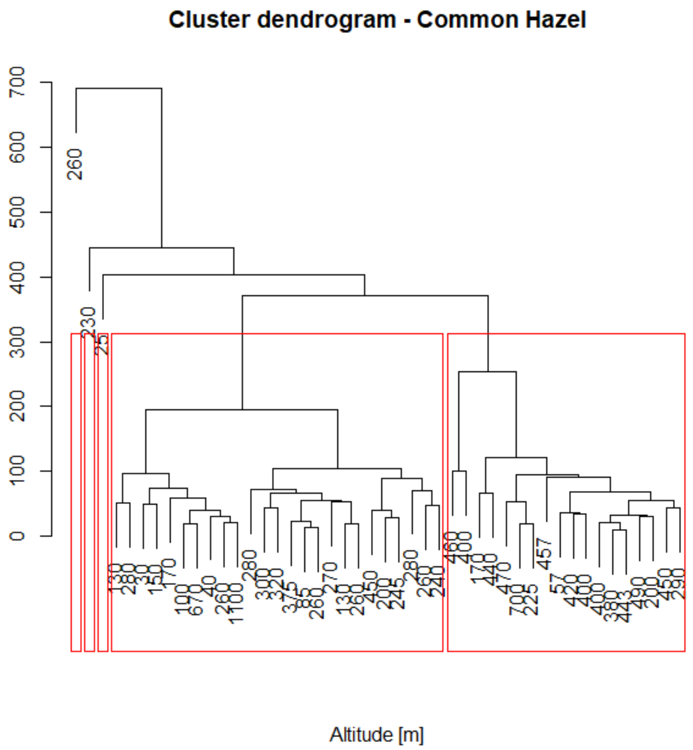


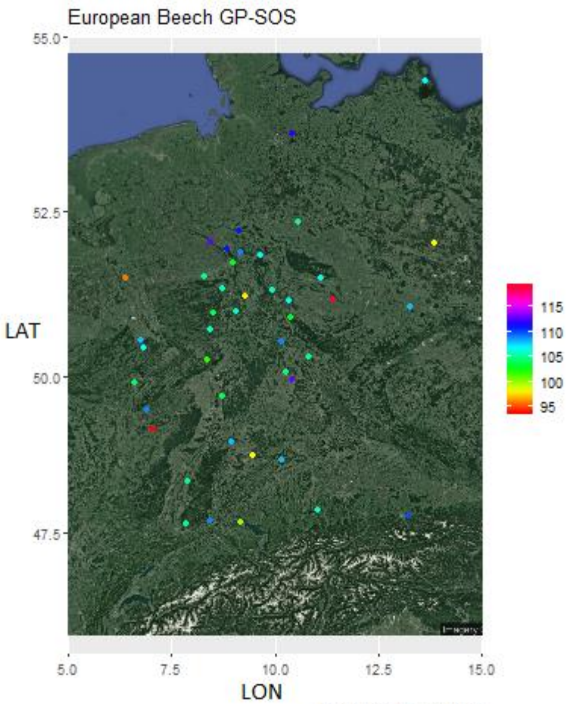
Figure 40: Dendrogram showing clusters of PEP-stations for the European Beech with altitude as labels for the PEP-stations.

4.2.4.2. Geographical position

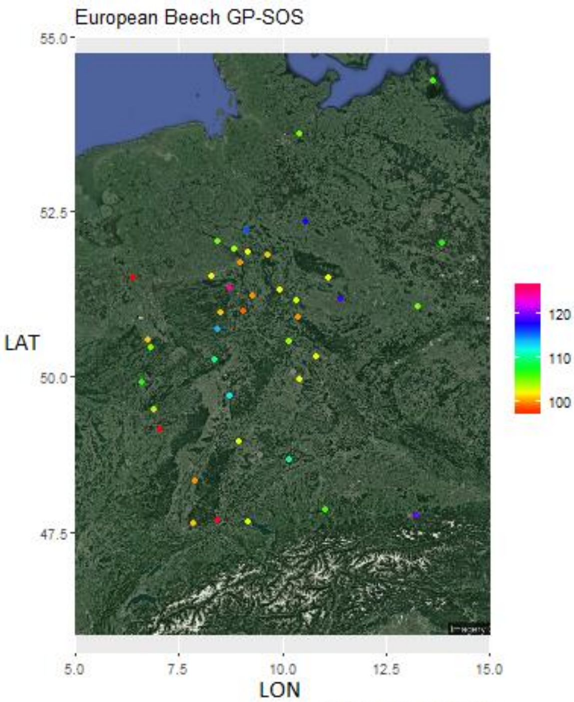
The geographical position of PEP-stations has been analysed for both species groups, with their representatives, European Beech and Common Hazel. The analysis has been carried out by plotting the GP-SOS for key years on the study area map. The extreme years regarding GP-SOS, discussed in subchapters 4.2.1.1 (for European Beech) and 4.2.1.2. (for Common Hazel), have been chosen as key years. The following plots are standardised and overlaid on google maps satellite images, with the x-axis representing the longitude in degrees and the y-axis representing the latitude in degrees. In the lower right corner of each image the species is mentioned, as well as the year depicted in the plot. The colour coding is available in the right side of each plot.

