Edge Effects on Climate Sensitivity in an Eastern Hemlock (*Tsuga canadensis*)

Forest of the Upper Peninsula of Michigan

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BIOS 35502: Practicum in Environmental Field Biology

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2018

Abstract

Forest edge effects influence the majority of forests on the planet, and are highly variable in nature. Edge effects can impact tree mortality, biodiversity, and carbon storage. The extreme conditions that exist at these edges often impact forests negatively, leaving them more vulnerable to disturbances such as pest infestations or increased stress from wind or temperature. Previous studies have indicated that heat stress may explain a third of interannual variability in forest growth in forest edges. The type and magnitude of edge effects are also highly dependant on adjacent land-cover type. Man-made forest edges are relatively well understood; however, much of the Northwoods landscape is characterized by forests which are fragmented naturally through rivers, lakes, and edges to different forest types. In this study, I explore the differences in climate sensitivity at interior and edge locations in a stand of Eastern Hemlock (*Tsuga canadensis*) in the Upper Peninsula of Michigan. The forest to lake edge was found to be less sensitive to temperature than the interior and forest to forest edge. While results indicated that forest to forest edges were comparable to an interior forest, more work may need to be done to answer questions about how large a stand must be in order to maintain a true interior.

Introduction

Over 70 % of the Earth's remaining forests are located within 1 km of a forest edge (Haddad et. al, 2015). Habitat fragmentation was prominent in the Great Lakes region in the form of clearcutting in the 18th and 19th centuries, and subsequently shaped the composition of the forests there (Nyami et. al, 2014). Eastern Hemlock (*Tsuga canadensis*) forests, once dominant in the region, have now become highly fragmented and partially replaced by hardwood species as a result of logging activities (Davis et. al, 1995). This extensive fragmentation of Eastern Hemlock has potentially left many of the remaining stands vulnerable to harmful edge effects.

The structure and functions of forest edges are highly variable, depending on the type of edge, e.g. forest to forest, forest to non-forest, as well as man-made edges or natural edges (Smith et al, 2018). Though the impacts of forest edges on ecosystem functions are still poorly constrained, man-made forest edges are best understood. Man-made forest edges can be

predisposed to biotic disturbances such as pest infestations (Smith et al, 2018). Forest edges

characterized by differences in biomass are more exposed to solar radiation, creating a more

fluctuating microclimate than present in the interior (Murcia, 1995). Increased exposure to solar

radiation at edges can also cause desiccation stress (Smith et. al, 2018). Other edge effects

include vulnerability to rare weather events, such as windstorms or drought (Laurance et al,

2011). Due to the fact that trees at forest edges are more exposed to stressors such as solar

radiation and wind disturbance, forest edges can have an impact on climate sensitivity. This

connection between radial growth patterns and climatic trends is important for making

predictions about forest dynamics and for developing policies related to forest management

(Zhang et. al, 2018). According to Reinmann and Hutyra (2017), heat stress, which they define

as the number of days in June and July above 27 ℃, explained 30% to 36% of interannual

variability in forest growth between 1990 and 2014 in a study done on forest edges. This could

be explained by an increased exposure to solar radiation at forest to non-forest edges because of

a lack of shelter from adjacent vegetation.

  In general, the magnitude of edge effects are highly variable depending on adjacent land-

cover type (Smith et al, 2018). As previously stated, most of our understanding of edge effects is

derived from man-made edges such as roads and agricultural fields. To our knowledge, very few

studies testing the influence of edge effects on climate sensitivity in general, and on Eastern

Hemlock forests specifically have been published. Without information on the way natural forest

edges function, there are limited metrics against which the mechanisms of man-made edges can

be measured. In many systems, including those found in the Great Lakes Region, much of the

edges are results of natural fragmentation of landscapes; such as lakes or rivers, as well as edges

of different forest compositions, that result either from edaphic differences or as legacies of past

land-use. The former can be classified as forest-non-forest edges, the latter as forest-forest edges. Since natural forest edges are understudied, and they are prevalent in the Upper Midwest, I sought to investigate how natural forest edges affect the sensitivity of tree growth to climate (climate sensitivity), and whether this sensitivity has changed over the last century.

