

Painting With Forest Phenology:
Developing a spatial computer model for testing options of
phenology- and color-based tree planting

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Introduction

Next to climate change, the immense loss of biodiversity is among the biggest threats to the long term stability of our planet (Rockström et al., 2020). Terrestrial and marine species are found on red lists where they are classified in categories ranging from “least concerned” to “extinct “ (IUCN, 2012). Nearly 27% percent of all assessed species are threatened with extinction, and the observed species extinction rate by far exceeds values that can be considered natural (IUCN 2019). With climate change proceeding, entire ecosystems are under the additional stress of changing environmental conditions. Because habitat deterioration and habitat loss are seen as the key drivers of the loss of biodiversity, sustainable land-use practices may pose a potential solution to the problem (Kok et al., 2018).

One solution strategy that claims to tackle both climate change and the loss of biodiversity is maintaining natural forests and engaging in afforestation or reforestation of land. Especially afforestation is nowadays seen as a promising approach: Recent studies highlighted that global afforestation measures could significantly contribute to the large-scale sequestration of carbon, eventually mitigating climate change (Finegold et al.).

However, it is still debated whether further incentives to invest in carbon sinks actually help to halt the loss of biodiversity (Burrascano et al., 2016; Cormont et al., 2016). This is due to a general dilemma that many forest managers face: On the one hand, forest areas are valuable ecosystems and provide habitats for many species. On the other hand, forest areas need to be used efficiently in order to absorb CO₂ and build up biomass for exploitation. Newly planted forests in Europe are often designed as monoculture tree plantations since focusing on one tree species increases efficiency of work processes and reduces costs. As monotonous tree plantations do not offer as many small habitat niches as primary forests, the diversity of mammals, birds, and plants is significantly lower in monocultures (Parrotta et al., 2008; Iezzi et al., 2018). Studies even indicate that some grasslands come with a higher diversity of species than monoculture forests.

The second criticism of afforestation projects concerns the selection of trees. In many newly planted forests, fast-growing tree species can be found. These species are often alien to the location and thus not optimally adapted to the local climate. In Germany, for example, beech trees would naturally be the dominant forest tree (Leuschner, Wulf, Bäuchler, & Hertel, 2014). However, due to human intervention, spruce trees are nowadays the most common tree species, making up more than a quarter of the national forests (Bundeswaldinventur, 2012). Yet, spruce originally grew at high elevation in the mountains and Scandinavia, where they are well adapted to colder climate and shorter vegetation periods (Brandl, Paul, Knoke, & Falk, 2020). When planted in central Europe, spruce can benefit from the comparably long vegetation period, leading to fast growth rates and high accumulation of woody biomass (Vacek et al., 2019). However, enduring and repetitive periods of hot and dry weather is known to severely stress spruce trees to an extent that they struggle to withstand common perturbations such as pests and storms (Spiecker, 2000). Due to hot and dry periods in 2018 and 2019, more than 110.000 hectares of spruce plantations were lost in Germany. To increase forest stability, a mixture of well-adapted native tree species could be planted. Research indicates that with higher biodiversity in temperate forests, the ecosystem becomes more stable and sequesters more atmospheric carbon over a longer time.

Although forest managers might know that monocultures of exotic tree species are at higher risk when periods of extreme weather occur more frequently, the financial attractiveness of fast growing species persists. For this reason, a sustainable business model that incentivizes the planting of well-adapted native trees could offer a solution to the problem.

Sustainable Entrepreneurship

Environmental, social or economic problems can be addressed by entrepreneurs that perceive a sustainability related issue as a business opportunity (Ganescu, 2012). Enhancing biodiversity and species richness in temperate forests can be such a challenge that requires a business solution of sustainable entrepreneurs. One idea that might have the potential to enhance species richness in afforestation projects is the concept of a pattern forest.

In order to account for both climate action and measures to promote biodiversity, future forests could be planted with different priorities in mind. Local and, therefore, best-adapted tree species could be prioritized over fast-growing exotic species. As the CO₂ sequestration rate and the annual gain in biomass may be lower, additional revenue streams need to be generated from the forests. One approach that could reconcile the ecological and economic demands on forests is color- and phenology-based tree planting. By selecting native tree species based on their phenology characteristics and their appearance, it could be possible to deliberately arrange trees in a way that their canopy presents colorful patterns. In case deliberate planting of patterns is possible, afforestation companies could use species rich pattern forests to offer visible marketing places. The customers of afforestation companies could utilize marketing tool to promote their brand and raise awareness about their sustainability initiatives.

One business segment for which this approach may be interesting is the booming CO₂ offsetting market. The service of companies such as MyClimate or Carbon Footprint Ltd addresses environmentally conscious consumers who like to decrease their personal CO₂ footprint by compensating unavoidable CO₂ emissions from flights or car rides. So far, customers who do offset their emissions can hardly track the afforestation measures taken and cannot control if the planted forests contribute to the local biodiversity.

By planting phenology-based forests, it could be possible to account for biodiversity needs while also creating unique marketing value, media attention, and emotional attachment to the forests. However, the exact potential and the limitations to phenology based forestry are not known yet and will therefore be explored during this master thesis.

Spatial Modelling

Although it is known how single trees change their appearance throughout the year, it is difficult to conclude how the entire canopy of a forest appears as a whole. For this reason, spatial models can be created that allow to calculate the canopy structure of the entire forest ecosystem (Jansen, 2002).

In order to find out if, when, and in which resolution it would be possible to plant colored patterns using trees, the growth of the trees canopy has to be studied over several years. Since questions about the long-term development of ecosystems are difficult to answer in field experiments, researchers make use of computer-aided ecosystem modeling for related research.

Particularly in the case of long-term trends in land use and land cover (LULC), computer models are often chosen to simulate possible developments based on multiple future scenarios. One type of model that explains spatial-temporal trends particularly well is a cellular automata (CA). A cellular automata consists of a grid of cells, each of which has a particular status that can change over time. Rules can be defined to determine the extent to which cells influence each other concerning their distance from each other. Examples of where CA can be applied are the modeling of forest fragmentation, urban development (Adams et al. 2019), and ecosystem services attached to forests (Hernández, 2019).

Remote sensing is commonly used as data input because the multispectral satellite imagery provides specific information on land use. For example, an area of land covered by grass reflects light of a particular wavelength that helps to recognize it. The data on the type of land use is then the basis for

future modeling in cellular automata. By mapping existing land and simulating possible future trends, researchers have already been able to model the effects of future urban development and agricultural expansion on (forest) ecosystems. Since these models are based on the physical appearance of land surfaces, they are also called phenological models.

Although a CA will be used for this study, a slightly different approach will be followed. The phenology-based model for this study will not use existing remote sensing images as input but rather create images that resemble remote sensing pictures. Data gathered from literature research will help to digitally “plant” forests on a CA grid that, as a whole, should resemble a remote sensing image. By modeling the growth over specific time steps, it will be possible to track both the seasonal tree phenology and the long-term growth of the canopy. As to now, there are no comparable types of models available, which is why the model for this study will be coded from scratch. However, related models that explore trees’ phenological response to changing climatic conditions do exist (Article 2003).

Unlike biological models, the proposed phenological model will not be based on the physiological processes of the trees. It will not be possible to calculate the metabolism of single trees or tree-to-tree interactions. Besides, the model will not be suited to determine specific ecosystem services. For this purpose, existing software tools such as the TerrSet suite by Clarc University are more appropriate (TerrSet, 2020).

Study area

The central premise for this thesis project is the observation that plants - and in this case trees - undergo annually reoccurring development stages that shape the appearance of the plant species. The study of the chronological sequence of these recurring developmental stages is called phenology. As the growth of a plant is influenced by weather conditions at site, the timing of phenology is subject to interannual variation. Most prominent factors known to influence tree phenology are temperature and photoperiod (Singh, 2017). The combination of influencing factors leads to spatially and temporarily different environments for plants to grow at. Factors such as day and night lengths depend on the geographic location, with an almost seasonally constant daily solar radiation along the Equator and vast differences in day/night lengths at places of high latitude (Jaakola & Hohtola, 2010).

Beginning with leaf unfolding in spring, tree canopies quickly take on a bright green appearance, that is caused by the production of green chlorophyll pigments in the leaves’ chloroplast organelles. From the visible spectrum of sunlight, chlorophyll absorbs radiation of certain wavelengths, being red light and blue light (le Maire et al., 2008). As most of the green light is reflected by chlorophyll, photosynthetically active plant organs are perceived as green by the human eye (Gitelson, 2005). Although plant leaves are equipped with carotenoids and flavonoids that reflect a different range of sunlight than chlorophyll, the vast abundance of chlorophyll during spring and summer overpowers the effect of the other underlying pigments (Baltzer & Thomas, 2005). With increasing availability of sunlight in spring, the leaf chlorophyll content increases over time, which even increases the green color strengths of the leaves.

It is known that tree species in temperate forests present different mechanisms to cope with seasonally changing radiation intensity of sunlight. When autumn is approaching on the northern hemisphere, tree species are forced to adapt to the decreasing availability of sunlight, increasing risk of night chilling and changes in water supply. In broadleaf trees the lower radiation intensity triggers physiological processes on cell level, that eventually lead to a decrease of leaf chlorophyll content. Since the creation and maintenance of chlorophyll requires nutrients and energy, it is beneficial for deciduous trees to lower the level of chlorophyll and save energy for the dormant phase in winter. At lower levels of leaf chlorophyll, the light reflected by carotenoids and flavonoids makes the foliage

appear yellow to the human eye (Renner, 2019). Surprisingly, trees are found to actively produce anthocyanins while they begin to extract nutrients from the leaf tissue (Lee & Gould, 2002). Accumulating anthocyanins is energy intensive and demands nutrients and energy that is stored as glucose. It is assumed that the red color helps the tree to attract animals, which may eat the fruits and thereby spread the trees' seeds (Hoch, 2001).

Evergreen conifers in contrast are known for retaining their photosynthetically active organs during the winter period where deciduous trees usually enter the dormant phase. A reason why needle-trees exhibit an entirely different behavior lies in the needles morphology. Having needles that are protected by a thick wax cuticula and are compact in shape, evergreen conifers are well protected against the cold and are able to better prevent leakage of water vapor than deciduous trees (Gower, 1990). Although chlorophyll remains in the needles during winter, the trees enter a reduced activity state where photosynthesis is carried out in a limited range. As an exception, the European larch tree is known to shed the leaves and assumes a dormant phase during the winter months. It is hypothesized that shedding needles helps larch trees to avoid damage on their canopy caused by high winter snow loads (Busetto et al., 2010). Morphologically, the special growth strategy of larch can be seen in the soft, thin needles that are not as sturdy and thick as the needles of evergreen tree species.

As presented above, native tree species have to adapt to seasonally changing climate conditions. Evolutionarily, they developed two distinctive strategies that involve leaf shedding in broadleaf trees and a sturdy, protected design of needles in ever green trees. Due to the different strategies, it is assumed that planting a forest with trees of these categories allows to display patterns in the forest canopy structure that are visible from autumn until spring, potentially even during the entire year.

Research aim

Since it is known that native tree species exhibit distinctive and predictive growth strategies, there is reason to believe, that their morphological differences could be used to deliberately plant patterns in the canopy structure of a forest. Within the scope of this master thesis, this theory is tested, assuming multiple different growth scenarios. As mentioned above, planting pattern could act as a tool for marketing while also promoting species richness in forestry. To critically evaluate if and under what circumstances patterns could be planted, a spatial computer model is created that allows to plant a customized forest area. With the model, the growth of the planted forest can be modeled under certain growth scenarios. If the model indicates, that it is possible to plant patterns under a realistic assumptions, the model findings may be the basis for further transdisciplinary research on the potential and the impact of this planting approach. By answering seven sub questions, it is tried to answer the following research question

Research Question

What are the technical prerequisites to display different patterns using tree phenology?

1. What are the technical prerequisites to display different patterns using tree phenology?
 - 1.1. What density of trees is needed to generate distinctive patterns of colors?
 - 1.2. During which phenological phase are patterns visible from above?
 - 1.3. What is the minimum spatial scale to display one distinct pixel?
 - 1.4. Stemming from the resolution of a single pixel, what are the minimum spatial requirements to display common brand logos, slogans, or artwork?
 - 1.5. What colors can be planted by using native trees (native to the Netherlands)?
 - 1.6. For how many years are the color patterns visible, assuming no or low human intervention?
 - 1.7. Which locations are attractive for a forest that show the patterns?

2. Methods

For more than 100 years the so-called BBCH code has been used to scientifically record the phenological development of plants. The abbreviation is derived from Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und Chemische Industrie, which were the stakeholders responsible for defining it (DWD, 2007). This framework assigns a score to morphological stages of plant development and is applicable to a variety of monocotyledon and dicotyledon plant communities. The BBCH code widely employed in agriculture but also allows the general public to classify plant development of perennials and annual plants. The BBCH code divides plant growth into ten principal growth stages also called macro stages, each of which can be subdivided in up to ten additional micro stages.

Given that the BBCH code should be applicable to as many plant species as possible, it covers many developmental stages that occur in both monocotyledon and dicotyledon plant communities. Some of these macro stages are only relevant for annual plants and grasses, which is why in great parts the code does not refer to tree species. More detailed specifications are provided by the Julius Kühn Institute in Germany that updates and expands the framework.

Macro stages that are relevant for describing the growth of native tree species are leaf development (10-19), flowering (60-69), fruit ripeness (80-89) and leaf senescence (90-99). The relevant development stages are listed in figure 1.

Scale	Phenological development stage
00-09	Germination, sprouting, bud development
10-19	Leaf development
	10 First leaves separated (mouse ear)
	11 Leaf unfolding (first visible leaf stalk)
20-29	Formation of side shoots
30-39	Stem elongation or rosette growth, shoot development
40-49	Development of harvestable vegetative plant parts, bolting
50-59	Inflorescence emergence, heading
60-69	Flowering
	60 Beginning of flowering
70-79	Development of fruit
80-89	Ripening or maturity of fruit and seed
	86 First ripe fruits
90-99	Senescence, beginning of dormancy
	94 Autumnal coloring of leaves (50%)
	95 Autumnal leaf fall (50%)

Figure 1 List of phenological macro stages according to BBCH framework. Micro stages that are relevant for describing tree growth are listed

Interpretation of phenology data

Before the phenology data is explained in greater detail, it should be noted that phenology only studies the occurrence and the timing of characteristic development stages of plants but not their actual physical appearance. Changes in coloring of plants can be triggered by some of the stages defined in the BBCH framework (such as leaf coloring) but it is no prerequisite for it. For example, the leaf chlorophyll concentration is known to strongly increase at the beginning a growing season, changing the physical appearance of the a trees canopy. As the process of leaf chlorophyll accumulation is not covered by the BBCH framework, these changes in coloring cannot be accounted for by the given phenology data.

Furthermore, the spread of BBCH data cannot be interpreted as the duration of a growth process. If for example the first observation for leaf unfolding of a tree species was recorded on day 100 and the last observation for leaf unfolding of this species was taken on day 130, it cannot be concluded that the plant physiological process of leaf unfolding for a given tree takes 30 days. In fact the data can only be interpreted in the sense that the onset of unfolding the first leaf of a tree falls within a time span of 30 days for all trees observed. Sub-question 1.3. will investigate which of these developmental stages are of importance for planting patterns.

Data basis

The BBCH framework has been used to collect phenological data for more than a hundred years. In the so called Pan-European Phenology Database the historical data of 33 European countries are collected, supplemented by new observations and made accessible for download by researchers (PEP725 Data base, 2020). The current database is funded by the Austrian ministry for science & research and the network of European meteorological services (EUMETNET).

More than 12.4 million entries are collected in the PEP data pool, describing 150 plant species. The individual entries of different contributors are summarized as data series and can contain more than 100.000 observations. Due to the sheer volume of data, it is difficult to trace back who collected the data and under which circumstances. Therefore, it is necessary at this point to trust that the contributors adhere to the BBCH code definitions when gathering data.

ID	name	stations	min. altitude	max. altitude	avg. altitude	records	first	last
BE	Belgium	57	4	500	133	2364	1949	2004
DE	Germany	6794	0	1485	236	11127410	1951	2018
IE	Ireland	25	14	116	58	3189	1966	2018
LU	Luxembourg	1	221	221	221	183	1966	2004
NL	Netherlands	541	-9999	25	-9999	14770	1868	1978
PL	Poland	34	3	431	187	9915	1951	2018
GB	United Kingdom	10981	-9999	84	-9999	163520	1950	2005

Figure 2 Data summary retrieved from <http://www.pep725.eu/statistics.php>

For the thesis, a climate conditions should be assumed that prevail in the Netherlands or are comparably to the climate in the Netherlands. Thus, for example, only data from countries that are located at a similar latitude and have a similar altitude structure as the Netherlands can be used.

Unfortunately, most data series recorded in the Netherlands cover varying time periods and often begin well before 1900. Since the Dutch observation series contain relatively small datasets spanning the last 50 years, their suitability for describing the growth of trees at the present-day time is limited. A comparable climate to that in the Netherlands can be found in Belgium, Germany, Ireland, Poland and the United Kingdom, therefore making observations originating from these countries interesting for the thesis project.

By far the most observations in the PEP data pool stem from Germany, followed by the UK and the Netherlands. As an advantage, the German data series include complete observation series from 1951 to 2015 for most important tree species. For the Netherlands and UK this is not the case. Hence, this master thesis will mainly use phenological data from Germany. To ensure that the data collected in Germany is as representative and as transferable to the Netherlands as possible, only data from a selected area of Germany will be used in the course of the data analysis. The paragraph on geodata explains the procedure in more detail.

After registration, interesting data sets can be downloaded from the website for scientific purposes. Each data set contains three Excel files.