4.2.4.2.1. European Beech

For the European Beech, the extreme years regarding GP-SOS, discussed in the course of the inter-annual variability analysis (subchapter 4.2.1.1) are: 2007, 2009, 2011 and 2014 as exponents of lower values, and 2013 as an exponent of higher values. *Figure 41* presents the geographical distribution of GP-SOS for each of the years mentioned above. As can be observed in these images, the distribution of the GP-SOS is quite heterogeneous; between low and high latitudes and longitudes a similarity in the distribution of GP-SOS cannot be observed. The onset of spring does not seem to occur earlier or later in a particular geographical area. Therefore, the geographical position of the PEP-stations with European Beech does not seem to have any influence on GP-SOS.



European Beech 2007



European Beech 2009

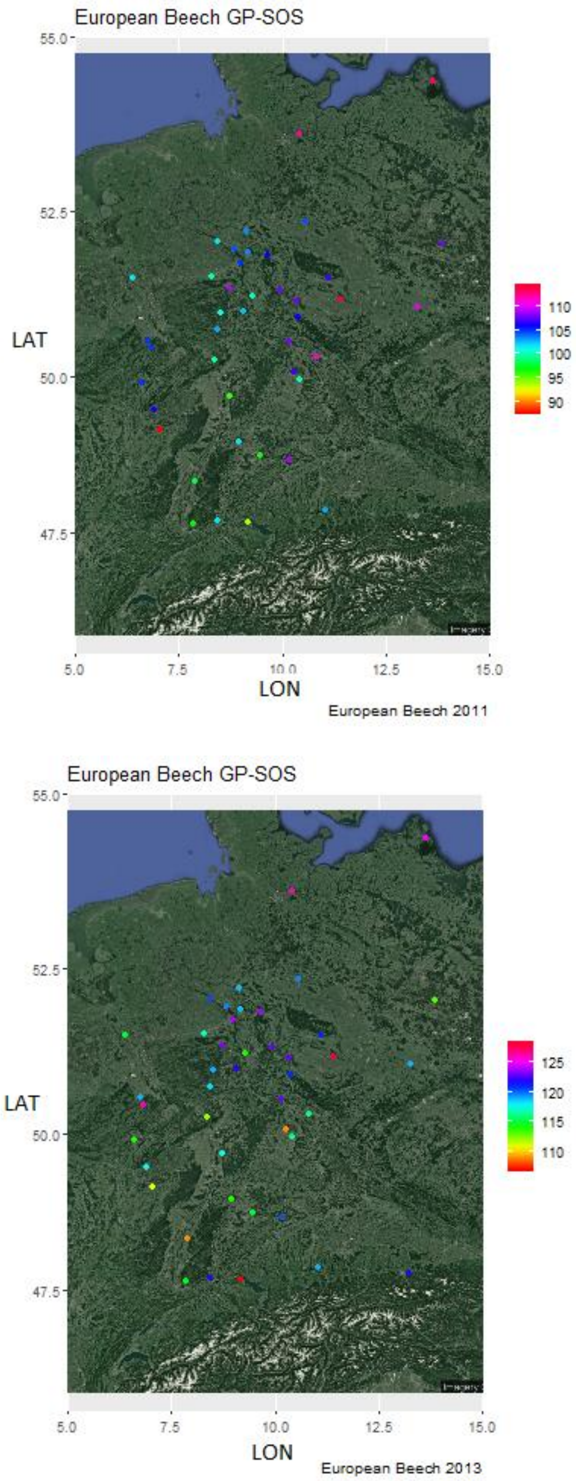


Figure 41: Geographical distribution of GP-SOS for the European Beech for key years. Google maps satellite images were used as background (Source: <u>https://maps.googleapis.com/maps/api/staticmap?center=50.5,10&zoom=6&size=640x640&scale=2&maptype=satellite&language=en-EN</u>).