We conducted our sampling at the University of Notre Dame Environmental Research Center (UNDERC). This area is a particularly suitable study system to address the topic of natural edge effects, because it is comprised of many different types of forests with variable tree species composition, which are often fragmented by lakes or wetlands. We hypothesized that forest-non-forest edges should be more sensitive to climate, since these kinds of edges are more exposed to heat stress and other disturbances. Conversely, interior forests and forest-forest edges should be less sensitive to climate due to less fragmentation in the canopy protecting trees from solar radiation and other stressors. We further hypothesized that in lieu of rising global temperatures over the last century, climate sensitivity will have decreased over this time period as a form of acclimation to environmental changes.

Materials and Methods

Study area - All sampling was conducted on the UNDERC property, located on the border of Wisconsin and the Northern Peninsula of Michigan. We chose to survey a Hemlock stand around the southeastern end of Crampton Lake, which is located on the southeastern part of the UNDERC property. We elected to study this specific stand due to the fact that it was nearly exclusively populated by *T. canadensis*, and was not broken up by large canopy gaps at the time of data collection. It is also located approximately 450 m away from the nearest road which receives little traffic overall as it is not open to the public. This decreases the effect that any man-

made edges would have on the edge effects and the climate sensitivity of the stand as a whole. This area was the only stand of its size and continuity to be found at UNDERC at the time of sampling. Therefore, it is important to keep in mind that the results of this study are specific to this area.

Plot Setup and Data Collection - We set up three plots around the larger area of the southeastern peninsula on Crampton Lake; an interior forest plot (INT), a forest-to-lake edge plot (LOW), and a forest-to-forest edge plot (FFE). Each plot was circular, and measured 20 m in diameter. The center of LOW was plotted 10 m away from the lake. The center of INT was located 90 m away from the nearest shore of the lake. FFE bordered on a mixed deciduous forest, and was comprised of 71.4 % *T. canadensis*, and 28.6 % Red Maple (*Acer rubrum*). FFE was located 40 m away from the nearest shore of the lake. Cores from every *T. canadensis* measuring at least 15 cm in diameter at breast height (DBH) were extracted using a Haglof increment borer (INT: 23 trees, FFE: 15 trees, LOW: 33 trees). Standing dead trees were not cored. In the laboratory, each core was mounted on wooden boards and sanded for further analysis.

Data Manipulation - All cores were scanned and time series of ring widths were measured using Coorecorder and Cdendro (v 9.3) programs. Cores were crossdated using cofecha (Grissino-Mayer, 2001). Trees that could not be crossdated or that did not line up with ring widths of other trees in the site were removed from the rest of the data; leaving 18 trees in INT, 11 trees in FFE, and 23 trees in LOW. The ring width index (RWI) was determined for each site by detrending ring width series by removing trends in the growth rates caused by age-related growth and other responses not caused by climate. We ran Pearson's correlations for several climate parameters

using data for the Upper West Michigan climate domain (1895-2017) obtained from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NOAA's CLIMDIV). For each site, we analyzed Pearson's correlations using R studio (R Core Team, 2017) between individual tree RWI and total annual precipitation, average temperature, as well as maximum and minimum temperature. We used these correlations as measures of climate sensitivity. We chose specific months to examine for each of these parameters based on the highest correlation values across sites. For precipitation, highest correlations and most coherent across sites occurred in May (Figure 1), while for all of the temperature values, the highest correlations occurred in March (Figures 2, 3, 4).

Data Analysis - Using R studio (R Core Team, 2017) we performed four unbalanced one-way ANOVAs to test if sites had significant differences in sensitivity of growth to total annual precipitation, average temperature, maximum temperature, and minimum temperature. In accordance with the highest correlation values previously determined, we tested for annual precipitation sensitivity in May, and for all types of temperature sensitivity (average, maximum, minimum) in March. We elected to run an unbalanced test so that all of the cores that could be crossdated properly could be included in this study. We also ran unbalanced one-way ANOVA tests in order to assess the differences in climate sensitivity of two equally sized time periods; 1895-1954 and 1955-2017.