1. BBCH data

This file lists all observations chronologically according to the BBCH classification system. For each entry a PEP_ID, the BBCH status, the year of observation and the calendar day of the observation are given.

PEP_ID	BBCH	YEAR	DAY
1072	11	1951	89
2318	11	1951	91
1651	11	1951	100
2631	11	1951	100
...

Figure 3 Example of BBCH data file

2. Specifications of the measuring site

Each observation in the BBCH file is assigned a so-called PEP-ID. In the station file these PEP_IDs are listed with the corresponding coordinates and altitude details. This geographical information allows phenological events to be investigated in a locally confined manner and trends to be identified at any regional level.

PEP_ID	National_ID	LON	LAT	ALT	NAME
1	11110000	9.43333	54.7667	25	Flensburg, kreisfreie Stadt Flensburg
2	11120000	10.15	54.4	25	Kiel-Pries
3	11120001	10.15	54.3333	29	Kiel-Düsternbrook
4	11120002	10.5	54.3167	30	Kiel-Mettenhof
5	11130000	10.6833	53.8833	10	Lübeck-Schlutup
...

Figure 4 Example of data file containing additional information to the observations

3. BBCH definitions

This datafile contains a description of all BBCH stages

Geolocation of data

As already indicated, the computer model is intended to represent the phenological development of tree species in the Netherlands. For this reason, the German observational data must be selected in such a way that they are gathered from an area with similar geographical and climatic conditions to the Netherlands. Through literature research three main criteria were found, that help select data that is as comparable as possible.

1. similarly strong solar radiation

Since sunlight provides the energy necessary for plant growth, many plant physiological processes are regulated by light. In particular, the intensity of sunlight and the length of day or night influence the development of plants and thus the timing of the phenological stages of development.

The solar radiation intensity and the day/night length, which varies substantially over the course of the season, are primarily defined by the latitude of a location. The greater the degree of latitude, the greater the seasonal differences in day-night-length and solar radiation. This difference is reflected in the duration of the vegetation period, which is significantly shorter in Scandinavia than in Spain, for example. It can therefore be assumed that when using data from a large geographical area, the different latitude positions will cause a dispersion of the data. For this reason, an attempt is made to

retrieve data from the narrowest possible range of latitudes. Nevertheless, it is essential for further data analysis to maintain sufficient observations for all tree species over the observation period. At least 30 observations per year, BBCH value and tree species should be provided.

The narrowest possible latitudinal range that meets these conditions is the area between the latitudes N51.25 and N53.25. This corridor has a width of about 222 km. The selection of the data in Python.

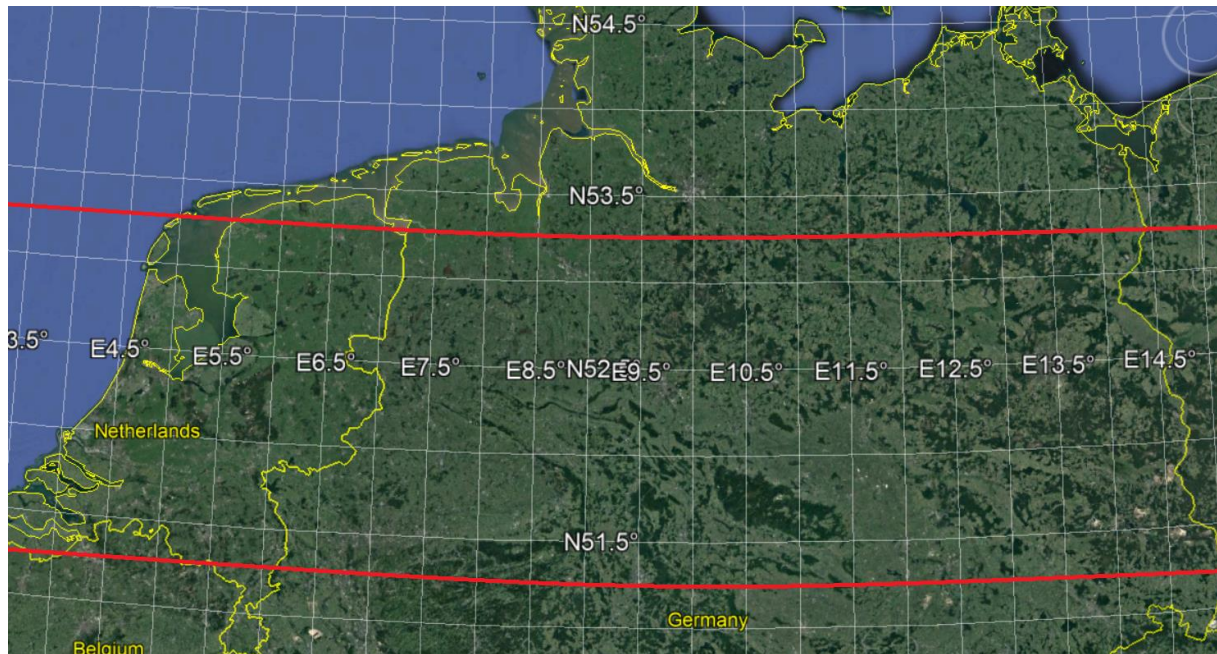


Figure 5 Area of data selection in the latitude range between N51.25 and N53.25

2. comparable height profile

Phenological studies have shown that the altitude also affects plant growth. Especially in mountainous areas, it was found that along an altitude gradient, even within the same tree species, there are significant differences (Source Vitasse et al.). As the Netherlands, except for the province of Limburg, are characterized by low altitude, only German data from a similar altitude range will be used. Therefore, only observations with a maximum height of 50 meters will be used for the data analysis.

3. climatic similarity

In order to ensure that the data from Germany are as transferable as possible to the Netherlands, it should be considered in which climatic zones Germany and the Netherlands lie. A useful framework for this is the Effective Climate Classification by Köppen and Geiger, which draws up so-called climate zone maps taking into account the prevailing climate and vegetation (“World Map of Köppen – Geiger Climate Classification Main climates A : equatorial B : arid C : warm temperate D : snow E : polar W : desert S : steppe f : fully humid T : polar tundra,” 2010). As can be seen in Figure X, both the Netherlands and the country from which the data originate are located in the same climate zone Cfb. The Cfb climate is characterized by the relatively even distribution of precipitation with the warmest months being above the 10°C average. The warmest month is usually below the 22 °C average and the coldest month is above the freezing point for the average. As both Germany and the Netherlands are in the same climate zone, there are no restrictions, it can be assumed that tree species in Germany are

influenced by a similar climate as trees in the Netherlands. In this respect, it can be reasonably assumed that the data from Germany are also transferable to the Netherlands.

World Map of Köppen–Geiger Climate Classification

observed using CRU TS 2.1 temperature and GPCC Full v4 precipitation data, period 1976 to 2000

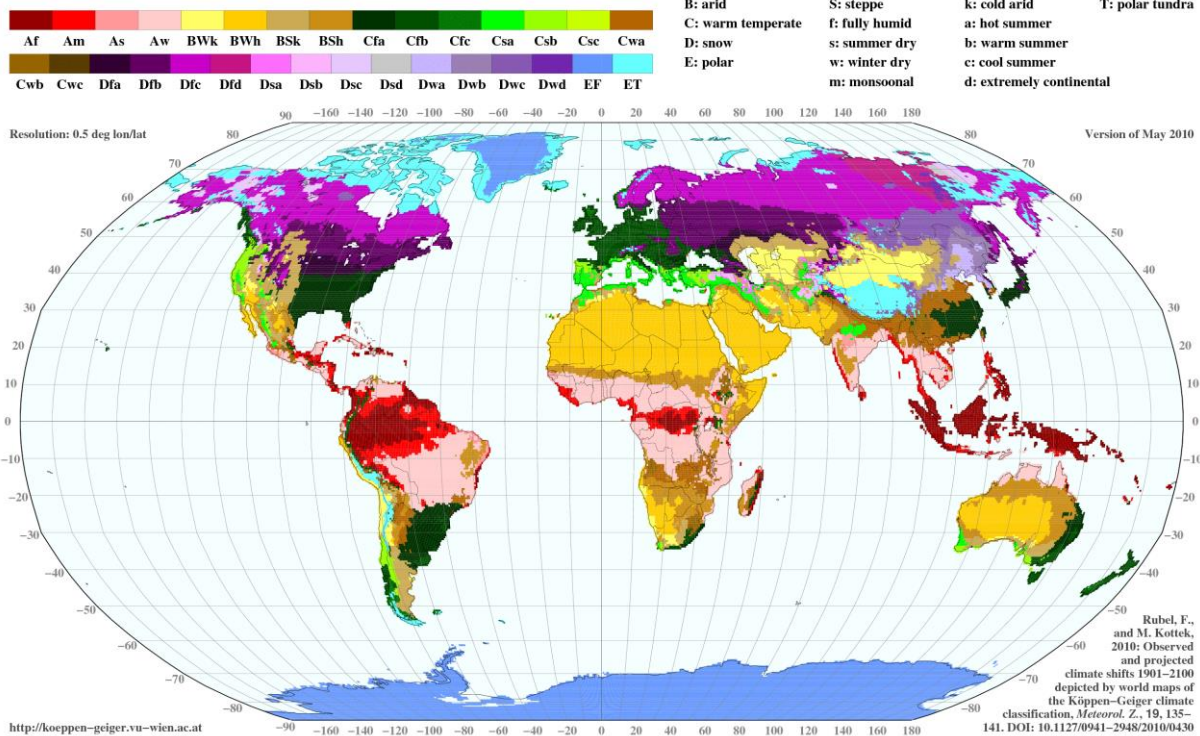


Figure 6 Köppen–Geiger Climate Classification retrieved from <http://koeppen-geiger.vu-wien.ac.at/>

In addition, the temperature plays a key role on phenology. Although the observations already come from a geographically limited area with a similar climate and comparable altitude structure, it is nevertheless theoretically possible, that local peculiarities on site create their own microclimate. It is conceivable, for example, that trees in cities or in the proximity of urban areas are influenced by the warm urban environment. Since the exact environmental conditions at the observation sites are not known, this influence can unfortunately not be accounted for in the data analysis.

Fructification

The phenological stages of flowering and fruit development are not taken into account for the spatial model. Although BBCH data on the timing of these phenological development stages is at hand, the development of flower and fruit proves to be not useful for modeling. This is due to the fact, that newly planted tree saplings need to grow for decades to reach an adult stage where they are able to sexually propagate by developing flowers and seeds. As trees of one species do not reach the adult stage at a specific age, it is difficult to predict how old the trees would need to be to certainly undergo flowering. Furthermore, it is known that trees can skip the flowering period for certain years. Due to the high uncertainty and the long time until flowering occurs, it will be excluded from the spatial model. Figure 7 represents the time after which different tree species undergo phenological growth stages of sexual reproduction for the first time.

Tree species	forest	single stand
Silver fir (<i>Abies alba</i>)	60-80	50-60
Silver birch (<i>Betula pendula</i>)	20-30	10-15
Beech (<i>Fagus sylvatica</i>)	50-80	40-50

European ash (<i>Fraxinus excelsior</i>)	30-50	20-25
Scots pine (<i>Pinus sylvestris</i>)	30-50	15-30
Aspen (<i>Populus tremula</i>)	Ca 10	Less than 10
Oak (<i>Quercus robur</i>)	50-80	40-50

Figure 7 Onset of fruitification for selected tree species

Color scaling of trees

What is the color of trees? This rather trivial sounding question cannot be answered easily and unambiguously, contrary to expectations. Although methodological frameworks to determine the color of single leaves via spectrophotometrically analyses exist, it has proven to be difficult to assign distinctive colors to entire tree tops. Due to the multilayered, 3-dimensional canopy structure of trees, some branches and leaves in the tree canopy partly shade each other, making them appear darker than the branches that are exposed directly to sunlight. Besides, the hue of leaves depends on the amount of sunlight that they reflect. As the leaves can be oriented at different angles within the 3-dimensional canopy, the share of sunlight they reflect can be different throughout the canopy. For these reasons it is difficult to find single color values that actually represent the appearance of tree tops. More realistically, tree crowns can be described by a range of dominant colors.

Although no detailed spectral data on the coloring of trees is at hand, satellite images obtained by remote sensing can be used to identify the coloration of forests from a top-down view. It is tried to obtain remote sensing data from the Copernicus project by the European Union which is based on the European Space Agency's sentinel missions. The Sentinel -1, -2, -3, -5P missions collect data on the Earth's surface absorption profile using different spectral bands (Demarez, 2010). The measurements provide valuable information on the state of vegetation which is used in agriculture and forestry (Wang, Tenhunen, Granier, & Reichstein, 2004). For example sentinel 2 was used to analyze biophysical variables in forestry. However, the spatial resolution of 300m does not allow to find monospecific and homogeneous stands for all tree species. As neither of the sentinels remote sensing data had a sufficient spatial resolution, the Copernicus data pool could not be used to analyze the coloration on single tree level.

For this reason, satellite images from Google Earth Pro are used. The satellites WorldView 1 and 2 that provide Google with the images, offer a greater spatial definition, with the highest spatial resolution being ca. 50 cm in some urban areas. With Google Earth Pro it is possible to choose sections of selected individual tree species. For unambiguous and comparable coloring data, areal views with known tree composition are used. Especially parks in cities are a good source as their tree population is often well documented. As a disadvantage, Google Earth Pro does not provide images of small in regular timesteps.

With the help of Google Earth pro, satellite-based images of Berlin are studied and compared to tree populations maps offered by the municipality of Berlin. It is then searched for sections that show trees that can clearly be classified. The images are cropped to the sizes that the image only represent the canopies of one tree species. The cropped images are then examined with Python to determine the dominant colors of the trees 'canopy. The colors are summarized in the additive RGB code (Red, Green, Blue). For red, green or blue a numerical value between 0 and 255 is given. For Autumn coloring, each 5 dominant colors per deciduous tree species are selected. For spring time from March to June 3 dominant colors are selected. In central Europe the average leaf-chlorophyll concentration of deciduous trees remains almost constant during the summer months of June, July and August, which is why the tree colors are not adjusted for this period.

Seasonal colors

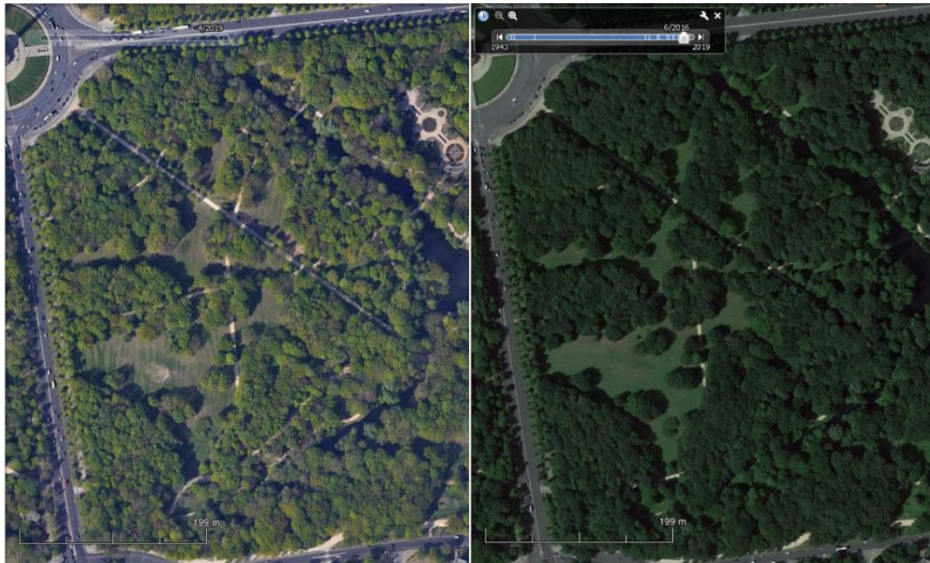


Figure 8 Google Earth Pro satellite images of same location in Berlin taken in April (left) and June (right)

It should be noted, that changes in the appearance of trees do not necessarily need to be triggered by changes in phenology. For example, leaves of deciduous trees appear in much lighter green hue in early spring than in summer. The differences in color are explained by physiological processes that take place while the leaves are already unfolded. Right after leaf unfolding, the tree's foliage is still relatively thin. It takes time to build up leaf tissue which makes the leaves thicker and lets them absorb more radiation. Secondly, the leaves' chloroplasts continue to develop when the leaves are unfolded, resulting in a rise of leaf chlorophyll content from spring to summer. As a result of this physiological process, the leaves gradually absorb more red light which makes them appear darker. The darkening of foliage can be confirmed by comparing satellite images of forest canopies taken in March, April, May and June. However, from a phenology perspective, the trees may still be in the same development change. Thus, the darkening of green leaves in spring is not accounted for by the BBCH framework and data that describes the change of color is lacking. Analyzing satellite images taken in the time from March until June tries to close this data gap. As the satellite images are taken under different light conditions, the colors might not be comparable between the images. Nevertheless, the analysis helps to narrow down the time period of the leaf coloring.

Due to the lack of comparable datasets, it cannot be concluded whether the darkening of leaves is linked to timing of the onset of leaf development of a certain tree. In other words: it is unclear, if an early begin of the vegetation period leads to an earlier darkening of leaves compared to a year where the vegetation period begins rather late. In order to account for the darkening of leaves during spring, the spatial model works with a newly introduced status that tells the program to gradually adjust the leaf color to a darker green hue for the summer time. Based on literature research, the darkening will take place within the time from calendar week 19 to 24 and begins 3 weeks after the first observations of leaf unfolding

Leaf shedding

During the end of the vegetation period in deciduous trees, leaf chlorophyll levels decrease as the pigments are metabolized and remote from the leaves. As the level of chlorophyll drops, red and yellow pigments become more visible resulting the known leaf coloring phenomena. To find out how the trees appear during this phase it is crucial to know how the fall of foliage develops over time.