4.2.4.2.2. Common Hazel

For the Common Hazel, the extreme years, as discussed in the inter-annual variability analysis for GP-SOS (subchapter 4.2.1.2) are: 2007 and 2008 as exponents of lower values and 2006 and 2011 as an exponent of higher values. *Figure 42* presents the geographical distribution for each of the years discussed above. In accordance with the findings for European Beech, no clusters of PEP-stations with similar values can be observed in any geographical area. Thus, the influence of geographical position on GP-SOS for the Common Hazel remains unclear.

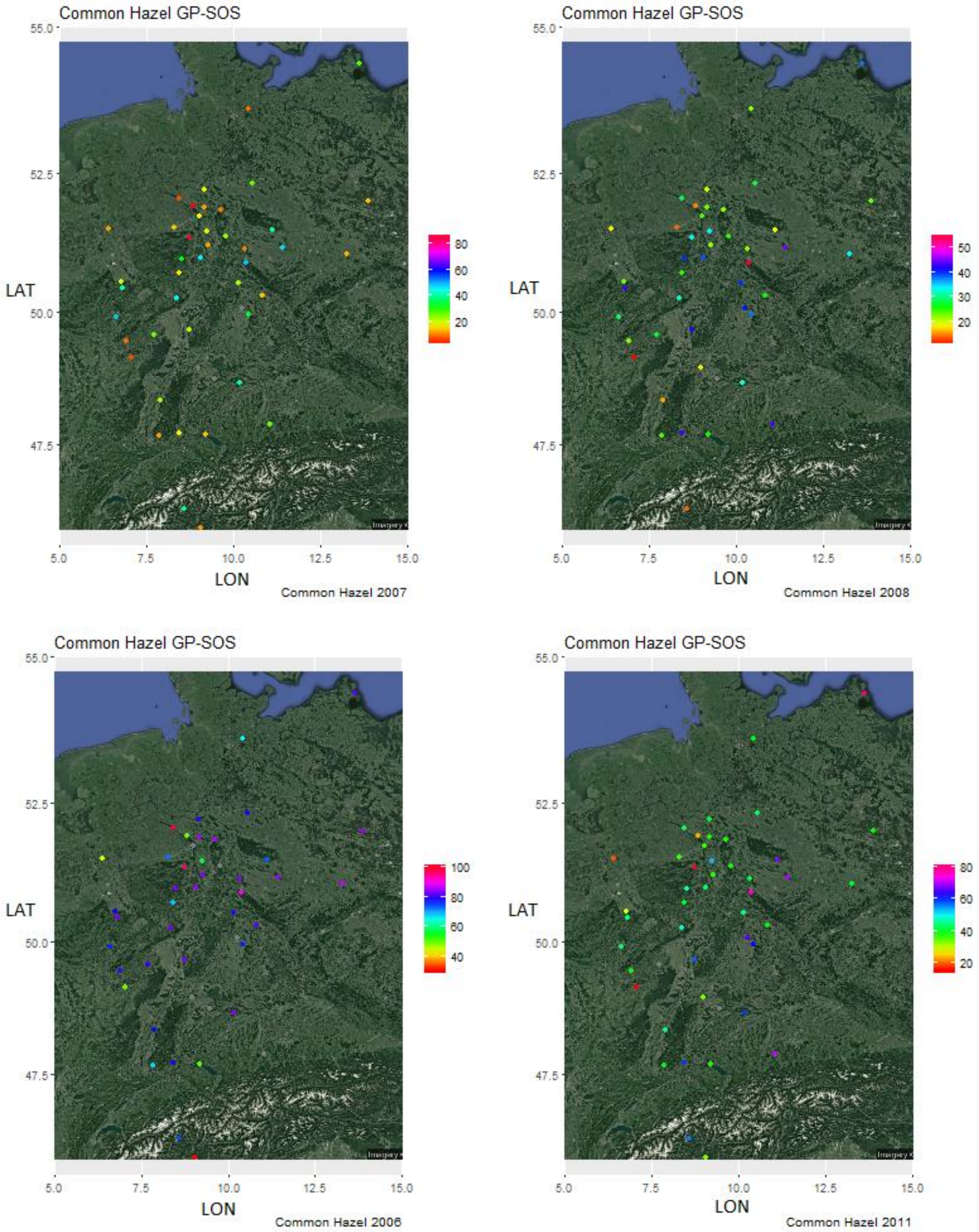


Figure 42: Geographical distribution for GP-SOS for the Common Hazel for key years. Google maps satellite images were used as background. (Source:

https://maps.googleapis.com/maps/api/staticmap?center=50.5,10&zoom=6&size=640x640&scale=2&maptype=satellite&language=en-EN).