Results

Across the entire time period analyzed, differences in precipitation sensitivity in May between sites were not statistically significant (mean ± SD; FFE, 0.2410 ± 0.1198; INT, 0.2336 ±

0.1087; LOW, 0.1824 ± 0.1222; F= 1.3740, p= 0.2630; Figure 5). For all temperature-related

metrics, significant differences between sites could be detected. Average temperature sensitivity

in March was significantly different between sites (mean ± SD; FFE, 0.3390 ± 0.1368; INT,

0.3018 ± 0.1138; LOW, 0.1996 ± 0.1045; F= 5.312, p= 0.0082; Figure 6). Post-hoc analysis

using the Tukey's Honest Significance Test showed no significant differences between INT and

FFE, but the test did show a significant difference between LOW and INT, as well as between

LOW and FFE ($p_{INT-FFE}$= 0.8637, $p_{LOW-FFE}$= 0.0203, $p_{INT-LOW}$= 0.0310). On average, LOW was

69.8% less sensitive than FFE, and 33.9% less sensitive than INT.

Similar results were found for maximum and minimum temperature sensitivity.

Maximum temperature sensitivity in March was significantly different across sites (mean ± SD;

FFE, 0.2819 ± 0.1240; INT, 0.2673 ± 0.1211; LOW, 0.1757 ± 0.0999; F= 4.8150, p= 0.0123;

Figure 7). There was a significant difference in maximum temperature sensitivity between LOW

and FFE, as well as between LOW and INT ($p_{LOW-FFE}$=0.0349, $p_{INT-LOW}$=0.0339). On average,

LOW was 60.4% less sensitive than INT, and 34.3% less sensitive than FFE. However, no

difference could be found between FFE and INT ($p_{INT-FFE}$= 0.9389). Minimum temperature

sensitivity in March was also different across sites (mean ± SD; FFE, 0.3335 ± 0.1304; INT,

0.3058 ± 0.1195; LOW, 0.2108 ± 0.1089; F=5.381, p=0.0077; Figure 8). A significant difference

was found between LOW and FFE, as well as between LOW and INT ($p_{LOW-FFE}$=0.0171, $p_{INT-LOW}$=0.0344). On average, LOW was 58.2% less sensitive than INT, and 31.1% less sensitive

than FFE. No significant difference could be detected between INT and FFE ($p_{INT-FFE}$=0.8121).

Over all temperature metrics, LOW was less sensitive to temperature than FFE and INT.

Significant differences between the time periods 1895 to 1954 and 1955 to 2017 could

not be found for precipitation sensitivity for the interior (mean ± SD; pre 1954, 0.2793 ± 0.1970;

post 1954, 0.2195 ± 0.1183; F=0.9350, p=0.3430), the forest to lake edge (mean ± SD; pre 1954,

0.1651 ± 0.2166; post 1954, 0.1806 ± 0.1074; F=0.0870, p=0.7700) or the forest to forest edge

(mean ± SD; pre 1954, 0.3209 ± 0.1250; post 1954, 0.2301 ± 0.1302; F=1.7120, p=0.2120;

Figure 9). Average temperature sensitivity also showed no significant difference between time

periods across all sites surveyed (mean ± SD; pre 1954_{INT}, 0.2355 ± 0.2264; post 1954_{INT}, 0.3018

± 0.1138; F_{INT}=1.0090, p_{INT}=0.3250; pre 1954_{FFE}, 0.2274 ± 0.1835; post 1954_{FFE}, 0.3390 ±

0.1368; F_{FFE}= 1.8620, p_{FFE}= 0.1940; pre 1954_{LOW}, 0.1538 ± 0.1815; post 1954_{LOW}, 0.1866 ±

0.1193; F_{LOW}=1.2250, p_{LOW}=0.2760; Figure 10). The same could be observed for maximum

temperature sensitivity (mean ± SD; pre 1954_{INT}, 0.2859 ± 0.2485; post 1954_{INT}, 0.2660 ±

0.1220; F_{INT}=0.0770, p_{INT}=0.7840; pre 1954_{FFE}, 0.1937 ± 0.1970; post 1954_{FFE}, 0.2998 ± 0.1282;

F_{FFE}= 1.6980, p_{FFE}=0.2140; pre 1954_{LOW}, 0.1463 ± 0.1802; post 1954_{LOW}, 0.1546 ± 0.1179;

F_{LOW}= 0.0290; p_{LOW}=0.8650; Figure 11) and minimum temperature sensitivity (mean ± SD; pre

1954_{INT}, 0.1974 ± 0.2336; post 1954_{INT}, 0.3199 ± 0.1071; F_{INT}=3.4600, p_{INT}= 0.0751; pre

1954_{FFE}, 0.2447 ± 0.1648; post 1954_{FFE}, 0.3572 ± 0.1436; F_{FFE}=1.9350, p_{FFE}= 0.1860; pre

1954_{LOW}, 0.1512 ± 0.1785; post 1954_{LOW}, 0.2048 ± 0.1208; F_{LOW}=1.2250, p_{LOW}=0.2760; Figure

12).