It was tried to come up with a detailed description of this process, that would allow to accurately determine the onset and the end of leaf coloring and shedding for every tree species in every year. As the BBCH alone does not allow to determine the duration of phenological stages, related studies commonly employ dense time series observations by remote sensing. Especially Vegetation indices (VI) offer valuable insights as they are tailored to describe the vegetations reflection patterns of photosynthetically relevant light spectra (Tillack, 2012; Archetti, Richardson, Keefe, & Delpierre, 2013). One of the widely used indices is the normalized difference vegetation index (NDVI) which describes the “greenness” of a surface of remote sensing measurements. The NDVI is calculated by measuring how much of red light and near-infrared light (NIR) is reflected in certain area. As green plants absorb more red light than near-infrared radiation, green vegetation shows a particular reflection pattern. The NDVI is calculated as followed (Balzarolo, Dox, & Leys, 2019):

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Next to the NDVI, the Leaf area index is used which describes the ratio between the leaf area per area of soil.

The NDVI and the LAI can be measured on a regular basis, making it possible to establish detailed time series that describe the development of vegetation cover over time. However, available data on NDVI and LAI comes with a low spatial resolution of a few hundred meters, making it difficult to investigate the coloring and leaf fall behavior of single tree species. Nevertheless, they provide average data on the duration of leaf coloring which is used for the spatial model.

By combining remote sensing data, on-ground observations of tree species and meteorological data, the onset of different phenological stages could be described on single tree level. Following such an approach allows to describe the onset of phenological stages in dependence of climate conditions. However, such calculations are time-intensive and could be the objective of an own research project. As the spatial model does not work with a daily time step but adjusts the phenology for every calendar week, precise data on the onset of phenology could only be incorporated to a limited extend. Thus, even rough data on the duration of the leaf coloring is considered being sufficient to meet the model requirements.

In studies on the onset and duration of growth stages, logistic models are often assumed to best describe the phenological states (Dixon, 1976). In an accumulated form, time-dependent functions describe the leaf coloring to be symmetrical. This means that the day to which half of the tree’s foliage is colored is assumed to be the day with the highest leaf coloring rate. Before and after this date, the leaf coloring continues at the same rate at equal distances from the mean. Same is assumed to be true for leaf shedding.

The equation for the leaf coloring can then be described as:

$$f(t) = \frac{1}{1 + e^{\left(\frac{2.2}{P_3}\right) * (P_2 - t)}}$$

With $f(t)$ describing the accumulated share leaves of colored. P_3 describes the time period in which the share of leaves being colored increases from 10% to 50%. Due to the symmetrical increase, P_3 also describes the time period in which the share of colored leaves increases from 50% to 90%. Based on literature this value was assumed to be 3 calendar weeks. P_2 equals the DOY of BBCH 94 and marks the day where presumably 50% of the leaves are colored. In case the leaf coloring for a tree was observed in calendar week 42 and literature gives 3 weeks as a realistic value of P_2 , the function gives following results. For leaf shedding, a similar behavior was assumed. Also with a P_3 value of 3 calendar weeks.

Calendar week	37	38	39	40	41	42	43	44	45	46	47	48
Accumulated leaf fall in percentage of all leaves	0,03	0,05	0,10	0,19	0,32	0,5	0,67	0,81	0,9	0,95	0,97	0,98

Figure 9 Example for accumulated leaf fall based on equation 1

With this approach it is not possible to incorporate tree specific characteristics of leaf coloring or leaf shedding. Nevertheless, the description is a workable approximation that matches the requirements of the model and helps to make scientifically-based assumption on the duration of BBCH 94 and BBCH 95 without carrying out extensive field work. The phenomenon of leaf coloring is still not understood in full detail and scientific frameworks that help determining or predicting the exact coloring of foliage in tree species are still lacking. As a workable compromise, the spatial model chooses from a pool of observed leaf colors of a species and randomly assigns the grid cells one of these colors during each iteration. To obtain the colors of the foliage, satellite images of the colored tree species were studied (also outside of Berlin) and the 5 most dominant colors were identified per deciduous tree.

Winter color

Satellite image show that in absence of foliage, the color of the ground highly influences the appearance of a forest. Therefore, the ground in the spatial model will be set to the dominant color seen in satellite image. As a limitation of this approach the color of the ground will stay constant throughout the year and does not take into account grass that could grow on the ground or snow that could accumulate during winter.

Tree growth parameters

Tree growth is often described by allometric functions that calculate tree height or crown dimensions in relation to other growth parameters such as trunk diameter at breast height (DBH) (Evans et al., 2015; Cañellas & Montero, 2007). Although allometric formulas are widely used for research purposes, the equations are limited in their use for the spatial model for two reasons. Firstly, a coherent species specific dataset describing the age related increase of the tree species' DBH beginning at the time of planting is lacking. However, values of DBH are a prerequisite for determining the crown width. Further measured values or environmental factors that may influence the growth of the canopy are also not available. Secondly, allometric growth equations are typically applied to model the growth of young or adult trees, but hardly to newly planted samplings. The growth behavior of seedlings and sampling differs from the growth patterns of older trees which is why their growth can hardly be described by allometric functions of mature trees.

Due to restricted resources and limited data availability of the trees growth behavior the spatial model cannot take into all of the above mentioned factors that may influence the growth. Although a detailed description of the canopy growth is desirable, the limited spatial resolution of the model restricts exact representation of tree top growth. The development of the model prototype reveals that the graphical calculations of tree tops requires a substantial amount of calculations that cause long processing times for each model run. For this reason, the maximum spatial resolution is set to 0.2m. With such a resolution, each grid cell covers an area of 40cm². Obviously, newly neither newly planted seeds nor tree saplings cover an area of 40 cm² which is why the model struggles to model the appearance of the forest in the first years after planting. Therefore, a simple approach for the description of tree growth is needed, that matches the models requirements. For this reason, a logistic growth function is introduced, that helps determining the expected crown widths. It assumes that the crowns radius increases with the growth rate k , which is influenced by the distance to the time of peak growth at x_0 . Besides, the function assumes a saturation s for the crown width, which was taken from literature as the average crown width of a tree species at 50 years stand ages (*Mathews, 2016*). Nevertheless, the saturation point is a theoretical boundary, that cannot be reached due to the high tree density. With equation 3, the potential crown area that can grow in a certain time is defined.

$$f(x) = \frac{S}{(1 + e^{(-k)*(x_0-x)})}$$

Where S defines the saturation point of the crown diameter in number of grid cells, k describing the growth constant and x_0 representing the time period of the highest increase (also referring to the inflexion point of the function).

With the growth function, a crown area is defined, within grid cells can be assigned the states of limb or leaf. To further determine the crown structure, the spatial model need rules on how to allocate these grid cells to limb and leaf. Based on the grid cell that represents the trunk, neighboring grid cells can turn into limbs by the probability factor “is limb”. Provided that a tree is in the vegetation period, leaves may grow on the edges of limbs, defined by the probability factor “is leaf”. By adjusting “is limb” and “is leaf” the crown density and composition can therefore be regulated. The growth parameter mentioned describe the potential of the tree top growth which may be limited by the conditions at stand. In densely planted tree plantations it can be assumed that trees planted in a row will eventually grow into the crown of a neighboring tree and will compete for access to sunlight. For simplicity, the spatial model assumes that in such a case, the tree tops stop growing into each other. In a real situation, the competition for light will lead to some trees overgrowing and shading others, which cannot be accounted for by the model. To actually account for the 3-dimensional canopy structure, data on the tree specific canopy structure and would be needed and specific rules for competition would need to be defined. Due to the lack of data, the limited time resources and the restricted processing capacity of the hardware, the height-dependent modelling of the canopy had to be abandoned and excluded for them the spatial model.

As a result of the restrictions mentioned, the appearance of the canopy structure was checked for plausibility after modelling and the growth parameters “is limb” and “is leaf” where adjusted for each species to obtain results that resemble photography’s obtained from remote sensing. It should be mentioned, that trees in afforestation projects be planted in three different ways: As seeds that germinate at site, seedlings that may stem from a tree nursery or saplings that may even be 1 meter high. As the definitions seedlings and saplings are

Trough literature research it becomes apparent, that different approaches for planting tree plantations exists. Trees can be planted by using saplings obtained from tree nurseries or by applying seeds that germ at the location. Especially the term sapling is a loose term and is not defined by a trees age. For the spatial model, the trees could be seen as seedlings or small saplings. As mentioned earlier, the growth of the first years cannot be modeled accurately, as the spatial resolution and the lack of data do not allow to calculate the growth in all detail.

Data gaps for leaf senescence

As shown above in table X, phenology data is not available for leaf coloring and leaf fall for all species. For this reason the model will primarily use trees with full data availability. In a second step, missing phenology data will be drawn from literature research.

Software environment

The data analysis as well as the spatial computer model for the simulation of phenology-based growth are carried out using Jupyter notebooks in Python. Jupyter notebook is a web-based interactive software development environment that allows to create Jupyter Notebook documents. A JSON document consists of a list of input and output lines, which may contain code, text, or plots. The code for analyzing data and modeling forests is written in Python. Python was chosen as it is open source and comes with variety of different libraries that cover a wide range of possible applications. Furthermore, a great community of researchers and software developers use Python for related spatial modeling issues which is why coding errors and solutions are usually well documented in platforms such as Stackoverflow.

Spatial Model Setup

After analyzing the phenological data and processing satellite images for data on tree coloration, the spatial modelling of the forest canopy takes place with the program SILVESTRA. In five main steps the sample forests can be graphically modelled, taking into account the above mentioned parameters and variables.

1. Load Libraries and Configurations

Firstly, the necessary Python libraries are loaded and the tree species that are used for the model are set. It is decided what tree species should be planted in the background (majority of the pattern) or foreground to what share. Furthermore, the time step and the function describing the horizontal canopy growth is introduced. Due to limited computing power, SILVESTRA models the canopy structure with the timestep being equal to one calendar week. Thus, it takes the model 52 time steps to model one full calendar year. Following a logistic growth curve, SILVESTRA calculates the time-dependent growth of the tree canopies using species-specific parameters.

2. Read Model Data for Selected Species

The files for BBCH timing and the color appearance of the trees are loaded and stored in dictionaries. The weekly BBCH data is transformed in a way that it represents the cumulation of the weekly BBCH occurrences. The data frames containing information on growth, BBCH and timing for each species are summarized and stored as arrays.

3. Logo Preparation

A) Allocate a status to certain colors

A chosen logo is loaded as a BMP file and the targeted size of the modelling is set. The colors in the logo are assigned to values that are linked to the foreground and background that was defined earlier.

B) Seed function

With the seed function, the tree density is defined by setting the distance between grid cells that represent a tree. The spatial resolution of one grid cell should be equal to 0.2m which means that a grid of 500 x 500 grids is needed to represent one hectare of forest canopy at this resolution. The seed function allows to customize the density of trees per hectare by adjusting the distances of grid cells that are set to be a tree trunk. If for example, every 10th grid cell along the x and y dimension represents a trunk, the distance between the center of the tree trunks is 2 meters which results in a density of 2500 trees per hectare. Below is shown, which densities can be achieved by adjusting the distance between tree trunks.

Density n/ha	625	1.111	1.736	2.500	3.086	3.906	5.100	6.944	10.000
Distance between trees in meters	4	3	2.4	2	1.8	1.6	1.4	1.2	1
Distance of trunks in grid cells	20	15	12	10	9	8	7	6	5

Figure 10 Possible tree densities that can be modeled by assuming certain distances between the grid cells

```
trees = np.zeros((bx*by, 5), int)
```

```
p = np.zeros((nx,ny,6), int)
```

C) Lumberjack: Include Customized Mortality Rate

Here the user can define a species-dependent mortality rate according to which a desired proportion of the planted trees dies. The Lumberjack function comes into play at a selected calendar week and randomly kills trees at a given rate. Dead trees will be removed from the grid and the open space in the canopy can be occupied by neighboring trees. Test runs are performed for an annual mortality rates of 1%, 3%, 5%, 10%, and 20%.

4. Initialize Ground with Plants and its Visual Image Representation

This is where the field is initialized and each possible status of a grid cell is assigned a value. Default colors for the ground, the trunks and the limbs are assigned. In the iterate function, the rules are defined how the model should find the weekly BBCH data and further process it. Trees are assigned their parameters and the modeling steps per calendar week are defined.

In the beginning of the iteration process, the SILVESTRA calculates the growth of the tree tops and determines which empty grid cells become limbs or leaves or remain empty. For each calendar week, the model takes the configuration data of the arrays `df_pheno` and `df_bbch` and checks if a tree can grow at the current time step. If a tree is in the growth period, SILVESTRA calculates how far the limbs in the crown can grow. Further, it is checked whether the tree has passed leaf unfolding. If so, the growth of leaves on the limbs is modeled. Lastly, it is checked, whether the BBCH status entails leaf shedding. In that case, grid cells in the status of leaves become empty at the given leaf fall rate.

After calculating the canopies growth, the model assigns colors to all cells of the modeling grid. Based on the information stored in `df_pheno`, SILVESTRA determines the color of all cells. To account for some natural variability in color, the model selects the hues from a defined color range around the proposed color.

```
random.randrange(-5,5,1)
```

5. Simulate Growth over Desired Time Span

In the last step, the tree top for each calendar week is captured as a frame. From the sum of frames, an animation is created and presented as an MP4-video file.

Hardware

For the study, a Lenovo ThinkPad T550 with an Intel i5 quattro core is used. Depending on the time period, the grid size and the complexity of the calculations in the program, running the program can take between 30 minutes and 14 hours. With the hardware used, around 3 Million status calculations of grid cells can be performed per minute. The total number of grid cell status calculations is the product of the time steps (number of weeks*number of years) and the grid size (number of grid cells $x*y$). Modelling 20 years of a squared grid with 1600 cells would therefore require 1.331.200.000 calculations which approximately takes 7 hours and 20 minutes. As the model uses only one core of the laptops four CPUs, the modeling time could be shortened by parallelizing the calculations. However, implementing the parallelization proved to be difficult and would have gone beyond the scope of this master thesis.

Results

1.1. What density of trees is needed to generate distinctive patterns of colors?

With this sub question, it was tried to determine how the density of the trees planted affects the development of the forests canopy structure and as a result the ability to plant distinctive patterns using colored tree crowns. Although the lack of a coherent data on the trees individual crown development limits conclusions on the crown development of single trees, the model helps to understand the development of the overall canopy structure.

The tree density in the model cannot be adjusted gradually as the distances between the tree trunks can increase or decrease with the step size of 0.2 meters. To assume plausible values for tree density in following model runs, literature research on tree density in plantations was conducted. The research revealed the trees are often planted in rows with smaller distances within the row than between the rows. The initial tree density in plantations decreases over time due to mortality of trees. If trees are to be planted as monoculture, species specific distances can be recommended. Below are realistic distances for the tree species if the trees are planted in monoculture. The distances mentioned are not strict norms but rather recommendations which distances will enable the most optimal forest growth.

Knowing that in the spatial model different tree species will be mixed and that the size of the pattern forest should be determined in a simple way, a more general approach for determining the tree density is needed. To reduce complexity of the model, the model works with one density parameter for all species. As another simplification, the tree spacing along the x axis and the y axis will be the same. It is assumed that spacing the trees equally, the canopy will close as equally as possible, which should increase the visibility of the patterns. In order to obtain a closed crown as quickly as possible, the tree spacing must probably be slightly closer than suggested in the literature. Based on the recommended distances as seen in figure 11, a low, a medium and a high tree density was defined for the spatial model.