5. Discussion

This master thesis aims to pre-process, compute, compare and statistically analyse two geospatial databases. The first database, GP, consists of PEP725 stations with the phenological observations first flowering date (FF) and leaf unfolding (LU), for several broadleaf species, which were aggregated to two main groups with European Beech and Common Hazel as group representatives. The second database, namely LSP, has been derived from MODIS NDVI time-series and has been calibrated to match the GP.

The discussion in this chapter aims at providing answers to the 4 research questions presented in the introduction, each of them being presented in the following subchapters.

5.1. Agreement of LSP with GP

Regarding the first research question, the results for the *correlation analysis and evaluation of the model* (chapter 4.1) as well as the *regression analysis* (chapter 4.2.3) are very conclusive.

In the course of the correlation analysis, it has been established that the LSP-GP of the European Beech shows a generally good agreement with the GP-SOS. The best results in this regard show that 79.5% of the PEP-stations correlate significantly. The evaluation of the model using RMSE shows a difference between GP and LSP of 10.87 days per year and 10.29 per station, while using MAE shows a difference of 8.77 per year and 8.78 per station. This shows that the difference between simulated observations (LSP) and actual observations (GP) ranges on average between 9 and 11 days, with the latter occurring earlier. The correlation analysis shows a poorer agreement of LSP-SOS with GP-SOS for the Common Hazel. The best results for this species, shows that 45,65% of the stations correlate significantly. The evaluation of the model using RMSE shows a difference between GP and LSP of 33.75 days per year and 28.16 days per station and using MAE shows a difference of 22.96 days per year and 22.43 days per station. This means that the GP occurs earlier by 23 to 34 days.

The regression analysis for all the stations shows poor results both for European Beech and Common Hazel. Very few observations are aligned along the regression line, with most of the data being scattered away from it. The regression analysis conducted for each individual PEP-stations, shows that the stations with high, significant correlation coefficients show positive linear relationships and those with low correlation coefficients show no apparent relationship. Therefore, the relationship between GP and LSP should be modelled separately for every single PEP-station in order to be able to draw insights from it.

It is important to keep in mind that the MODIS NDVI data used in this study have a resolution of about 250 m^2, which means that each pixel has an area of about 62 500 m^2. The land cover of the pixels covering the PEP-stations is broadleaf forest, but as we know from the GP, each station has several broadleaf species. This means that the pixels from which the LSP was derived are not homogenous but consist of mixed signals from more than one specie. This could be an explanation for the poorer results for the Common Hazel in comparison with those for European Beech. Almost each PEP-station which was analysed for Common Hazel observes several species from the European Beech group. Thus, having mixed signals, one cannot be sure whether the values of the pixels are representative for this one species. For this reason, the calibration for LSP might not suit the GP.

Another relevant factor for this question, is that the phenological parameter observed as GP-SOS for European Beech is LU (leaf unfolding – first visible leaf stak) and that of Common Hazel is FF (beginning of flowering). The NDVI is a vegetation index, determining the green density on a patch of land (Earthobservatory.nasa.gov, 2018). For Common Hazel, this explains the need for lower thresholds, since FF does not imply the same level of green density as for LU. This could also mean that for FF the understory sends stronger signals to the sensors. Therefore, the LSP computed for the stations observing FF could be more representative for the understory.

The studies focusing on LSP, especially Misra et al. (2016) generally agree that the relationship between LSP and GP is governed by the species and phenophase under study. This study also analyses LU, for a wide range of broadleaf species and understory, and reveals that broadleaf forest with GP occurring later the 90^{th} day of year (such as the European Beech), has a good agreement with LSP methods such as a threshold of 75%. Hamunyela et al. (2013) analyses several deciduous tree species, including the European Beech, but finds a generally poor agreement between GP and LSP.

Taking all the above-mentioned facts into account, regarding the first research question, the LSP-SOS shows a good agreement with the GP parameter LU. The results of the correlation analysis for European Beech confirm that as well. When it comes to the GP parameter FF, the results of this study find a poor agreement, for which some factors such as the course resolution of the MODIS data, the mixed signals in the sensors and the understory, could be liable. A research with a GP database consistent of stations observing just FF would clarify if LSP does not agree with FF or if the mentioned factors were at fault for these results.