Discussion

The experimental results partially support the initial hypothesis; climate sensitivity was

significantly different for some, but not all parameters used to measure sensitivity. For

parameters that exhibited significant differences across plots, the forest-non-forest edge was

always less sensitive to climate than the interior and forest-forest plots. While strong correlations

occurred with spring precipitation across all sites, no significant differences were found for

sensitivity to annual precipitation in May across sites. This can be interpreted to mean that at all sites, as May precipitation increases, RWI increases in comparable manners at all sites surveyed. This could be due to the relatively small sample area; it is likely that precipitation conditions were not different enough to exhibit differences in sensitivity across sites. Alternatively, these results may indicate that at this location, growth is not limited by water, but rather by temperature. Further studies on larger scales may be useful in further investigating this topic, as it has not been widely researched thus far.

Conversely, all metrics of temperature sensitivity in March (average, minimum, maximum) showed significant differences between the forest-lake edge compared to the interior and the forest-forest edge. Furthermore, the temperature sensitivities of the interior and the forest-forest edges were similar to one another. These results align with our initial hypothesis, however the direction of the differences were not what we expected. The forest-lake edge was less sensitive to temperature than the interior and the forest-forest edge. This phenomenon might be explained by taking the location of the plot as well as conditions that would be present during March into account. The close proximity to the lake and the fact that it would be frozen during this time likely influenced the lowered sensitivity of the forest-non-forest edge.

While the forest to lake edge plot was more exposed to solar radiation due to a lack of sheltering vegetation in comparison to the interior and forest to forest edge plots, its close proximity to the lake likely affected the temperature that plot was experiencing at the time. Ice cover on the lake may have provided cooler temperatures around this plot, and decreased the severity of heat stress the plot received. During other times of the year, the lake likely affected the climate of this area by absorbing heat and light, potentially creating a unique microclimate at this site. This likely resulted in the effect that in years with high temperatures, trees at the forest-

lake edge did not exhibit as much growth as trees at the interior and the forest-forest edge. This result contrasts with previous reviews that have been conducted on the topic, which stated that with lower exposure to solar radiation, physical edge effects become weaker (Murcia, 1995).

The interior and the forest-forest edge plots did not exhibit significant differences for temperature sensitivity in March. While this finding supports our hypothesis, this is a striking result if one considers the conditions at this time of year due to the type of adjacent forest. In March, the deciduous trees at the forest-forest edge would not yet be foliated, leaving the edge more exposed to solar radiation. While it is feasible that both the interior and forest-forest sites were sufficiently sheltered from lake effects, the specific location of the interior plot may have influenced our results. It is possible that this plot was not located far enough into the interior of the stand, potentially influencing the sensitivity to temperature that this plot exhibited.

This calls into question how extensive edge effects are, and how large a stand would have to be in order to have a true interior, unaffected by factors influencing growth at the edges. Previous studies have concluded that the distance to which edge effects can penetrate into a forest are highly variable depending on the conditions. At the Biological Dynamics of Forest Fragments Project (BDFFP), edge effects influenced the forest from 10-300 m into the interior, while in parts of the Amazon with frequent edge fires, fire edge effects can penetrate 2-3 km into the interior (Laurence et. al, 2011). Since the world's forests are becoming increasingly fragmented (Smith, 2018), it is critical to understand exactly how fragmentation affects forest function, and to what extent edge effects permeate the interior of a forest. Further studies would be useful to assess whether it is even possible to use Hemlock stands for research on forest edges and interiors, as they remain highly fragmented and extremely rare (Davis et. al, 1995).

No significant differences between any climate sensitivities could be found for the time periods 1895 to 1954 and 1955 to 2017. This indicates that despite changing climate patterns such as rising temperatures or CO_2 fertilization, this Eastern Hemlock forest has not changed the way it responds to climate. With high confidence that global temperatures will continue to rise due to the production of greenhouse gases (Parry et. al, 2007), it is possible that the forest-lake edge at this site will not exhibit as much growth during warmer years as the interior and forest-forest edge sites. Previous studies have concluded that while hemlock seedlings are less abundant in hemlock stands today, enough hemlock trees are present in the understory to ensure continued canopy recruitment for the next several centuries (Davis et. al, 1995). This data may suggest that with continued canopy recruitment of hemlock stands, climate sensitivity may not have as prevalent an effect on *T. canadensis* located at the forest-non-forest edge when compared to the interior. Considering the extent of this study, more research should be done to further investigate the mechanisms and extents of natural edge effects as a contrast to man-made edges.