Species	Distance	Density of trees per hectare (TPH)
<i>Acer platanoides</i>	2,0 * 1,5	3.333
<i>Alnus glutinosa</i>	2,0 * 1,5	3.333
<i>Fagus Sylvatica</i>	1,5 * 1,0	6.667
<i>Fraxinus Exelsior</i>	2,0 * 1,5	3.333
<i>Larix decidua</i>	2,5 * 2,0	2.000
<i>Picea abies</i>	2,5 * 1,5	2.666
<i>Quercus robur</i>	2,0 * 1,0	5.000
Low	2,6 * 2,6	1480
Medium	1,6 * 1,6	3906
High	1,2 * 1,2	6944

Figure 11 Proposed tree densities per hectare (TPH) and low, medium and high densities values defined for the spatial model(LK Österreich, 2018)

Initially, it was thought that the trees need to be planted with a certain density to be able to see the patterns in the canopy. To test this assumption, the model was run with the low, medium and high density and for every run, with ca 10.000 trees planted in all runs. However, in all runs the model could be depicted to the same degree, only the time until the canopy closes differed. As can be seen in figure

12, for all tree densities tested, canopy patterns emerged after a certain time. The total number of trees planted was equal for all runs and the choice of tree density effected the spatial requirements of the forests. With increasing distance between the trunks, the size of the entire grid increases. For this reason, the size of the potential forests ranges from 1,44 hectare to 6,76 hectare – in case the number of trees used remains constant

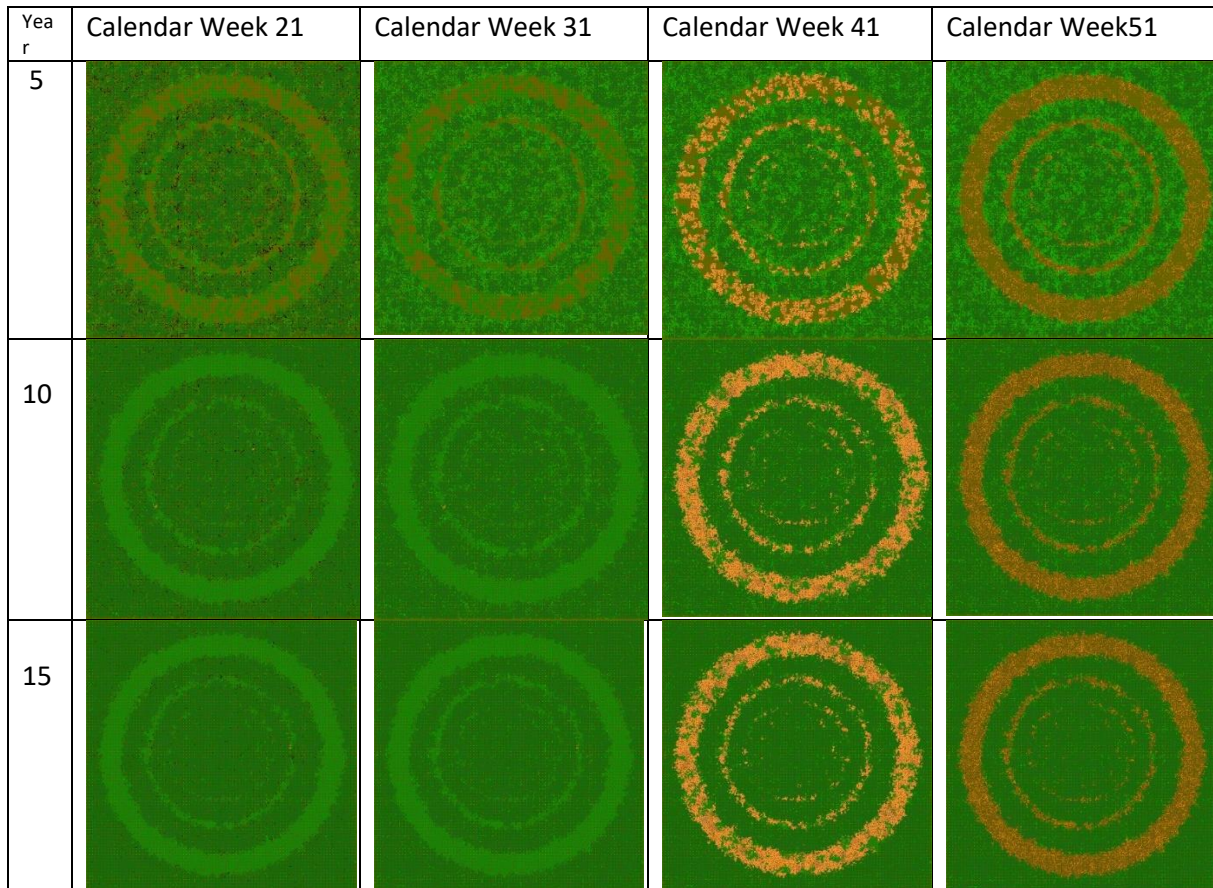
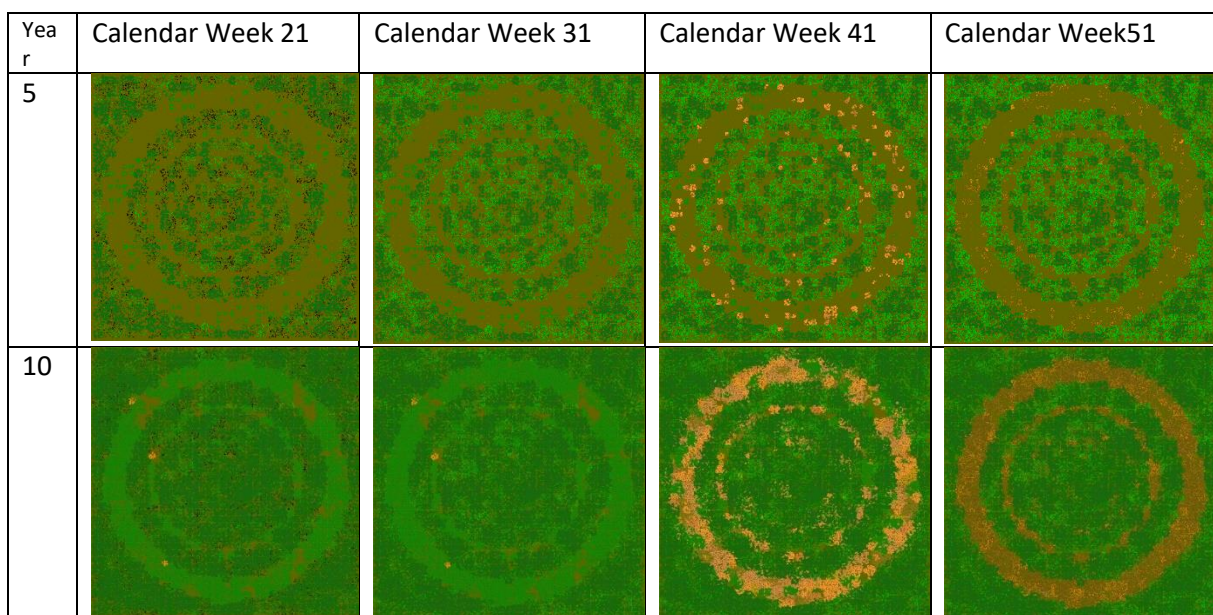


Figure 12: Test pattern planted with a tree density of ca. 6940 tree per hectare seen in calendar weeks 21, 32, 41 and 51 after 5, 10 and years. Planting the pattern would require a forest area of about 1,44 hectare.



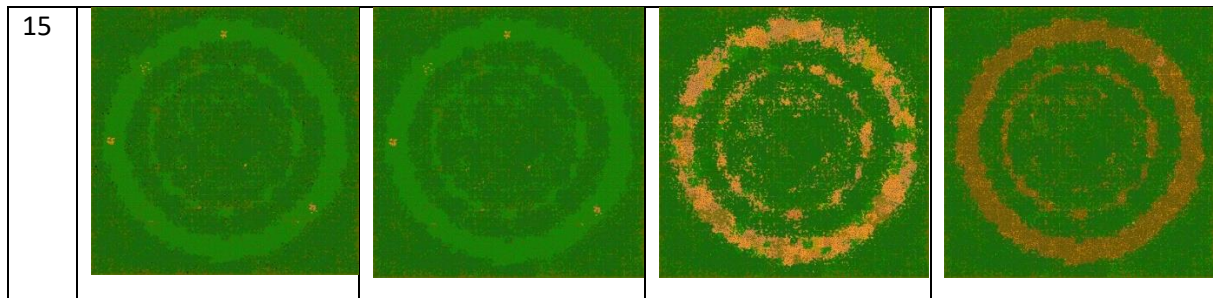


Figure 12: Test pattern planted with a tree density of ca. 3900 tree per hectare seen in calendar weeks 21, 32, 41 and 51 after 5, 10 and 15 years. Planting the pattern would require a forest area of about 2,56 hectare.

Another observation from the experiment is the fact that depending on the tree density, the time needed to recognize the patterns varies. It can be summarized, that at high densities the forests canopy closes earlier and less forest area is needed to show the pattern.

The main result of answering this research question was, that the plausible values for initial tree density that are tested in the model range from around 4000 to about 7000 trees per hectare. At high density of trees, the canopy closes faster and the desired pattern is visible at a comparably early stage. Furthermore, increasing the density reduces the forest area needed to plant a pattern. For the sake of color-based/phenology-based planting it is presumably interesting to compile the forest area in a way that the size of the forest is limited and that the patterns become visible already after a few years. Nevertheless, the tree density cannot be increased indefinitely.

1.2. During which phenological phase are patterns visible from above?

The phenology datasets were analyzed in the jupyter notebook environment to understand the interannual variation for each tree species. Figure X shows the distribution of the leaf unfolding (a), 50% leaf coloring (b) and 50% leaf fall (c) observations for *Fagus sylvatica*. The length of the boxes is defined by the lower and upper quartile of the observations and therefore contains half of the observations. The horizontal line in each box is the median and the whiskers mark the span of all observations. From figure 14, it can be seen that the timing of the phenology observations is subject to interannual variation that occurs for each of the observed phenological stages. From year to year, the median of the BBCH observations can be shifted by up to X calendar weeks. Additionally, the lengths of the boxes changes between the years, indicating that also the spread of observations is subject to interannual variation.

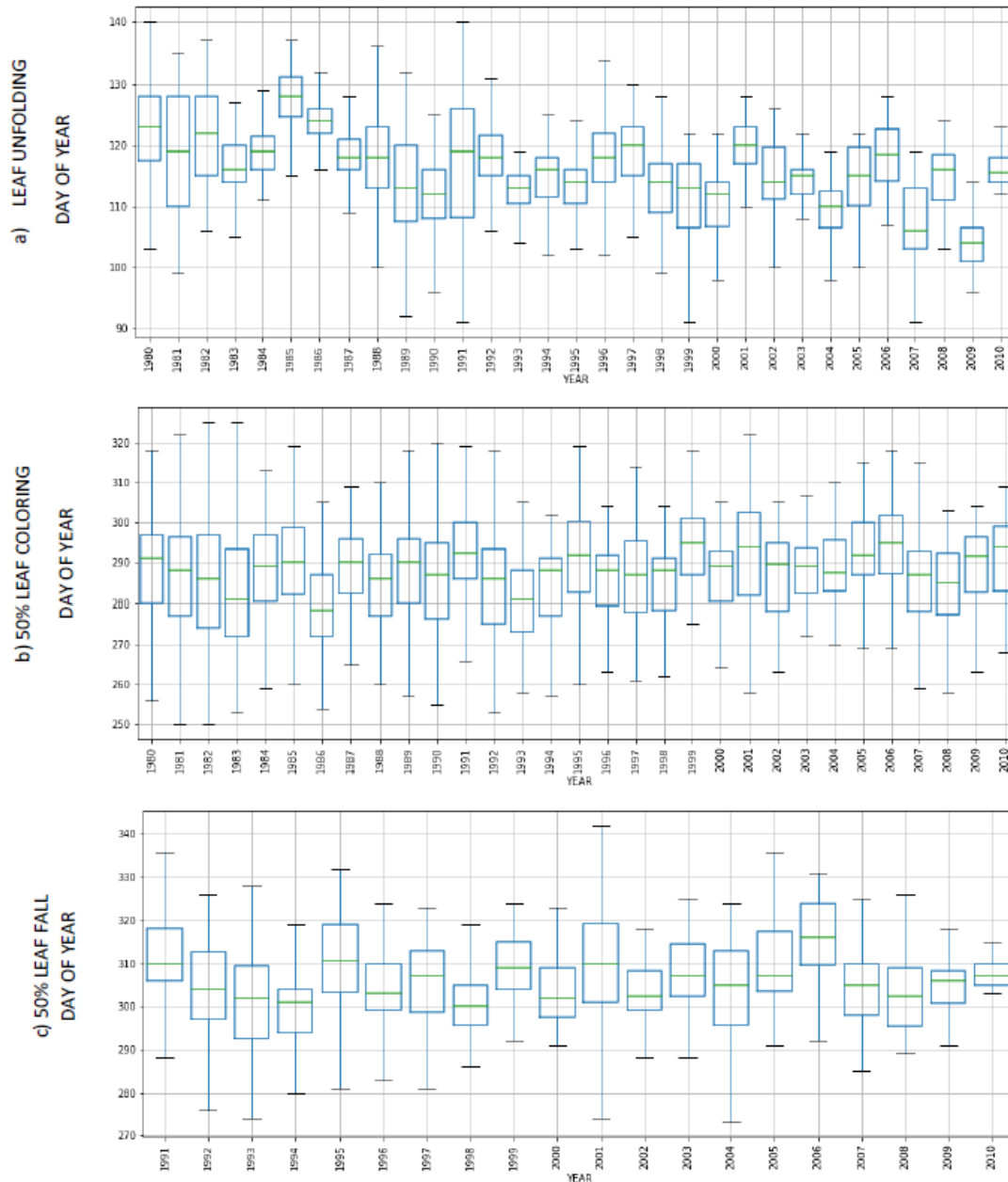


Figure 14 Boxplots showing leaf unfolding, leaf coloring and leaf fall in *Fagus sylvatica*

As a second step, the phenology data sets of different species are compared with each other to determine if the interannual variation in phenology occurs for all of the species. By plotting the medians of the species over the time horizon 1980 to 2010 if the interannual variations of different trees follows a common pattern. Figure x reveals that the leaf unfolding of different species correlates more or less strongly positive which indicates that certain climatic conditions may be beneficial for all tree species. Nevertheless, different it can be seen that different growth response strategies emerged. Indicated by strong positive correlation, the trees *Fraxinus excelsior*, *Pinus sylvestris* and *Picea abies* show almost identically interannual variation, both in the degree of change and in the absolute DOY emergence of leaf unfolding. The leaf unfolding of *Fagus Sylvatica* and *Quercus robur* seem to follow a similar dynamic, with the difference that BBCH 11 occurs about 10 days earlier than in *Fraxinus excelsior*, *Pinus sylvestris* and *Picea abies*.

Figure 15 shows that the leaf unfolding in *Larix decidua*, *Sorbus aucuparia*, *Aesculus hippocastanum*, *Betula pendula* and *Alnus glutinosa* follows a slightly different pattern. Over the entire time horizon, the median of the BBCH observations occurred distinctively earlier than in the other trees.

With figure 15, 16, and 17 it can be concluded that the tree species observed generally react in similar way to environmental conditions. Nevertheless, BBCH stages may occur characteristically earlier in some species than in others. Within the tree species observed, slightly different patterns of growth response can be seen and detected by the degree of correlation between the trees. Figure X shows the BBCH 94 leaf coloring for several species and shows tree timing of leaf coloring follows a certain order in the tree species, with *Aesculus hippocastanum* having relatively early peaks of leaf coloring, followed by *Fagus sylvatica*, *Quercus robur* and *Larix decidua*. In figure X one can see the phenology of leaf dropping over the period of 1981 to 2010. Again, the peaks for leaf coloring come in a certain order with sorbus showing the earliest peak leaf fall followed by *aesculus hippocastanum*, *Fagus sylvatica* and *Quercus robur*.

To find out, what colors can be planted together at what time, the spatial model needs information on the spread of tree phenology and the overlap of phenology observations between the tree species. As the spatial model works with calendar weeks as time steps, the phenology data needs to be summarized in 52 bins of each seven days. With the binned data, heat maps are created that allow to estimate to what degree the phenology of the species overlaps. Phenology data from the years 2001 to 2010 was taken. Figure x shows heatmaps with weekly probabilities for BBCH 11, BBCH 94 and BBCH 95 for the species where data was available. As seen in figure x, the binned data still represents the species dependent characteristics. However, the timing of phenology overlaps, which indicates, that it is not possible to plant patterns where different deciduous assume different phenology stages. For example, it might be difficult to plant a pattern that depends on the colorful foliage of deciduous tree species A and the green leaves of deciduous tree species B to be present at the same time. As seen in figure x, overlapping phenology is also seen for leaf unfolding and leaf fall. Since data for BBCH 94 and BBCH overlaps with each other, it seems to be challenging and risky to plant patterns by solely using broadleaf trees.

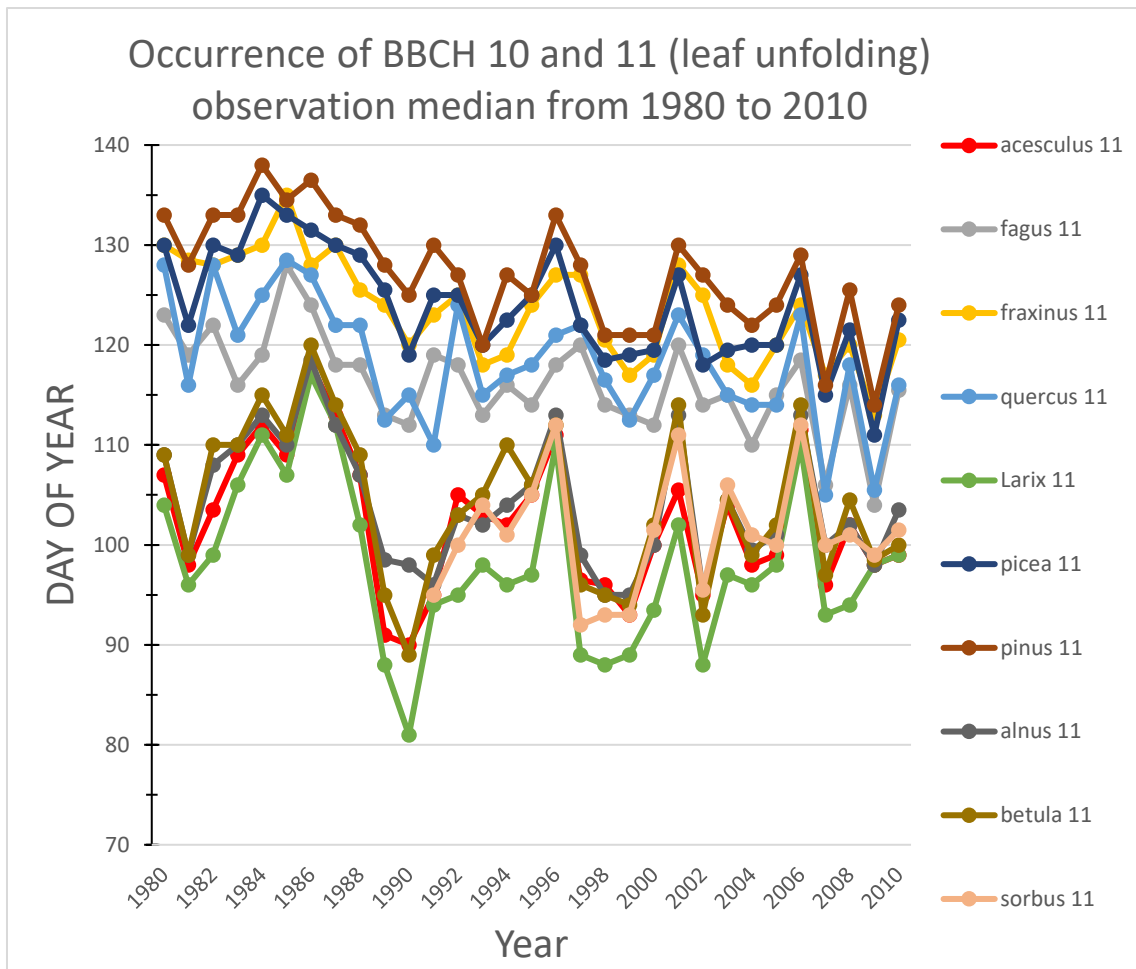


Figure 15 Occurrence of BBCH 10 and 11 (leaf unfolding) observation median from 1980 to 2010