5.2. Threshold of Seasonal Amplitude

The second research question addresses the subject of the so-called threshold, the percentage of seasonal amplitude used to calculate the LSP. Again, the *correlation analysis* as well as the *evaluation of the model* are best suited to clarify this issue. For both representative species, European Beech and Common Hazel, several thresholds have been used in order to calibrate the relationship between GP and LSP. For the European Beech the thresholds 0.5 and 0.7 and 0.8 have been used, with 0.7 providing the best results, as mentioned for the previous research question. For the Common Hazel 0.5, 0.2 and 0.1 have been used, with the latter being the most successful. As mentioned for the first research question, the reason for the poor result for Common Hazel remain unclear and cannot be clarified with this GP database.

In this study, another calibration step has been carried out–the mean of the neighboring pixels with broadleaf forest as land cover has been computed for every PEP-station. This step has provided an improvement in the number of stations correlating positively for both species. For the European Beech the evaluation of the model also improved while for the Common Hazel it decreased by 0.2 days on average. The improvement caused by this procedure could be accounted by a reduction of noise in the satellite sensors, which was cancelled out due to the calculation of a mean.

A similar statistical correlation per station carried out by Hamunyela et al. (2013) for the same study area, also using MODIS NDVI with a threshold of 50% and the PEP725 database, shows just 15,4 % of the stations for European Beech correlating significantly.

Taking into account all these findings as well as those of the above-mentioned paper, correctly calibrating the threshold seems essential for the computation of LSP. In order to do just that, the species as well as the type of phenological parameter used for GP are of great importance. Looking at the *correlation analysis* as well as at the *evaluation of the model,* one can affirm that, for European Beech and the group it represents a threshold of 0.7, which means that 70% of the seasonal amplitude is most suitable for the computation of LSP. For Common Hazel the most suitable threshold is 0.1, which means 10% of the seasonal amplitude.

5.3. Trend of GP and LSP

The third research question investigates the trend of GP and LSP. Very relevant in this regard is the inter-annual variability analysis described in chapter 4.2.1. The findings of this analysis show that, for both representative species, the regression lines are negative for GP, as well as for LSP. For European Beech GP, the regression line decreases throughout the time-series from day 114 to day 106. For LSP it decreases from 114 day to 110 day. For Common Hazel, for GP the regression line goes from day 51 to day 47, while for LSP it goes from day 59 to day 55. These results are indicative of an earlier onset of spring phenology.

In the LSP literature one can find quite controversial results regarding the trend of spring phenology. For both GP and LSP, White et. al (2009) found no change at all during their study period (1982-2006); Fu et al. (2014) found stronger advancing trends between 2000 and 2011, while Misra et al. (2016) found even positive trends for some understory species, meaning later springs for 2001 - 2013. However, in these works, the species being studied, the study areas, the phenophase parameters, as well as the methods for calculating LSP are slightly different.

Taking into account the result of this study, as well as the findings of the above-mentioned research papers, one can affirm that the species and the phenophase parameters used as GP are very important for establishing the trend of GP and LSP. For the species investigated in this study, European Beech and Common Hazel and their phenological parameters LU and FF, the trends are negative for both LU and FF, which is indicative of earlier springs.

5.4. Influence of environmental variables on GP

The fourth research question investigates the influence of environmental variables on GP. The environmental variables researched are altitude and geographical position, the results being described in chapter 4.2.4. The findings of this research show that none of these variables have an influence on the GP. However, the database analysed consists of just 44 stations for the European Beech and 46 stations for the Common Hazel. The stations are very heterogeneous, with an altitude variation between 25 and 1100 m, and are spread between 5°E -15°E latitude and 45°N - 56°N longitude. Given the low number of stations having been analysed, even though the analysis shows no influence of the environmental variables on GP, one could say these findings are rather inconclusive.

6. Conclusion

Phenology is currently being studied from two different perspectives: GP and LSP. GP has the advantage of long temporal coverage but gathering records is time-consuming and thus impossible to perform at a global scale. Also, unifying records across countries and species is very difficult. LSP is a feasible alternative, providing regional and global coverage, but is still not exempted from uncertainty. Estimates may include signals from multiple sources such as noise in the satellite sensor or errors in the processing methods and the signals can be mixed on account of multiple land-covers (Rodriguez-Galiano et al., 2015). Since the currently available research comparing LSP with GP is scarce and provides non-conclusive results, the need arises for further studies.