Figures

(a)

(b)

(c)
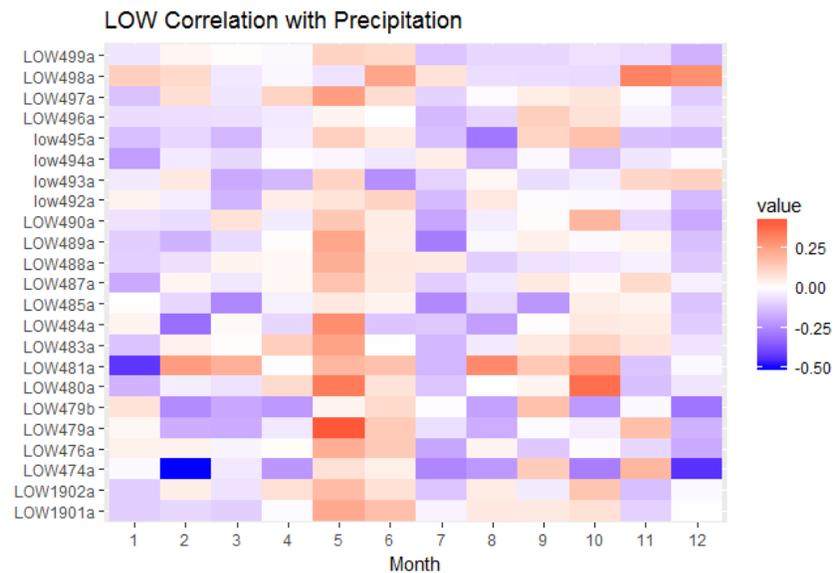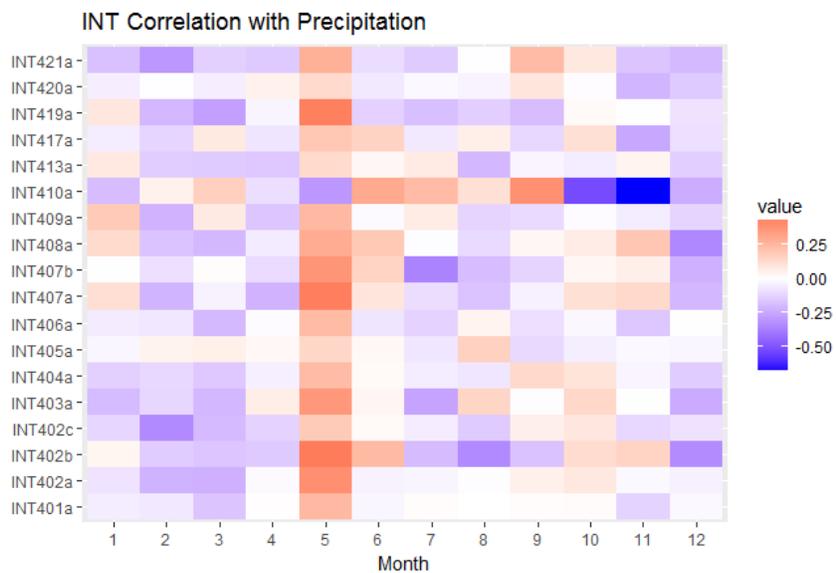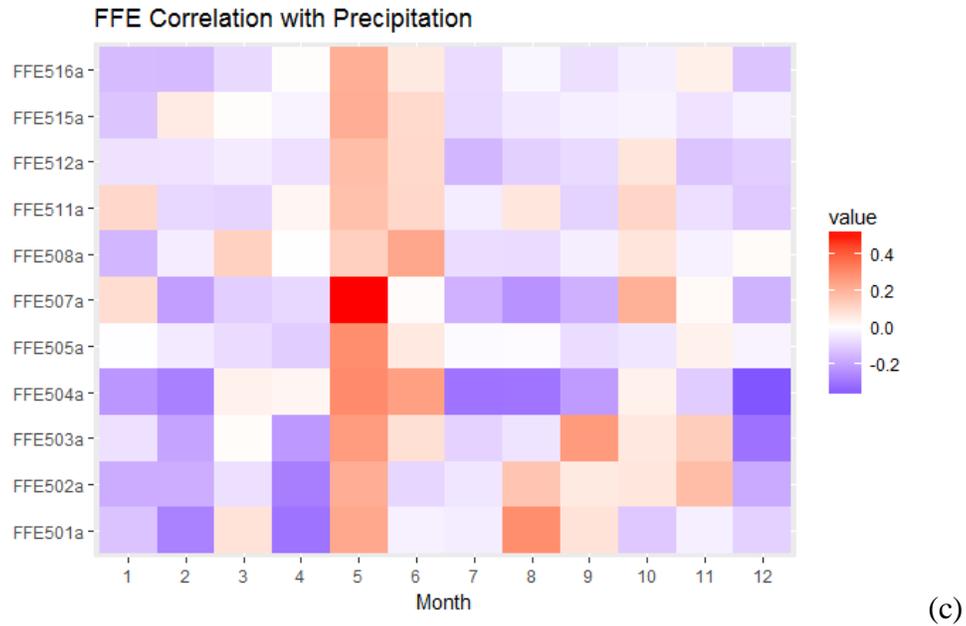
Figure 1: Correlation coefficients of ring width index (RWI) with annual precipitation in millimeters at the forest to lake edge site (LOW; a), the interior forest site (INT; b), and the forest to forest edge site (FFE; c). Highly positive correlation values indicate that with increasing precipitation, RWI increases. Across sites, the highest correlation values line up to occur in the month of May.