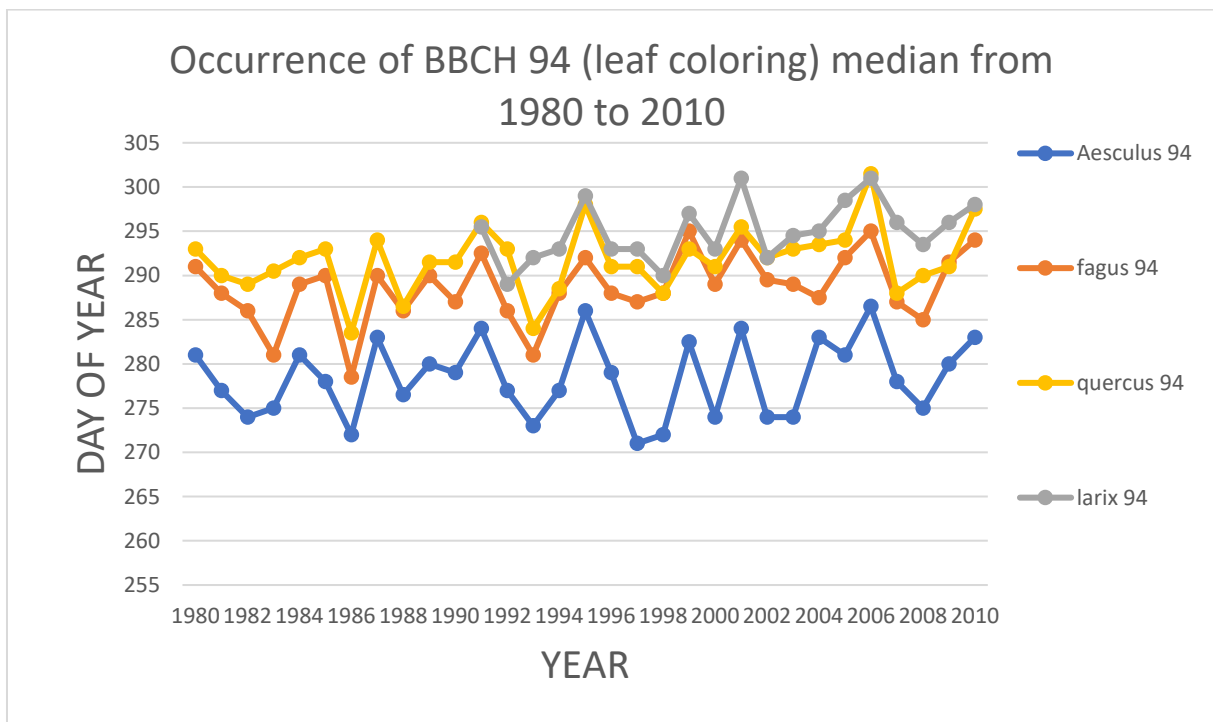


Figure 16 Occurrence of BBCH 95 (50% leaf coloring) observation median from 1980 to 2010

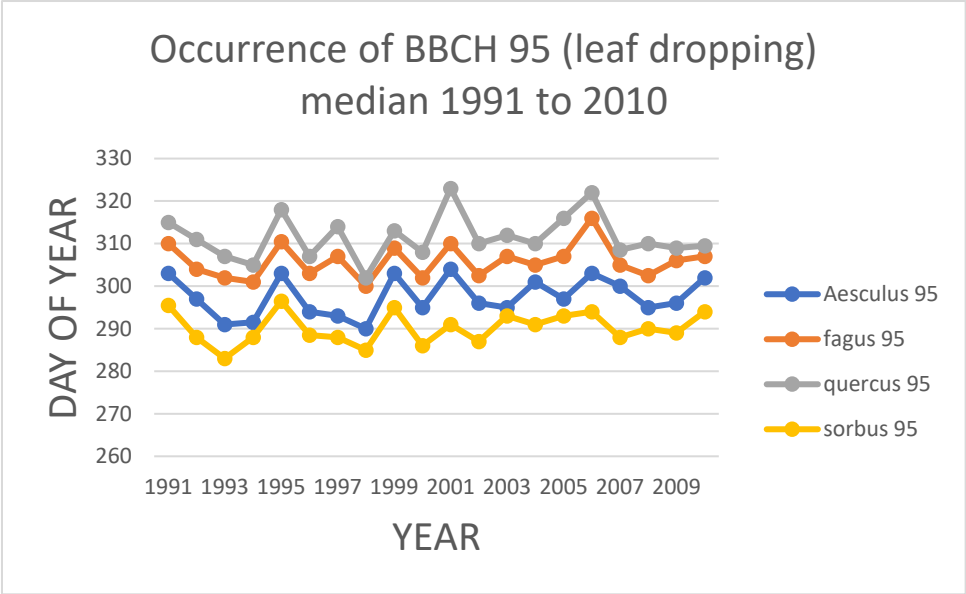


Figure 17 Occurrence of BBCH 95 (50% leaf fall) observation median from 1991 to 2010

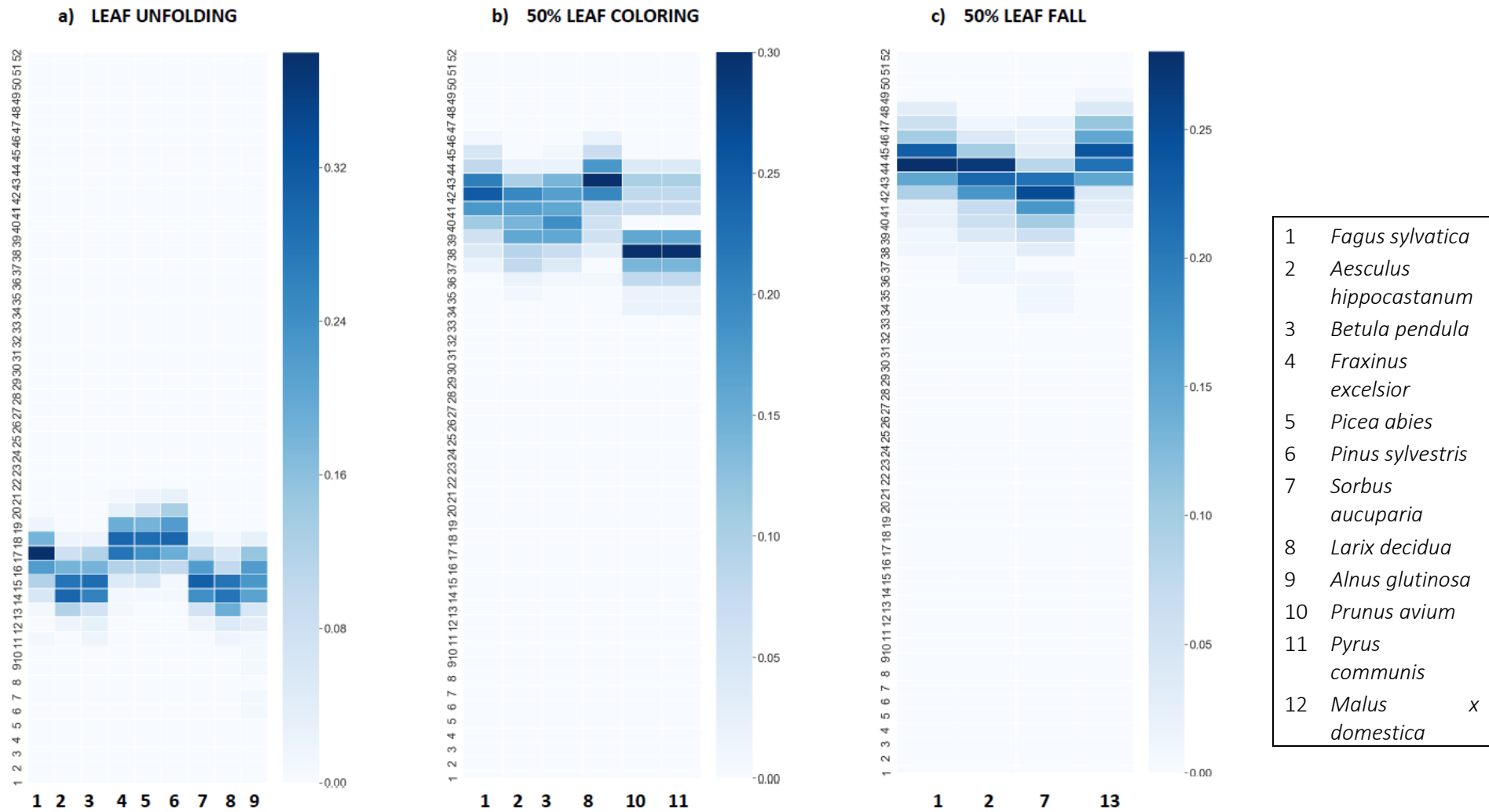


Figure 18 Heatmaps revealing the distribution of phenology observations for a) leaf unfolding, b) 50% leaf coloring and c) 50% leaf fall

1.3. What is the minimum spatial scale to display one distinct pixel?

The previous tests showed that each pattern requires a certain minimal forest area to be accurately depicted by the tree crowns. In the spatial model, increasing the tree density helps reducing the minimal forest area that is needed, but extremely high tree density would be impractical for real afforestation projects. Of course one could iteratively adjust the model parameters or simplify the pattern until sufficient values the required forest area are found. Due to the long calculation times for each run, this procedure could take a long time though. Therefore, a measure is needed that describes the a patterns spatial requirements. Initially it was thought that the pixel size of the MBP-image could indicate how big the pattern needs to be planted. However the pixel size of a pattern alone does not have an impact on the spatial requirements of the model. Company logos for example can be found in different sizes, although they might show essentially the same logo in all cases. Instead of taking the pixel size of the logo as a proxy of required forest size, the relation between the size of the entire logo to the size of the smallest visible objects within the logo should be considered. This ratio describes the proportion between the size of the entire logo and the size of a detail that should be depicted. By describing the proportions in the logo, it can be assessed how large the forest for an entire logo needs to be, if the smallest details need to be depicted correctly. With these estimates, the model can be applied to check if the proposed parametrization delivers acceptable outcomes.

$$m = \frac{\textit{size of entire logo}}{\textit{size of smallest depicted detail}}$$

In the test pattern for example, the thin circle is 1 pixel thick and the entire pattern comes with a size of 500 pixel. The ratio of the size of the small element circle to the entire pattern is therefore 500. This ratio can be calculated for the x and the y dimension. With this ratio at hand, plausible values for the grid size can be assessed before actually beginning with the time intensive modeling process.

$$\textit{grid size}_x = m_x * n_x * d_x$$

$$\textit{grid size}_y = m_y * n_y * d_y$$

Where m describes the size proportions in the logo, n stands for the number of trees that should cover the smallest detail and d represents the distance between the trees.

In the example mentioned above, all elements should be visible in the canopy, giving a value $m=250$. The width of the smallest circle should be covered by 2 trees and the trees are planted at a distance of 1.6 meters which equals the medium tree density of 3906 trees per hectare. According to the equation, a forest area of 800 meters * 800 meters is required, which equals an area of 64 hectares.

If it is decided to simplify the logo and accept, that some details of the logo will not be represented in the canopy pattern, the required forest area decreases accordingly. After rendering the logo for the first time, the smallest detail that is included has a width of 5 pixels. Again, the smallest details should be covered by 1-2 trees and the trees are planted with the medium tree density. As a result, the simplified logo would now only requires a forest area of 320 meters * 320 meters, which equals 10,24 hectares. Further simplification of the pattern reduces the spatial requirements as seen below. This example highlights, that some patterns might require a large area if every single detail needs to be presented accordingly. Simplifying logos can be a workable approach to drastically reduce the required spatial area.

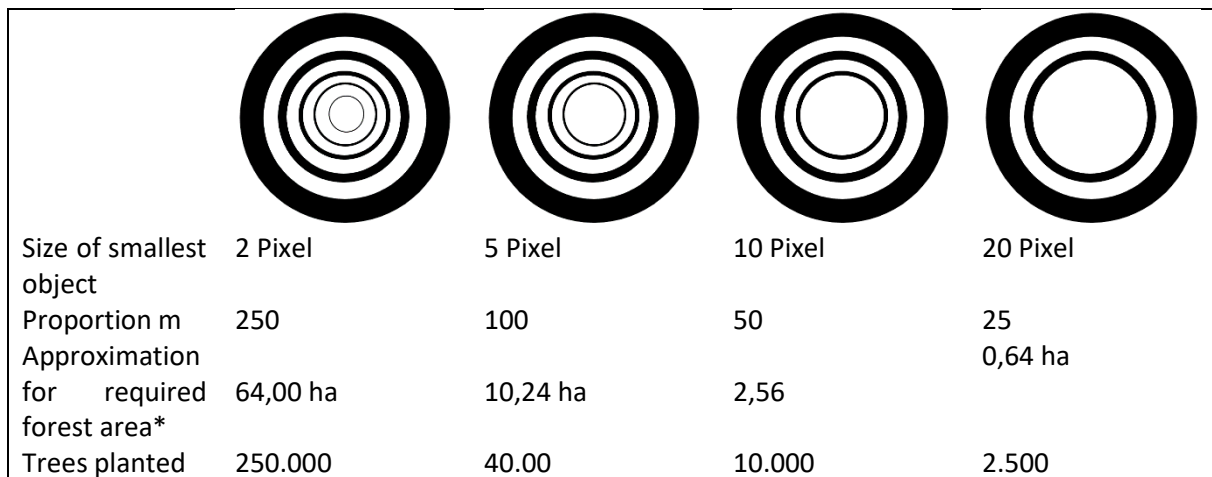


Figure 19 Effect of pattern simplification on spatial requirements of the model. The rings of the pattern to the left have different widths, with the thinnest being 2 Pixels thick. The entire pattern has a size of 500*500 pixels. A medium tree density of 3906 TPH is and minimal 2 trees covering the smallest ring is assumed

To roughly predict, how much area is needed to plant a customized pattern with trees, the complexity of the pattern should be considered. The ratio of the size of the smallest detail in the pattern in relation to the size of the entire pattern indicates how complex the logo is. By rendering and removing smaller objects within the pattern, this ratio can be improved. By assuming that a certain number of trees should represent the smallest detail of the logo, it can roughly be approximated how much forest area is needed to plant the pattern. With these assumed parameters, SILVESTRA can then model the development of the canopy for the given pattern. If using the chosen parameters does not result in satisfying model outcomes, the tree density or the grid size can be adjusted until the model gives sufficient outcome.

1.5. What colors can be planted by using native trees (native to the Netherlands)?

In order to find out what kind of patterns can be planted with native trees, it needs to be determined which colors planted trees can exhibit throughout the year. Can multi-colored patterns or even pictures be simulated with the variety of seasonal colors or are native forests at most suitable to show contrasts in a 2-coloured pattern? Here it is intended to find out which colors can occur simultaneously, how long a combination of different colors can be shown and how certain it is that the trees can actually present these colors. From these answers it can be concluded how many and which colors a given pattern can have.

The challenge of answering this question is, that crucial phenology data for some species is lacking. Missing data can only to a limited extent be taken over from other studies, as phenology observation are only in the rarest cases taken within the same spatial and temporal context as the data from the observation series used. As the phenology of the trees however is dependent on climate and properties of the stand sites, the informative value of other studies is limited. Another restriction is, that the coloration of trees is not necessarily linked to tree's phenology. Despite the above mentioned challenges, plausible phenology data was required for the spatial model. If no literature data on the phenology was available for the required spatial and temporal context was at hand, the earliest and the latest observation for the particular BBCH stage noted for the other tree species were considered as boundaries for the BBCH occurrence. For the spreading of the phenological data over time a normal

distribution is assumed. The disadvantage of this method is that added data comes with a high dispersion and the validity cannot be checked in detail.

A further challenge was the difficulty in determining the exact duration of the different stages. As described in the methods, it was not possible to determine precisely when in the respective years the coloration of the leaves began, when the leaf fall started and when came to an end. This is a methodological limitation of the BBCH framework. For this reason, literature was searched for reasonable values of for the duration of leaf coloring and leaf shedding. As the spatial model works with a time step of one week, it was not necessary to find day-specific data on the onset of BBCH 94 and BBCH 95. A range of 3 weeks was chosen as the time period between the onset of leaf coloring and the peak coloring at BBCH94. Another 3 calendar weeks are assumed between BBCH 94 and the end of the leaf coloring. I total, the leaf coloring is expected to last 7 weeks. For BBCH95, the onset of leaf fall was again assumed to be 3 calendar weeks before peak leaf fall, which is indicated by the BBCH95 date.