The area investigated in the present research is situated in Central Europe and covers Germany, Austria and Switzerland. PEP725 has been used to build up a GP database by filtering the data points for the study area, which record observations for broadleaf species and have broadleaf forest as land cover. The obtained GP database has been gap filled by means of robust regression and the species have been aggregated into two main groups, each having a representative species: European Beech and Common Hazel. The GP database contains LU observations for the European Beech and FF observations for the Common Hazel. A corresponding LSP for the representative species has been created and calibrated with different seasonal amplitude thresholds in order to fit the GP observations. Statistical analysis has been used in order to establish the agreement between GP and LSP.

For the European Beech, the best results have been achieved with a threshold of 70.0% of the seasonal amplitude. For this threshold, 79.5% of the PEP-stations show significant positive correlations. The evaluation of the model using RMSE shows a difference between simulated observations (LSP) and actual observations (GP) of 10.9 days per year and 10.3 per station. For the Common Hazel, the best results have been obtained with a threshold of 10.0% of the seasonal amplitude. The correlation analysis shows that 45,6% of the stations correlate significantly and that the RMSE shows a difference between LSP and GP of 33.7 days per year and 28.2 days per station. The poor results obtained for Common Hazel in comparison to the European Beech could be a consequence of the heterogenous pixels (each PEP-station observes several species). The signals sent to the sensors by the understory could also be an important reason for these results.

The regression analysis has shown for both species that the relationship between GP and LSP should be modelled for each PEP-station individually, rather than for the whole database at once. The PEP-stations with high, significant correlation coefficients show positive linear relationships and those with low correlation coefficients show no apparent relationship.

The inter-annual analysis conducted in the course of this research, shows that both the European Beech and the Common Hazel show a negative trend, indicating that the spring phenology tends to occur earlier every year.

In order to better understand the occurrence of the GP SOS, the influence of the environmental variables has been investigated. However, no evidence for the influence of altitude and geographical position could been found. Given the fact that only 44 observation time-series for European Beech and 46 observation time-series for the Common Hazel have been analysed, we remain careful with interpreting this result.

For future research, the use of a broader phenological network, which focuses on observations outside of settlements and gathers them from forests would be advisable. With PEP725, when filtering for land cover, the research was left with around 40 viable stations for each species. Another important requirement would be for the stations to represent only one species. Regarding the LSP, MODIS is a very good choice because of the temporal resolution and of the broad timespan of the available data. However, deriving phenological metrics from satellite observations with higher spatial resolution, for example with Landsat (30 m) or Sentinel-2 (10 m), would help to avoid heterogeneous pixels with multiple land covers.

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Annex

1. Excerpt of the R script for extracting values out of the MODIS NDVI stack:

```
library(raster)
#set the working directories
inPath <- "C:/Users/Ruxandra/Desktop/REFALL/"
csvFile <- "C:/Users/Ruxandra/Desktop/DE/cellnumbers_neighbours_beech.csv"
valNoData <- 255

# read csv with the cellnumbers of the PEP-stations
points <- read.csv2(csvFile)
points<-points[,-2]

# read raster
files <- list.files(inPath, pattern=".tif$", full.names=TRUE)

#the stack will be processed in batch sizes of 2
batch_size <- 2

stack1<-stack(files)
sizeImage<-dim(stack1)
global_res <- matrix(data = NA, nrow = dim(points)[1], ncol = sizeImage[3])

for(j in 1:round(length(files)/batch_size))
{
  print(j)
  from <- (1+(j-1)*batch_size)
  to <- j*batch_size
  print(from)
  print(to)
  img <- stack(files[from:to])

  #NAvalue(img) <- valNoData

  #get image dimensions (rows and cols)
  sizeImg <- dim(img)
  tr <- blockSize(img)

  results <- matrix(data = NA, nrow = dim(points)[1], ncol = sizeImg[3])

  # get rows
  row <- rowFromCell(img, points[,2])
  #Loop for blocks
  for (i in 1:tr$n)
  {
    # select rows of block
    idx <- which(row >= tr$row[i] & row <= (tr$row[i]+tr$nrows[i]))

    if (length(idx)>0) {
```

```
      v <- getValuesBlock(img, row=tr$row[i], nrows=tr$nrows[i])

      # index: cells - cell number of last pixel of previous block
      results[idx,] <- v[(points[idx,2] - (tr$row[i]-1)*sizeImg[2]),]

    }
  }
  global_res[,from:to] <- results

}

write.csv(global_res, file="European_beech_NDVI.csv " )
```