(a)
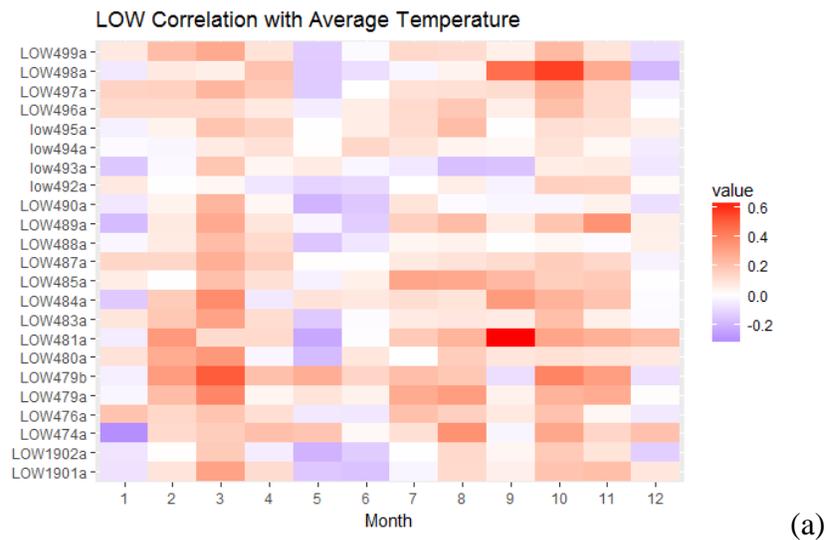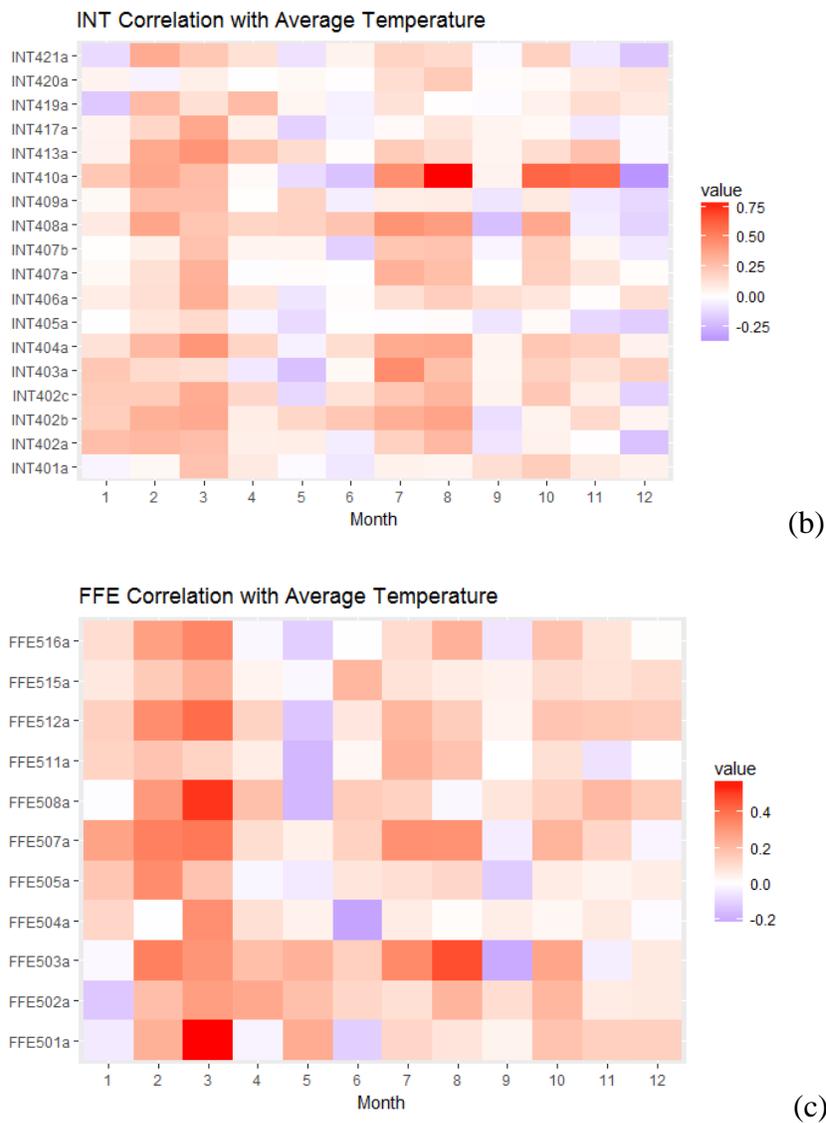
Figure 2: Correlation coefficients of ring width index (RWI) with average temperature in centigrade at the forest to lake edge site (LOW; a), the interior forest site (INT; b), and the forest to forest edge site (FFE; c). Highly positive correlation values indicate that with increasing temperature, RWI increases. Across sites, the highest correlation values line up to occur in the month of March.