	Species	10	11	94	95	
Deciduous trees	<i>Aesculus hippocastanum</i>		x	x	X	
	<i>Alnus glutinosa</i>		x			
	<i>Betula pendula</i>		x	x		
	<i>Fagus sylvatica</i>		x	x	X	
	<i>Fraxinus excelsior</i>		x			
	<i>Malus domestica</i>	x			X	
	<i>Prunus avium</i>			x		
	<i>Quercus robur</i>		x	x	x	
	<i>Sorbus aucuparia</i>		x	x		
	Needle trees	<i>Larix decidua</i>	x			
		<i>Picea abies</i>	x			
		<i>Pinus sylvestris</i>	x			

Figure 20 List of available data sets for leaf unfolding, 50% leaf coloring and 50% leaf fall.

In addition it was a challenge to assign the trees specific color values throughout the year. Literature research has shown that during the autumn, the leaves of individual tree species can take on a variety of different colors, with even the foliage of a single having multiple colors at the same time. Since the precise coloring on leaf-level is challenging to predict and time-extensive to model, a simpler approach was needed. In the spatial model, each tree can assume one out of five colors that were observed during the analysis of satellite images. To account for the natural variety of possible colors, a range-function in the spatial model further increases the range of possible colors.

As the analysis of the satellite images has already shown, patterns could be displayed in the growing season of deciduous trees (spring to autumn) and in the dormant period of deciduous trees (autumn to spring), provided that evergreen conifers are included in the pattern.

During the dormant period of the deciduous trees

This allows to create contrasts for the dormant period of the deciduous trees by combining herbaceous plants as well as the European larch (background color) with evergreen conifers (foreground color). These contrasts between the deciduous trees and conifers certainly occur every year as the deciduous trees undergo autumnal leaf coloring and leaf shedding. Annual climate fluctuations may influence the onset however. The phenology data suggest the contrast between grey/brown deciduous trees and dark-green needles trees is visible for about four months of the year. During this time the colors that can be shown remain quite constant.

	Species	Color
Background	Deciduous trees + <i>Larix decidua</i>	Brown, grey
Foreground	Evergreen needle trees	Dark-green

Figure 21 Color categories for planting patterns that are visible during the dormant phase of deciduous trees

During the Vegetation period of the deciduous trees

Alternatively, colored patterns can be displayed during the vegetation period of deciduous trees. As already stated in sub question 1.3, leaf unfolding, leaf coloring and leaf shedding of a species does not happen on a specific date but seems to be scattered over a number of weeks. The developmental stages of the trees overlap strongly with those of the others. This means that there is a high probability that several tree species are in the same phenological developmental stage at the same time. As there is much overlap in the leaf development of the different deciduous trees, it is not possible to plant a pattern in a way that one deciduous tree species has full green crown while in another deciduous tree species all leaves are already colored.

When looking at what colors the tree species can take on in autumn, no clear different categories could be seen. There are tendencies for the foliage of some tree species to take on a reddish or yellowish color in autumn. These tendencies were identified in the image analysis of the tree species and confirmed by literature. Therefore tests were carried out in the model and the respective trees were tried to be planted as a contrast. It was found that the crown of the examined trees could take on reddish or yellowish colors. However, these contrasts were rather weak and only visible for a short time.

Species	Color tendency
<i>Aesculus hippocastanum</i> , <i>Betula pendula</i> , <i>Fraxinus excelsior</i> , <i>Larix decidua</i>	yellow
<i>Fagus sylvatica</i> , <i>Prunus avium</i>	red
<i>Sorbus aucuparia</i>	Orange/ocher
<i>Alnus glutinosa</i> , <i>malus x domestica</i> , <i>Quercus robur</i>	Not clear

Figure 22 Color tendencies for deciduous trees and *larix decidua* during vegetation period

When looking at what colors the tree species can take on in autumn, no clear different categories could be seen. There are tendencies for the foliage of some tree species to take on a reddish or yellowish color in autumn. These tendencies were also identified in the image analysis of the tree species. Therefore tests were carried out in the model and the respective trees were tried to be planted as a contrast. It was found that the crown of the examined trees could take on reddish or yellowish colors. However, these contrasts were rather weak and only visible for a short time.

Given the lack of reliable data and the rather weak contrasts, it is questionable whether patterns can be shown with deciduous trees alone during the autumn coloring. However, it is known that some deciduous trees such as the copper beech or the copper maple generally exhibit a different coloration

as most other deciduous trees. In copper beech for example, a genetic mutation ensures that after the leaves have unfolded, anthocyanins are stored in the leaf epidermis, making the leaves appear purple. During the summer the coloring slowly fades. Furthermore, there are tree species such as blood maple available in horticulture, which also stand out due to their reddish color.

Using the trees from the present phenology data sets, two-colored patterns can be planted. Two categories of tree species were identified. The first category includes all deciduous trees and the European larch, which is characterized by its foliage coloring in autumn and then shed its leaves. In the second category are the conifers *Picea abies* and *Pinus sylvestris*. They are characterized by evergreen foliage.

1.6. For how many years are the color patterns visible, assuming no or low human intervention?

Due to limited computing capacity and the lack of necessary data sets, the forest crown structure cannot be modelled in full complexity. Therefore, simplifications are necessary, yet allowing the insight into the development of the crown structure as profound as possible. For this reason, rules have to be established with which the model represents the mutual interactions of the tree crowns. The rule was established that the treetops of neighboring trees cannot grow into each other. If two treetops come into contact, they cannot grow further at the point of contact. In the long term, this means that growth in the treetops comes to a halt as soon as the crown cover is closed. In a real forest, however, the crown structure will change continuously over the entire period of time, either through mutual competition, targeted forest management or the death of the trees.

Since the trees are all planted at the same time with a distance between them, the competition for light may be negligible at the beginning. The spatial model should take into account how the death of individual trees affects the overall crown structure. Based on the mortality rate, a certain percentage of trees are killed and removed from the grid at a certain time of the year. The open space can then be occupied by the neighboring trees. In test runs the mortality rate was adjusted from 0% to 2% and 5% and the crown structure was tracked over 15 years.

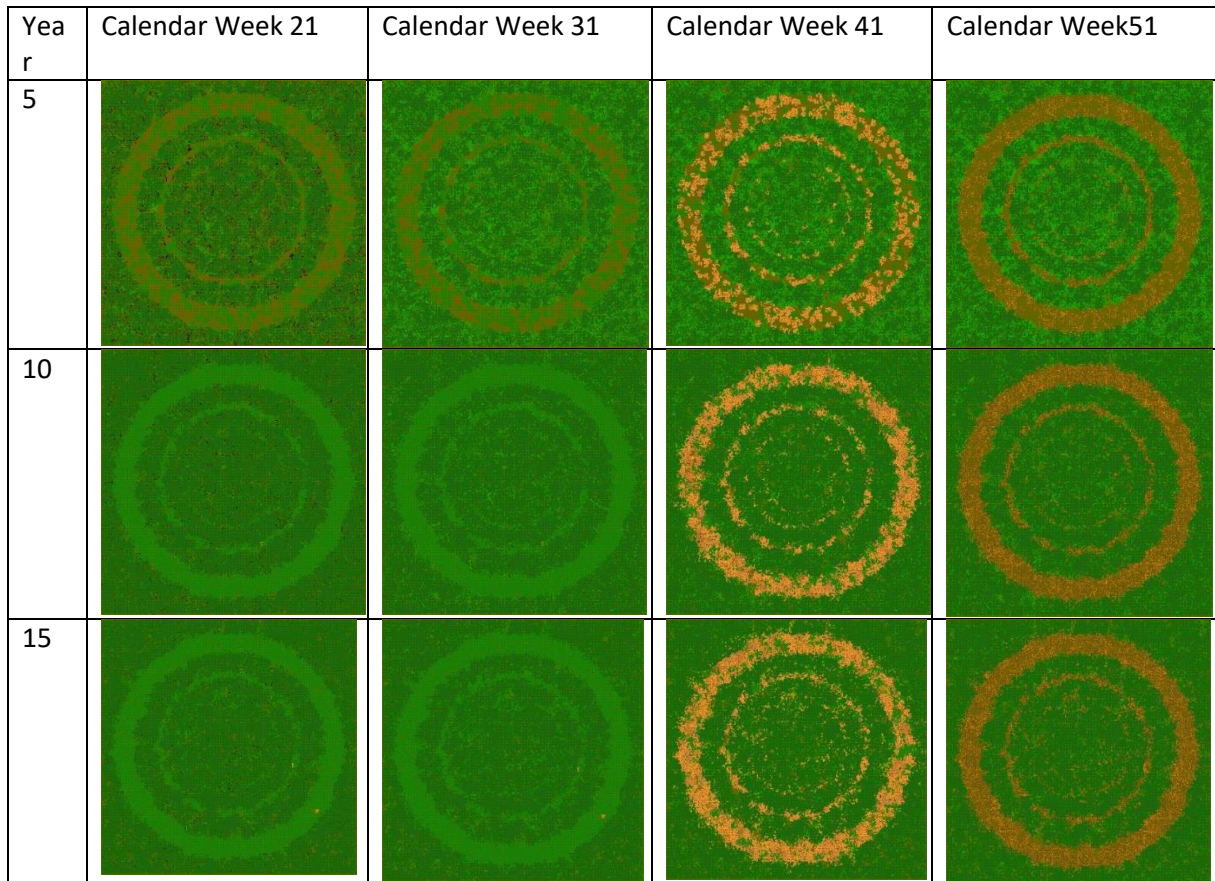


Figure 23: Test pattern planted with a tree density of ca. 3900 tree per hectare and an annual mortality rate of 2%. Plots show canopy state in calendar weeks 21, 32, 41 and 51 after 5, 10 and 15 years.

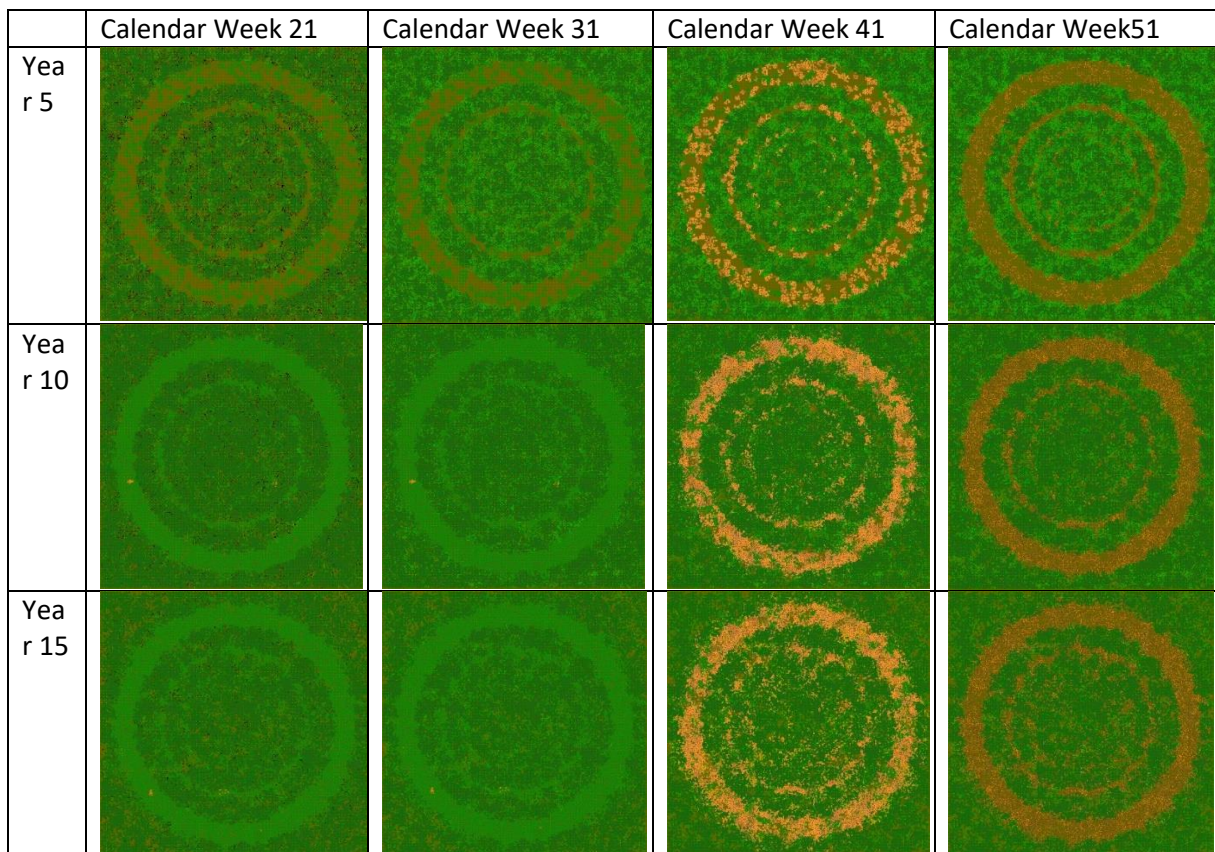


Figure 24: Test pattern planted with a tree density of ca. 3900 tree per hectare and an annual mortality rate of 5%. Plots show canopy state in calendar weeks 21, 32, 41 and 51 after 5, 10 and years.

As can be seen in figure 12, without a mortality rate the crown structure changes little over the years. Whereas in the scenarios 2% and 5% the appearance of the pattern becomes less clear over time. In order to reduce the impact of mortality on the pattern, possible damage can be anticipated at the planning stage by increase the tree density.

1.7. Which locations are attractive for a forest that show the patterns?

Economically speaking, the main added value of phenology-based planting is the ability to plant a pattern that can be used as a marketing tool for the stakeholders who invested in the pattern forest. For this reason, it should be considered how the pattern can best be seen from above. Based on available technology and characteristics, three possibilities were chosen, which generally allow to view objects from a top-down-view.

Remote Sensing

The best-known and most widespread application of satellite images among end consumers is probably google Googles web-based mapping service. An advantage of Google Maps is that the application is familiar to many people, with more than 1 billion people using every month. The satellite images are updated regularly, which means that the images usually are no older than 3 years. For the general public, the satellite images are provided free of charge in high resolution. In addition to recent satellite images, there are historical data that allow the development of the pattern to be tracked.

As a limitation it must be remarked that the user has no influence on when the satellite images are taken and in which intervals the images are updated. Phases with interesting coloring - for example in autumn - cannot be deliberately selected. For this reason, the marketing potential of the dynamically changing tree crowns cannot be fully exploited. Another limitation is that the perspective of the pictures is fixed and cannot be changed dynamically. Another disadvantage is that the commercial use of Google Earth is not defined precisely in their terms and conditions. Thus it is possible that Google, as the provider of the images, prohibits the use of their photography's for commercial purposes.

Besides the mapping service Google Earth, the company has an extended offering, addressing in first scientific but also for commercial use, the Google Earth Engine (Google Earth Engine, n.d.). Google Earth engine provides a plethora of satellite images. It is expected that Google Cloud services such as Google Compute Engine can be used to analyze the remote sensing data in a way that it can be used for marketing purposes (AI Platform Google Cloud, n.d.).

In addition to Google's mapping services, there is the Copernicus program of the European Union, which is managed by the European Space Agency ESA (Copernicus, n.d.). The ESA's Sentinel Missions - 1,-2,-3,-5P provide various types of information, including true images of forests and fields (User Guides - Sentinel Online, n.d.). Using a search filter, photographs can be found without cloud formation. However, the spatial resolution of the various satellites is not nearly as high as that of the satellite images from google Earth.

Under the present circumstances, the data obtained from the Copernicus project is not yet suitable for taking precise images of the patterns. However, since a forest planted today takes years to exhibit a pattern and can then persist for years, future sentinel missions with higher spatial resolution may offer valuable data.

Drones

Another way to capture objects from a top-down perspective are unnamed drones, also called unmanned aerial vehicles (UAVs), that take aerial photographs using special cameras (Tang & Shao, 2015). In recent years, the use of drones in the civil sector has increased significantly and drones are already being employed in agriculture and forestry for environmental monitoring worldwide.

The benefit of drones for farmers and forest owners is that they are able to assess the condition of the vegetation and quickly detect problems such as drought stress or pest infestation (Monitor, 2018). Due to the development in recent years, UAVs are available that can be equipped with a variety of sensors to provide multispectral images with visual spectrum and near-infrared view (Tiberiu Paul Banu et al., 2016). Time lapse images can also be generated by repeatedly flying the same path as wished. Cloud formation is not expected to be a problem for the aerial recordings since the drones only fly a few hundred meters in height and can be flexibly deployed when the weather is favorable. Appropriate software enables the mapping and versatile evaluation of drone recordings.

Various types of drones have already been developed that are optimized for the specific requirements in their field of application. Wing-fixed drones, which look like small aircrafts, are used especially in agriculture. Because of their energetically efficient design, they can carry the weight of the multiple sensors for long distances and are able to monitor an area of several hundred hectares per flight. Areas can be mapped by the drones flying over defined grids while collecting data. Owing to the sensor technology and the analysis software, a wing-fixed UAV can cost around 10,000-20,000 euros in 2020, although the costs are expected to fall in the future.

In the recreational and sports sector, on contrast, cheaper multi-rotor drones are often found, with four or more rotors often placed around a central body. The speed of the rotors can be regulated individually, which makes a variety of flight maneuvers possible. For example, multi-rotor drones can take off vertically and hover in the air in one spot. Thanks to the large number of possible flight maneuvers, this type of drones is even used in the film industry, for instance in nature documentaries. Compared to wing-fixed drones, however, multi-rotor drones are more susceptible to wind and cannot fly as far per flight.

A major advantage of drones compared to remote sensing is that many reforestation companies already own drones and use them to monitor their plantations. In this respect, these companies have little additional cost if they intend to monitor the canopy of their plantations by drone. If a company does not yet own a drone and aims to plant phenology-based forests, the drones can be used for many other useful purposes, such as monitoring pest infestation or drought stress. According to estimates, the market for drones will grow strongly in the future and the unmanned air vehicles will play an even more important role in environmental monitoring. For these reasons, it is reasonable to expect that in 10 or 20 years, drones will be more widely used in forestry than they are today.