2. Excerpt of the script for bringing the TIMESAT output to time-series per station

```
#read the TIMESAT output
rotbuche<-read.table("C:/Users/Ruxandra/Desktop/DE/CH/european_beech_threshold07.txt",
head=TRUE)

#read the European Beech stations
points <- read.csv2("C:/Users/Ruxandra/Desktop/DE/Stations_44_beech.csv")

#get rid of the "col"column and of the other parameters apart from SOS and EOS
rotbuche<-rotbuche[,-2 ]
rotbuche<-rotbuche[,1:4 ]
colnames(rotbuche)[1]<-"X"

#merge csvFile and rotbuche by "X" (to get the cell number instead of the row number)
rotbuche_cellnumber<-merge(rotbuche, points, by="X")

colnames(rotbuche_cellnumber)[3]<-"Beg"
colnames(rotbuche_cellnumber)[4]<-"End"
colnames(rotbuche_cellnumber)[2]<-"Seas"

rotbuche_cellnumber$Beg<-as.numeric(paste(rotbuche_cellnumber$Beg))
rotbuche_cellnumber$End<-as.numeric(paste(rotbuche_cellnumber$End))
#beginning
rotbuche_cellnumber$Beg_week<-as.numeric(paste(rotbuche_cellnumber$Beg))-
((rotbuche_cellnumber$Seas-1)*52)
rotbuche_cellnumber$End_week<-as.numeric(paste(rotbuche_cellnumber$End))-
((rotbuche_cellnumber$Seas-1)*52)

#calculate SOS in days
rotbuche_cellnumber$Beg_days<-ceiling(as.numeric(paste(rotbuche_cellnumber$Beg_week))*7)

#calculate EOS in days
rotbuche_cellnumber$End_days<-ceiling(as.numeric(paste(rotbuche_cellnumber$End_week))*7)


#add years to the table
```

```
Seas<-c(1:15)
years<-c(2002:2016)
id<-cbind(Seas, years)
colnames(rotbuche_cellnumber)[2]<-"Seas"
rotbuche_cellnumber<-merge(rotbuche_cellnumber, id, by="Seas")
write.csv2(rotbuche_cellnumber, file="timesat_output_clc _mean_beech_07.csv")

rm(list = ls())

dt <- read.csv2("timesat_output_clc _mean_beech_07.csv ")
colnames(dt)[6]<-"cellnumbers"
colnames(dt)[7]<-"PEP_ID"
PEP_ids <- unique(dt$PEP_ID)

years <- matrix(nrow=length(PEP_ids), ncol=15)
colnames(years)<-c(2002:2016)
rownames(years)<-PEP_ids
colnames(dt)[10]<-"SOS"
colnames(dt)[11]<-"EOS"
colnames(dt)[12]<-"YEAR"

#create a time-series per station
for (year in c(2002:2016))
{
  idx <- 1
  for( PEP_id in PEP_ids)
  {
    res <- dt[dt$YEAR == year & dt$PEP_ID == PEP_id,]
    if(nrow(res) > 0)
    {
      #print(res$DAY[1])
      years[idx,year - 2001] <- res$SOS[1]
    }
    else
    {
      #print("NA")

    }
    idx <- idx + 1
  }
}

#write.csv2(years, "European_Beech_threshold07.csv")
```

3. Excerpt of the code for gap filling the GP data

```
#read the GP time-series
hasel<-read.csv2(“Hasel_GP.csv)

#read the matrix with correlation coefficient between years
matrix<-read.csv2(“Hasel_matrix_correlation_years.csv)
matrix[matrix==1]<-0
```

```
#go through the correlations for each year
for(i in 1:length(matrix[1,]))
{  a<-matrix[,i]
   year<-hasel[,i+1]
while(!is.null(a)){
  max<-max(a)
  k<-match(max, a)
  yearcor<-hasel[,k+1]
  if(max>=0.5) {
    intercept<-rlm(hasel[,i+1]~hasel[,k+1], maxit=40)$coefficient[1]
    coefficient<-rlm(hasel[,i+1]~hasel[,k+1], maxit=40)$coefficient[2]
    for(j in 1:length(hasel[,1]))
    {if(is.na(year[j])==TRUE & is.na(yearcor[j])==FALSE)
      year[j]<-yearcor[j]*coefficient+intercept

    }
    haselsynt[, i+1]<-year
  } else a<-NULL
 a<-a[-k]
}
}

write.csv2(haselsynt, "Hasel_clc_25_syntethic_years.csv")
```