LOW Correlation with Maximum Temperature

(a)

INT Correlation with Maximum Temperature

(b)

FFE Correlation with Maximum Temperature

(c)
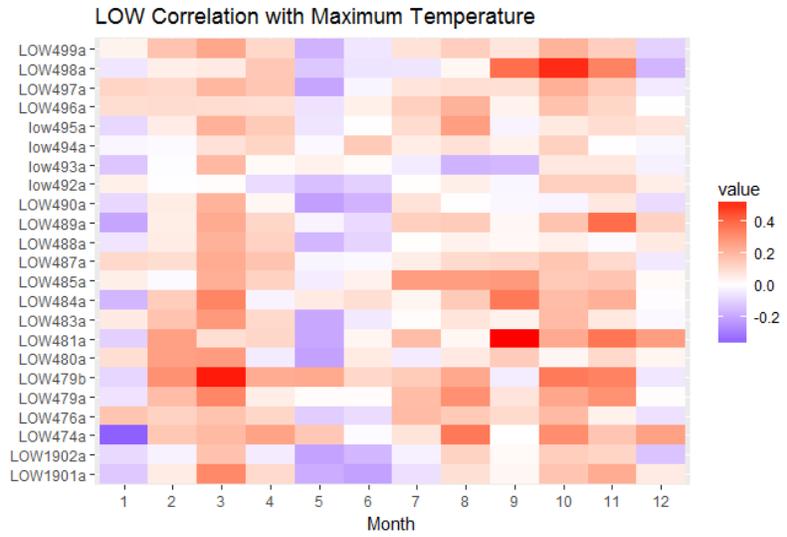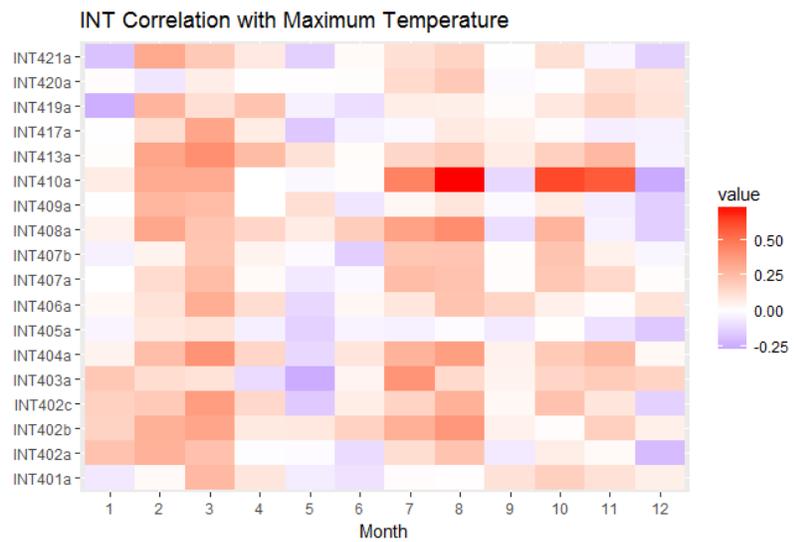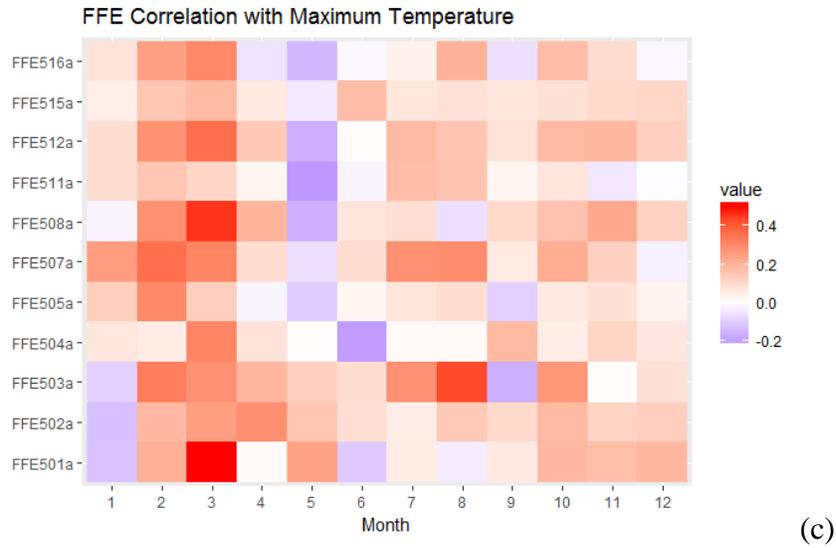
Figure 3: Correlation coefficients of ring width index (RWI) with maximum