Aircrafts and aerial Photography

Depending on the altitude, the model forests could also be seen by airplanes. With increasing flight altitude, however, the pattern becomes progressively smaller and the chance that clouds will impair visibility increases. The advantage of aerial photography with an airplane is that at low altitudes high resolution photographs can be taken of surfaces. For urban areas, Google Maps uses not only satellite images but also aerial photographs of low-flying aircraft. However, aerial photography by aircraft is associated with costs.

As a way to make the model forests visible to aircraft without causing further costs, the forests could be built in flight corridors near the airport. The drawback in this case is that only a limited audience might be able to see the samples. For the customer who has created the design, it might be unattractive and unhelpful if the logo can only be seen by aircraft. In addition, the restriction to flight paths severely narrows the choice of location for the forests.

Theoretically areas could also be visible from above in mountainous areas or from tall buildings. As a limitation to this approach, the pattern cannot be seen from a top-down perspective but only from a semi-diagonal birds-eye-view. As the spatial model does not account for the 3-dimensional canopy structure, it is not clear, if seeing the pattern semi-diagonally changes the appearance of the logo. Due to the geography, this option is not applicable to the case study in the Netherlands.

Discussion

As described in the introduction, the aim of this thesis is to investigate the basic requirements of phenology- and color-based tree planting and potential forests in a spatial model in dependence of different parameters. The underlying theory is that the species-specific seasonal coloring of tree crowns make it possible to plant forests representing customized patterns (Archetti et al., 2013). It is assumed that the coloring of the trees is dependent on the growth phases in which the trees are situated (Vitasse, Delzon, Bresson, Michalet, & Kremer, 2009). Furthermore, it is presumed that the growth phases of the trees follow a certain timing, which is mainly controlled by weather conditions (Way & Montgomery, 2015). It is known that some of these environmental conditions change with the same dynamics every year and can be predicted through mathematical formulas. For a given place north or south of the equator, the length of the day changes in the same way every year (Parmesan, 2007). It is also known that the change of other weather conditions such as temperature, roughly follows a certain annual scheme, although significant variations are likely (Gond, De Pury, Veroustraete, & Ceulemans, 1999). With this background, it is assumed that, triggered by the weather conditions, the growth and thus the coloring of trees follows a certain annual pattern (Vitasse, Porté, Kremer, Michalet, & Delzon, 2009). It is known that there are different strategies among the native tree species to deal with seasonal weather conditions and varying radiation intensity of sunlight (Polgar & Primack, 2011). One of these strategies is to reduce photosynthesis during autumn, deliberately extract nutrients from the foliage and shedding the leaves. During the dormant period, these trees do not photosynthesize. In the following spring, the leaves are completely replaced. Another well-known strategy that mostly coniferous trees pursue is to retain the photosynthetically active organs over the winter and supplement them with additional organs the following spring.

The assumption for this thesis is that through these different strategies of the trees it is principally possible to lay out forests in such a way that patterns can be seen in the crown at certain times. This assumption is supported by satellite images showing forest crowns in winter. Here the treetops of deciduous trees in their vegetation period can be clearly distinguished from the treetops of evergreen conifers. As a result, this thesis has several objectives: Firstly, it aims to find out under which circumstances desired patterns in the crown structure can be seen in which detail and what spatial requirements have to be fulfilled to plant a desired pattern. Secondly, it tries to clarify whether patterns also occur when only tree species of the same strategy are planted. Thirdly, the project investigates when patterns become clearly visible for the first time and whether the patterns change with increasing age of the forest. Finally, the thesis determines to what extent the patterns can be documented and how the footage can be best perceived by a broad public.

The study is based on phenological observations that provide information on when which tree species undergo characteristic growth stages and to what extent the growth stages are constant from year to year. Furthermore, by researching and analyzing tree crowns, it is assessed which colors dominate in the tree crowns during the year. These colors are then assigned to the growth stages and used as a data basis for the cellular automaton.

In the cellular automaton, the appearance of the crown during the year is modelled and extended by a growth function so that the development of the crown can be modelled over several years. The evaluation of the phenological data leads to the conclusion that the occurrence of growth stages such as leaf unfolding varies from year to year and that the observations are spread over a period of several calendar weeks. These findings can be expected in so far as the interannual differences have already been revealed in phenological studies. In addition, it is shown that the occurrence of growth phases such as leaf unfolding correlates positively between the different tree species. This means that all

observed species reacted similarly, although not equally strongly, to changing environmental conditions.

This study does not cover which environmental factors affect tree phenology to what extent. However, the data analysis shows that the tree species used in this study react similarly to a given environmental condition. This conclusion is not surprising, as it can be expected that certain temperatures, photoperiods or rainfall levels are generally favorable for the growth of native tree species (Ziello, Estrella, Kostova, Koch, & Menzel, 2009). It is also not surprising that the phenological timing of some species is particularly strongly positively correlated. The new leaf emergence of *Pinus sylvestris* and *Picea abies* correlates strongly positive and occurs relatively late. This can be explained by the fact that both trees are evergreen needle trees that do not need to replace their entire foliage, whereas deciduous trees are forced to rebuild new leaves in spring (Gamon et al., 2016). It is interesting to note that within deciduous trees, some species correlate particularly strongly with each other. This is the case with *Betula pendula*, *Sorbus aucuparia*, *Alnus glutinosa*, *Aesculus hippocastanum* and, surprisingly, the conifer *Larix decidua*. Throughout the observation time, the deciduous trees always develop their foliage about 10 to 20 days earlier than *Fagus sylvatica* and *Quercus robur*. Data analysis revealed that observations of leaf color and leaf shedding within one year per species are much more scattered than observations of leaf development. This may be explained by the rather ambiguous definition of the BBCH framework. It is probably much easier for observers to determine the first leaf unfolding than to estimate when exactly 50% of the leaves of a tree are colored or have already fallen to the ground.

A spatial model is created based on phenology data sets, which can be used to plan different tree species on a customized grid. The results of the computer model confirm the assumption that the crown structure of deciduous and evergreen trees differ significantly, especially from autumn to spring.

According to the model, the time until the crown closes also depends on the tree density TPH. This result is not surprising as the annual growth per tree is limited. The closer the trees are planted, the faster the canopy closes. Contrary to the initial assumption, the pixel count of a picture does not indicate how much forest area is needed to depict it. Far more important is how complex a logo's design is and how large the smallest details are in comparison to the logo's overall size. This is especially important when drawing lettering, thin lines or dots. In a simple formula one can calculate how much space is approximately required to plant a desired logo. This formula assumes a minimum number of trees that represent the width/thickness of the smallest detail in the logo. Based on the assumption that not all planted trees survive but a certain percentage of trees die over time, the mortality rate reflects the loss of trees.

By means of the freely selectable mortality rate it can be clarified how reliably the pattern can be recognized. The assumption is that as the mortality rate increases, it becomes more difficult to create specific patterns. For example, if a tree dies in the background and grows at the edge of the foreground, the open space can be occupied by a tree growing in the foreground. If this often occurs over several years, there is a risk that the edges will become less visible. The expectation is confirmed and as the mortality rate increases, the pattern becomes unrecognizable earlier and earlier.

The theory mentioned at the beginning assumes that it is possible that patterns can be planted by a combination of deciduous and evergreen trees. However, the spatial model also shows that contrasts can be planted if only deciduous species are used. The model suggests that reddish (*Sorbus aucuparia*) or yellowish (*Fraxinus excelsior*, *Larix decidua*) shades can be planted with deciduous trees for a short time in autumn. Although not listed in the data pool, there are some tree species that are known for their special purple-colored foliage. These types of trees include copper beech (*Fagus sylvatica f. purpurea*) and blood maple (*Acer palmatum*). In addition, numerous cultivars are offered for

horticulture, also showing reddish or even yellowish leaf coloring in summer. Thus, theoretically it is possible to plant 2-colored patterns using only deciduous trees. However, it must be critically questioned whether the use of ornamental trees support the purpose of a forest that is as biodiverse and natural as possible, since these species are seldomly found in natural forests and are more likely to be deliberately planted in parks as ornamental plants.

Finally, the question arises how possible patterns can be seen from a top-down perspective. In the case of the Netherlands, patterns are made visible by satellites, drones or airplanes. Drone technology in particular has the greatest potential to capture the crown structure in a flexible manner. Due to a lot of possible flight maneuvers, footage can be taken with an artistic claim. It is advantageous that drones are already being used in many different ways in the leisure sector as well as in agriculture, and even simple-equipped drones seem to be sufficient to take high-quality pictures or video recordings of the forests. If it is envisaged that ESA's Sentinel missions will be further developed in the future, satellite images from the European Copernicus project can also be used. Besides that, satellite images provided by Google's web based mapping services are already suitable for use. However, the commercial use of these images may be limited.

Conclusion

By creating the spatial model it was tested under what circumstances phenology- and color-based planting approaches work and what consequences follow from applying the novel approach. Modelling potential forests revealed that stable and visible-canopy pattern can be planted on if areas of a few hectares are available. As expected, the most distinctive patterns can be planted by using a mixture of evergreen and leaf-shedding tree species. Assuming no human interference, the model indicates that the planted patterns can be visible over decades.

This section is devoted elaborate on potential applications of the SILVESTRA model in its current state and to highlight possible improvements and further developments of the software. Furthermore, it is discussed, which limitations might restrict the informative value of the thesis project and what strategies could be followed to reduce the resulting uncertainty.

Potential applications for phenology- and color-based planting

Findings from the thesis and the computer model itself could be of interest for forest managers and afforestation companies, which like to create forests with value that goes beyond taking up atmospheric carbon. Presumably the most interesting aspect of phenology- and color-based planting is that species richness within the forest can be used to create a highly unique marketing place for stakeholders or organizations.

The added financial value of the customized forest lies within the visibility of the colorful tree tops, that could even be seen on satellite images. By planting a diverse mix of native forest species, stakeholders actively support climate action and biodiversity while transporting a message to customers, business partners or the general public. This combination of commitment to environmental goals and the ability to link these goals to the stakeholder, make pattern forests very interesting for the business model of carbon forests. Carbon forests address the issue of climate change by planting trees that can sequester carbon dioxide from the atmosphere. Such forests could be of interest for two groups of stakeholders:

1.1. Private companies

By supporting afforestation projects, companies can offset their unavoidable CO₂ emissions and position themselves as progressive climate leaders of their industries. As offsetting CO₂ emissions can cause high costs for the companies, they are interested to profit from the offsets in another way: Either through acknowledgement from critical shareholders, appreciation of environmentally conscious customers or by being seen as responsible thought leaders. However, offsetting of emissions remains often invisible to the public eye. Afforestation initiatives are rarely carried out in proximity to the offsetting stakeholder, which makes it difficult to establish a link between them. Pattern forest, however, can be used for innovative marketing strategies and can be easily tracked down by customers who like to know more about the project. The growth of the forests can be documented with colorful images or videos over many years.

1.2. Governmental and Non-governmental organizations

Next to private companies, national governments might be interested in employing phenology- and color-based planting methods. To raise awareness about climate change and biodiversity loss, countries already organize coordinated planting events that often take place on special occasions. German authorities for example, carry out the so-called "Einheitsbuddeln", where all citizens are

invited to plant trees on October 3rd (Einheitsbuddeln, 2019). Additionally to many individual plantings across the country, a pattern forest could be planted that shows a pattern matching to the narrative. By its event character, planting such a pattern forest on this occasion could lead to nationwide media reception and may provide identification potential.

Although it is true that promoting afforestation can help sequester atmospheric CO₂, it cannot be said that all carbon forests are also beneficial to their close environment. Depending on the selection and diversity of tree species, newly planted forests may even be detrimental to the local biodiversity, especially if planted in monocultures. Phenology- and color-based planting partially solves this issue as the diversity of species is the prerequisite for planting patterns.

Nevertheless, for successful implementation of pattern forests, specialist expertise is needed to select suitable tree species. For this purpose, forestry specialists may help develop a plant catalogue based on criteria such as water requirements, nutrient supply or pest susceptibility.

Limitations of the study

In the course of the literature search it became apparent that the visibility of patterns in forest crowns depends only to a limited extent on the phenology of trees. It is also influenced by plant physiological processes on cellular level, some of which are not covered by phenology frameworks. For the time in between the different phenological stages, it had to be determined when and how strongly the appearance of tree crowns changes during the course of the year. For some of these processes there was no complete methodology or other data sources available, so some parameters had to be estimated. By linking phenology data with color tones derived from satellite images and other sources, a spatial model was created that is actually based on color and phenology.

General limitations of models

"Essentially, all models are wrong, but some are useful" - George Box

Spatial models, representing the course of complex processes over time, are useful for understanding how individual processes function in a larger context. Examples in forest science are forest fire models, which allow to estimate how a fire may spread in time and space. Spatial models enable to describe the condition of the entire system (forest) beyond the state of single model components (tree). Especially in forestry, spatial models can be of great use, since they allow to describe large spatial processes for long periods of time, which cannot be investigated in field experiments to the same degree. In addition, spatial models, such as the CA used, allow to represent the behavior of processes under different scenarios with a set of assumptions each. By iteratively adjusting parameters and the functions describing the relation between them, the system can be understood. In this study the spatial model helps to place the appearance of individual trees in a large overall system context. This makes it possible to draw conclusions about the entire forest canopy over a long period of time.

Despite the great advantages of spatial models, it must be critically noted that all models are only able to describe and assess the parameters and functions to a certain degree. To some extent this may be due to the fact that parameters are poorly described scientifically, involve uncertainty or are not known as influencing factors and are therefore not included in the model. Consequently, models are not capable of accurately and fully depicting the development of complex processes with all possible influences. In the case of the spatial model the following parameters are subject to the limitation

1. Availability of phenology Data

The first model limitation concerns the availability of phenology data and its subjective character. Although the study planned to elaborate on phenology-based planting of forests growing in the Netherlands, the restricted data availability did not allow to use Dutch datasets. For this reason, phenology observations stemming from Germany were analyzed and used for the study. As shown in the section methods, the German data was filtered to only use data that was as comparable as possible to the Dutch climate conditions. As the data from Germany and the Netherlands cover different time horizons, it was not possible to check how well the datasets overlap for a given year. Furthermore, it was intended to compare locations for potential pattern forests, but the limited availability of phenology data made it impossible to reproduce pattern forests for countries like Spain or Sweden.

2. BBCH-Framework

To a certain degree, the collection of phenological data is subject to the personal judgement of contributing researchers. Especially the leaf coloration BBCH 94 and the leaf shedding BBCH 95 are subject to methodological uncertainty, since observers might have difficulties determining the exact point in time when 50% of the foliage is colored or fallen. It is therefore not surprising that observations for leaf fall are more widely scattered than for leaf unfolding. Additionally, literature research revealed that under certain circumstances, leaf fall may occur with less or no leaf coloration, which makes it difficult to assess these development stages. Furthermore, the vast amount of data does not allow to check for extraordinary site conditions that could have influenced the timing of phenology.

3. Determination of phenological development stages

The phenological BBCH datasets did either provide information on the onset of a phenological stage (leaf unfolding) or the peak of a plant's growth stage (leaf coloring and leaf shedding). However, the spatial model demands data on the duration of such processes. With the help of literature research, it was tried to find plausible ranges for the missing data. Nevertheless, most research frameworks applied for phenological studies have difficulties to relate the phenology to singular trees.

On a forest level, vegetation indices prove to be valuable proxies of plant development. However, when it comes to linking remote sensing data to the development of singular trees, the spatial resolution limits research. The lack of data and insufficient spatial resolution of remote sensing were a barrier to this research leading to suboptimal model results when comparing the phenology of deciduous trees with each other. For planting pattern with deciduous trees and evergreen needle trees, the methodological limitation is less severe. It was decided to accept the limitation as the focus of the project was the creation of the spatial model itself and the question of how deciduous trees and evergreen needle trees can be combined to plant pattern.

As mentioned earlier, the definition for leaf coloring and leaf shedding give room for subjective interpretation, which is why the observations for BBCH94 and BBCH95 are widely scattered. Due to the wide spread of observations and the ambiguous definition of leaf coloring, the autumnal leaf coloring includes uncertainty. Studies indicate that the onset of autumnal leaf coloring is not dependent on one single trigger. In contrast, it is believed that a multitude of interacting factors determines the leaf coloring onset which makes it difficult to predict autumn onset by climate data only.

4. Dynamic color values

When creating the spatial model, it was particularly difficult to assign colors to the trees at different times, which best matched the appearance of their crowns. In order to select the colors that are as representative as possible for the crown, satellite images of each tree had to be examined for their dominant colors. The challenge here was that data is incomplete. Time series of remote sensing data exist that analyze the photosynthetically relevant spectra with vegetation indices like the NDVI. However, these images were not available in a sufficiently high spatial resolution to obtain individual color values for each tree species. In order to obtain comparable color values for each tree species, satellite images from Google Earth Pro were therefore used, although these are not available at regular intervals.

5. Crown structure

The development of the crown structure could only be described approximately and indirectly in the spatial model. Although models exist that define the growth of different tree organs, they did not fit in the scope of the study. For example, species-specific equations which predict the growth of tree crowns in relation to the growth of other tree organs were available for the study. In many cases, however, the growth processes of trees are described without reference to the age of the trees, but refer to the DBH.

For seedlings, however, allometric functions with reference to the DBH are not suitable, since the growth of seedlings follows its own functions and, especially with small seedlings, the DBH cannot yet be measured. This is further complicated by the fact that seedling growth is strongly dependent on factors such as light availability and local environmental factors and is not primarily described by age. The lack of data and the inaccurate description of seedling growth therefore limits the validity of the spatial model for the first 10 years after planting. However, even with better data, seedling growth could only be reproduced to a limited extent due to the limited spatial resolution. With a resolution of 0.2m per grid cell it is not possible to resolve a seedlings initial crown size adequately.