4. Excerpt of an R script for calculating and illustrating the correlation between GP and LSP

```
rm(list=ls())
library(ggplot2)

#read the GP-SOS time-series
GP<read.csv("C:/Users/Ruxandra/Desktop/DE/more/European_Beech_GP_synthetic_years_engl_AT
_updated.csv")
colnames(GP)[1]<-"PEP_ID"

#read the LSP/SOS time/series
LSP<-read.csv("C:/Users/Ruxandra/Desktop/DE/more3/European_Beech_threshold07.csv")

colnames(LSP)[1]<-"PEP_ID"

#transform to matrix
A<-as.matrix(GP[,-1])
B<-as.matrix(LSP[,-1])

n<-length(GP[,1])

#avoid scientific writing
options(scipen=999)

#compute correlation matrix
corr1<-matrix(nrow=n, ncol=3)
corr1[,3 ]<-seq(1, n, 1)
```

```
corr1[,2 ]<-sapply(seq.int(dim(A)[1]), function(i) cor(A[i,], B[i,], method="pearson",
use="complete.obs"))
corr1[,1 ]<-(GP[,1])

#save p-value for each correlations
b<-rep(0, n)
for (i in 1:n) {
  tst<-cor.test(A[i, ], B[i, ], method="pearson", use="pairwise.complete.obs" )
  b[i]<-tst$p.value
}

#create matrix with p-value and correlation coefficient
pval1<-matrix(ncol=3, nrow=n)
pval1[,3 ]<-b
pval1[,1 ]<-GP[,1]
pval1[,2]<-corr1[,2 ]

#create plots
theme_set(theme_bw())
pval1<-as.data.frame(pval1)
pval1$V2<-as.numeric(paste(pval1$V2))
pval1$V3<-as.numeric(paste(pval1$V3))
colnames(pval1)[1]<-"PEP_ID"
colnames(pval1)[2]<-"Correlation_coefficient"


#a$V2_z <- round((a$V2 - mean(a$V2))/sd(a$V2), 2)
pval1$V3_type <- ifelse(pval1$V3 > 0.05, "above", "below")
#a <- a[order(a$V2), ]
pval1$PEP_ID <- factor(pval1$PEP_ID, levels = pval1$PEP_ID)


ggplot(pval1, aes(x=PEP_ID, y=Correlation_coefficient, label=Correlation_coefficient)) +
  geom_bar(stat='identity', aes(fill=V3_type), width=.5)  +
  scale_fill_manual(name="Pearson",
                  labels = c("Not Significant", "Significant"),
                  values = c("below"="#00ba38","above"="#f8766d")) +
  labs(subtitle="Correlation between GP and LSP SOS (amp 0.7)",
      title= "European Beech LC=broadleaf forest ") +
  scale_y_continuous(limits = c(-0.3, 1))+
  theme(axis.text.x = element_text(angle = 90, hjust = 1))
```

5. R script for the evaluation of the model (RMSE and MAE)

```
rm(list=ls())
library(nlme)
require(lme4)
library(hydroGOF)

#read LSP
LSP<-read.csv("C:/Users/Ruxandra/Desktop/DE/more3/European_Beech_ threshold07.cdv")
```

```
#read GP
GD<- read.csv("C:/Users/Ruxandra/Desktop/DE/ /European_Beech_GP_synthetic_years.csv")

    #root mean square deviation by year
    RMSE_year<-rmse(LSP[,-1], GD[,-1])
    mean(RMSE_year, na.rm=TRUE)

    write.csv2(RMSE_year,"RMSE_Year.csv")

    #root mean square deviation by station
    RMSE_station<-rmse(t(LSP[,-1]), t(GD[,-1]))
    RMSE_stations<-rbind(GD[,1], RMSE_station)
    mean(RMSE_station)
    write.csv2(RMSE_stations, "RMSE_stations.csv")

    #Mean absolute error by year
    mae_year<-mae(LSP[,-1], GD[,-1])

    mean(mae_year, na.rm=TRUE)

    write.csv2(mae_year, "MAE_year.csv")

    #Mean absolute error by station
    mae_station<-mae(t(LSP[,-1]), t(GD[,-1]))
    mean(mae_station)

    write.csv2(mae_stations, "MAE_stations.csv")
```