As a further limitation of the model, the crown structure of the tree is modelled as a 2-dimensional area - quasi the projection of the horizontal crown structure onto the ground. Neither the height of the trees nor the height of the crowns are considered in the model. It is therefore not possible to assess the effect of shading. Thus, the model cannot represent whether and how certain trees overgrow and shade neighboring individuals.

In order to describe the influence of tree height on competition in the crown, the spatial model could be extended by a third dimension in a further development, which would, however, significantly extend the running time of the model. Alternatively, the height growth of each tree species could be calculated in time intervals and rules for the overgrowth of neighboring trees could be established. These rules could then be used to determine which trees overgrow which other trees when updating the grid cells. Taking into account the competition in the crown could help to determine whether, for example, trees at the edges of the pattern can overgrow other trees and thus change the pattern.

Further application of the SILVESTRA model

In this study, the SILVESTRA model was developed to answer the specific research questions. The true potential of SILVESTRA, however, goes beyond the scope of the thesis as the model can be the basis for a variety of other research projects. After the thesis it is planned to publish the project on collaboration platforms like Github for general use. Thus, interested researchers can use SILVESTRA as a tool and continue develop it for their research purposes. If phenology- and color-based tree planting is to be investigated in more detail, further developments of the model could provide valuable insights:

- The grid could be extended by a third dimension, making it possible to model vertical stem and crown growth of trees. Thus the crown structure can be represented more realistically and mutual shading of the trees can be included as an influence on tree growth.
- The annual variations in the timing of phenology can be better understood by taking climate data into account. The climate data of the different measuring sites could be determined and related to the respective observations. Machine learning algorithms (Czernecki, 2018) could be trained with the data sets and possible future climate scenarios could be established. Based on the scenarios, the effect of climate change on plant phenology could be investigated.
- Other planting techniques could be tested in the model. For example, it could be investigated whether a higher tree density along the edges in the pattern ensures that the patterns remain visible over a longer period of time.
- Instead defining of a constant annual mortality rate, the trees could die with different probabilities depending on their stand age.
- In addition to native tree species, shrubs as well as annual plants could be included in the model.
- The spatial and temporal resolution of the model could be increased: Instead of calendar weeks, every day could be modelled. In addition, each grid cell could be assigned a smaller area, which would make it possible to better represent the crown structures. Furthermore, more precise growth descriptions could be defined.
- In addition to extensions in content, the efficiency of the model can also be improved, thus shortening the runtimes. This can be achieved, for example, through parallelizing time consuming calculations. In this way, individual calculation steps can be distributed to different processor cores of the computer.

Outlook on phenology- and color-based planting

The research conducted and the findings on phenology- and color-based planting raise questions that go beyond the scope of this thesis project. The novel planting approach was introduced with the intention of creating biodiverse forests that inherit both ecological and economic value. However, the premise of creating a species-rich, native forests is that local tree species are used that are well-adapted to the climate at site and offer food and habitat for other species that can be found at the location. For this reason, it cannot be generalized what tree species need to be chosen. Furthermore, the selection of tree species will be dependent on the soil conditions and water supply found at the location. A case study conducting field research to obtain data on these parameters could connect the modeling work with realistic, site-dependent requirements to the forest. The goal of such a research project could be to identify promising locations for afforestation projects, to take measurements on soil conditions and to analyze the abundance of other species at site. In collaboration with local forest managers and by the application of bioindicators, such as the Indicator Value of Dufrêne and Legendre,

the ecosystem at site could be assessed and mapped. Considering and anticipating global warming, it could also be studied, what tree species at the location might be more robust to withstand periods of extreme weather conditions.

Another research project that could derive from this master thesis could increase the spatial and temporal dimension of the model and include up-to-date phenology data for 2018 and 2019. By including data of these two years, it could be studied if the extreme climate conditions during the summers is reflected in a abnormal tree phenology. Provided that sufficient data is available, it could be studied if tree composition across Europe allows to plant patterns. Potentially, more complex patterns could be planted, if the tree phenology of deciduous trees in some areas shows less overlap or if tree species exist, that shat exhibit a generally different phenology.

Furthermore, interdisciplinary studies could investigate the public attitude towards bio advertisements in forests. By the means of stakeholder interviews, it could be tested, how potential customers, NGOs, political parties or experts on environmental ethics assess the presented planting approach.

Finally, it could be studied, if the concept of pattern- and color-based planting can be applied to other existing planting strategies. Potentially patterns could be planted in condensed areas following the concept of tiny forests with extremely high density of trees.

Bibliography

- AI Platform | Google Cloud. (n.d.). Retrieved August 17, 2020, from <https://cloud.google.com/ai-platform>
- Archetti, M., Richardson, A. D., Keefe, J. O., & Delpierre, N. (2013). Predicting Climate Change Impacts on the Amount and Duration of Autumn Colors in a New England Forest, *8*(3). <https://doi.org/10.1371/journal.pone.0057373>
- Baltzer, J. L., & Thomas, S. C. (2005). Leaf optical responses to light and soil nutrient availability in temperate deciduous trees. *American Journal of Botany*, *92*(2), 214–223. <https://doi.org/10.3732/ajb.92.2.214>
- Balzarolo, M., Dox, I., & Leys, S. (2019). Detecting the onset of autumn leaf senescence in deciduous forest trees of the temperate zone, (June). <https://doi.org/10.1111/nph.15991>
- Brandl, S., Paul, C., Knoke, T., & Falk, W. (2020). The influence of climate and management on survival probability for Germany's most important tree species. *Forest Ecology and Management*, *458*(August 2019), 117652. <https://doi.org/10.1016/j.foreco.2019.117652>
- BUNDESWALDINVENTUR ERGEBNISDATENBANK. (2012). Retrieved March 6, 2018, from <https://bwi.info/>
- Burrascano, S., Chytrý, M., Kuemmerle, T., Giarrizzo, E., Luyssaert, S., Maria, F., & Blasi, C. (2016). Current European policies are unlikely to jointly foster carbon sequestration and protect biodiversity. *BIOC*, *201*(May), 370–376. <https://doi.org/10.1016/j.biocon.2016.08.005>

- Busetto, L., Colombo, R., Migliavacca, M., Cremonese, E., Meroni, M., Galvagno, M., ... Pari, E. (2010). Remote sensing of larch phenological cycle and analysis of relationships with climate in the Alpine region. *Global Change Biology*, 16(9), 2504–2517. <https://doi.org/10.1111/j.1365-2486.2010.02189.x>
- Cañellas, I., & Montero, G. (2007). Generalized height-diameter and crown diameter prediction models for cork oak forests in Spain, 16(1), 76–88.
- Cormont, A., Siepel, H., Clement, J., Melman, T. C. P., Wallisdevries, M. F., Turnhout, C. A. M. Van, ... Berendse, F. (2016). Landscape complexity and farmland biodiversity : Evaluating the CAP target on natural elements. *Journal for Nature Conservation*, 30, 19–26. <https://doi.org/10.1016/j.jnc.2015.12.006>
- Czernercki, B. (2018). Machine learning modeling of plant phenology based on coupling satellite and gridded meteorological dataset, 1297–1309.
- Datenzugang: Copernicus in Deutschland. (n.d.). Retrieved August 17, 2020, from <https://www.d-copernicus.de/daten/datenzugang/>
- Demarez, V. (2010). Seasonal variation of leaf chlorophyll content of a temperate forest . Inversion of the PROSPECT model, 1161. <https://doi.org/10.1080/014311699212975>
- Dixon, A. K. R. (1976). Analysis of Seasonal Leaf Fall in North Temperate Deciduous Forests Published by : Wiley on behalf of Nordic Society Oikos Stable URL : <http://www.jstor.com/stable/3543909> REFERENCES Linked references are available on JSTOR for this article : reference # , 27(2), 300–306.
- Einheitsbuddeln. (n.d.). Retrieved August 17, 2020, from <https://www.einheitsbuddeln.de/home>
- Evans, M. R., Moustakas, A., Carey, G., Malhi, Y., Butt, N., Benham, S., ... Schäfer, S. (2015). Allometry and growth of eight tree taxa in United Kingdom woodlands, 1–9. <https://doi.org/10.1038/sdata.2015.6>
- Finegold, Y., Garcia, C. A., & Mollicone, D. (2019). The global tree restoration potential, (December). <https://doi.org/10.1126/science.aax0848>
- Forest Yield*. (n.d.).
- Fortbildung, M. (2007). *Phänologie*, 33.
- Gamon, J. A., Huemmrich, K. F., Wong, C. Y. S., Ensminger, I., Garrity, S., Hollinger, D. Y., ... Peñuelask, J. (2016). A remotely sensed pigment index reveals photosynthetic phenology in evergreen conifers. *Proceedings of the National Academy of Sciences of the United States of America*, 113(46), 13087–13092. <https://doi.org/10.1073/pnas.1606162113>
- Ganescu, M. C. (2012). Corporate social responsibility, a strategy to create and consolidate sustainable businesses. *Theoretical and Applied Economics*, 19(11), 91–106.
- Gitelson, A. A., Viña, A., Ciganda, V., Rundquist, D. C., & Arkebauer, T. J. (2005). Remote estimation of canopy chlorophyll content in crops. *Geophysical Research Letters*, 32(8), 1–4. <https://doi.org/10.1029/2005GL022688>
- Gond, V., De Pury, D. G. G., Veroustraete, F., & Ceulemans, R. (1999). Seasonal variations in leaf area index, leaf chlorophyll, and water content; Scaling-up to estimate fAPAR and carbon balance in a multilayer, multispecies temperate forest. *Tree Physiology*, 19(10), 673–679. <https://doi.org/10.1093/treephys/19.10.673>
- Google Earth Engine. (n.d.). Retrieved August 17, 2020, from <https://earthengine.google.com/>

- Gower, S. T., & Richards, J. H. (1990). Larches: Deciduous Conifers in an Evergreen World. *BioScience*, 40(11), 818–826. <https://doi.org/10.2307/1311484>
- Hoch, W. A., Zeldin, E. L., & McCown, B. H. (2001). Physiological significance of anthocyanins during autumnal leaf senescence. *Tree Physiology*, 21(1), 1–8. <https://doi.org/10.1093/treephys/21.1.1>
- Iezzi, M. E., Cruz, P., Varela, D., Angelo, C. De, & Bitetti, M. S. Di. (2018). Forest Ecology and Management Tree monocultures in a biodiversity hotspot : Impact of pine plantations on mammal and bird assemblages in the Atlantic Forest. *Forest Ecology and Management*, 424(May), 216–227. <https://doi.org/10.1016/j.foreco.2018.04.049>
- IUCN, T., List, R., & Species, T. (n.d.). *IUCN RED LIST CATEGORIES AND*.
- Jaakola, L., & Hohtola, A. (2010). Effect of latitude on flavonoid biosynthesis in plants. *Plant, Cell and Environment*, 33(8), 1239–1247. <https://doi.org/10.1111/j.1365-3040.2010.02154.x>
- Kok, M. T. J., Alkemade, R., Bakkenes, M., Eerd, M. Van, Janse, J., Mandryk, M., ... Esch, S. Van Der. (2018). Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation : A global scenario-study. *Biological Conservation*, 221(February), 137–150. <https://doi.org/10.1016/j.biocon.2018.03.003>
- le Maire, G., François, C., Soudani, K., Berveiller, D., Pontailier, J. Y., Bréda, N., ... Dufrêne, E. (2008). Calibration and validation of hyperspectral indices for the estimation of broadleaved forest leaf chlorophyll content, leaf mass per area, leaf area index and leaf canopy biomass. *Remote Sensing of Environment*, 112(10), 3846–3864. <https://doi.org/10.1016/j.rse.2008.06.005>
- Lee, D. W., & Gould, K. S. (2002). Why leaves turn red. *American Scientist*, 90(6), 524–531. <https://doi.org/10.1511/2002.39.794>
- Leuschner, C., Wulf, M., Bäuchler, P., & Hertel, D. (2014). Forest Continuity as a Key Determinant of Soil Carbon and Nutrient Storage in Beech Forests on Sandy Soils in Northern Germany. *Ecosystems*, 17(3), 497–511. <https://doi.org/10.1007/s10021-013-9738-0>
- Monitor, D. T. (2018). Drones in agriculture, (January).
- Nat, B., Pflanzzeitpunkt, W., & Aufforstungsmodelle, P. (n.d.). Standortsgerechte Aufforstung.
- Parmesan, C. (2007). Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology*, 13(9), 1860–1872. <https://doi.org/10.1111/j.1365-2486.2007.01404.x>
- Parrotta, J. A., Quine, C. P., & Sayer, J. V. (2008). Plantation forests and biodiversity : oxymoron or opportunity ? 1 C, 925–951. <https://doi.org/10.1007/s10531-008-9380-x>
- PEP725 Data Selection. (n.d.). Retrieved August 17, 2020, from http://www.pep725.eu/data_download/data_selection.php
- Polgar, C. A., & Primack, R. B. (2011). Leaf-out phenology of temperate woody plants: From trees to ecosystems. *New Phytologist*, 191(4), 926–941. <https://doi.org/10.1111/j.1469-8137.2011.03803.x>
- Renner, S. S. (2019). Tansley review The occurrence of red and yellow autumn leaves explained by regional differences in insolation and temperature. <https://doi.org/10.1111/nph.15900>
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Iii, F. S. C., Lambin, E., ... Liverman, D. (2020). Planetary Boundaries : Exploring the Safe Operating Space for Humanity.
- Singh, R. K., Svystun, T., AlDahmash, B., Jönsson, A. M., & Bhalerao, R. P. (2017). Photoperiod- and temperature-mediated control of phenology in trees – a molecular perspective. *New Phytologist*,

213(2), 511–524. <https://doi.org/10.1111/nph.14346>

- Spatial Modelling in Forest Ecology and Management: A Case Study - Martin Jansen, Michael Judas, Joachim Saborowski - Google Books. (n.d.). Retrieved August 17, 2020, from [https://books.google.de/books?hl=de&lr=&id=cvMqnkqMN9UC&oi=fnd&pg=PA1&dq=spatial+modelling+state+of+the+forest+system&ots=6XyHHKwBl0&sig=eo4lwRxwEq7cOL9rbgNhtK40oFs#v=onepage&q=spatial modelling state of the forest system&f=false](https://books.google.de/books?hl=de&lr=&id=cvMqnkqMN9UC&oi=fnd&pg=PA1&dq=spatial+modelling+state+of+the+forest+system&ots=6XyHHKwBl0&sig=eo4lwRxwEq7cOL9rbgNhtK40oFs#v=onepage&q=spatial%20modelling%20state%20of%20the%20forest%20system&f=false)
- Spiecker, H. (2000). *Spruce Monocultures in Central Europe – Problems and Prospects. Spruce Monocultures in Central Europe-Problems and Prospects.*
- Tang, L., & Shao, G. (2015). Drone remote sensing for forestry research and practices. *Journal of Forestry Research*, 26(4), 791–797. <https://doi.org/10.1007/s11676-015-0088-y>
- Tiberiu Paul Banu, Gheorghe Florian Borlea, & Constantin Banu. (2016). The Use of Drones in Forestry. *Journal of Environmental Science and Engineering B*, 5(11), 557–562. <https://doi.org/10.17265/2162-5263/2016.11.007>
- Tillack, A. (2012). Estimation of Seasonal Leaf Area Index in an Alluvial Forest Using High Resolution Satellite-based Vegetation Indices by, 1–40.
- User Guides - Sentinel-2 MSI - Level-1C Product - Sentinel Online. (n.d.). Retrieved August 17, 2020, from <https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/product-types/level-1c>
- Vacek, Z., Vacek, S., Slanař, J., Bílek, L., Bulušek, D., Štefančík, I., ... Vančura, K. (2019). Adaption of Norway spruce and European beech forests under climate change: From resistance to close-to-nature silviculture. *Central European Forestry Journal*, 65(2), 129–144. <https://doi.org/10.2478/forj-2019-0013>
- Vitasse, Y., Delzon, S., Bresson, C. C., Michalet, R., & Kremer, A. (2009). Altitudinal differentiation in growth and phenology among populations of temperate-zone tree species growing in a common garden, 1269, 1259–1269. <https://doi.org/10.1139/X09-054>
- Vitasse, Y., Porté, A. J., Kremer, A., Michalet, R., & Delzon, S. (2009). Responses of canopy duration to temperature changes in four temperate tree species: Relative contributions of spring and autumn leaf phenology. *Oecologia*, 161(1), 187–198. <https://doi.org/10.1007/s00442-009-1363-4>
- Wang, Q., Tenhunen, J., Granier, A., & Reichstein, M. (2004). Long-term variations in leaf area index and light extinction in a *Fagus sylvatica* stand as estimated from global radiation profiles, 238, 225–238. <https://doi.org/10.1007/s00704-004-0074-3>
- Way, D. A., & Montgomery, R. A. (2015). Photoperiod constraints on tree phenology, performance and migration in a warming world. *Plant, Cell and Environment*, 38(9), 1725–1736. <https://doi.org/10.1111/pce.12431>
- World Map of Köppen – Geiger Climate Classification Main climates A : equatorial B : arid C : warm temperate D : snow E : polar W : desert S : steppe f : fully humid T : polar tundra. (2010), 2948. <https://doi.org/10.1127/0941>
- Ziello, C., Estrella, N., Kostova, M., Koch, E., & Menzel, A. (2009). Influence of altitude on phenology of selected plant species in the Alpine region (1971 – 2000), (May 2014). <https://doi.org/10.3354/cr00822>