temperature in centigrade at the forest to lake edge site (LOW; a), the interior forest site (INT; b), and the forest to forest edge site (FFE; c). Across sites, the highest correlation values line up to occur in the month of March.


LOW Correlation with Minimum Temperature

(a)

(b)

(c)
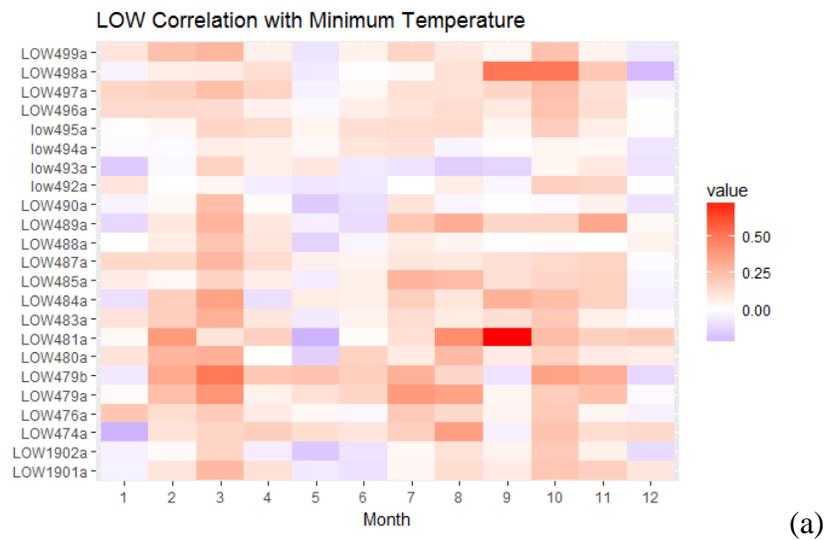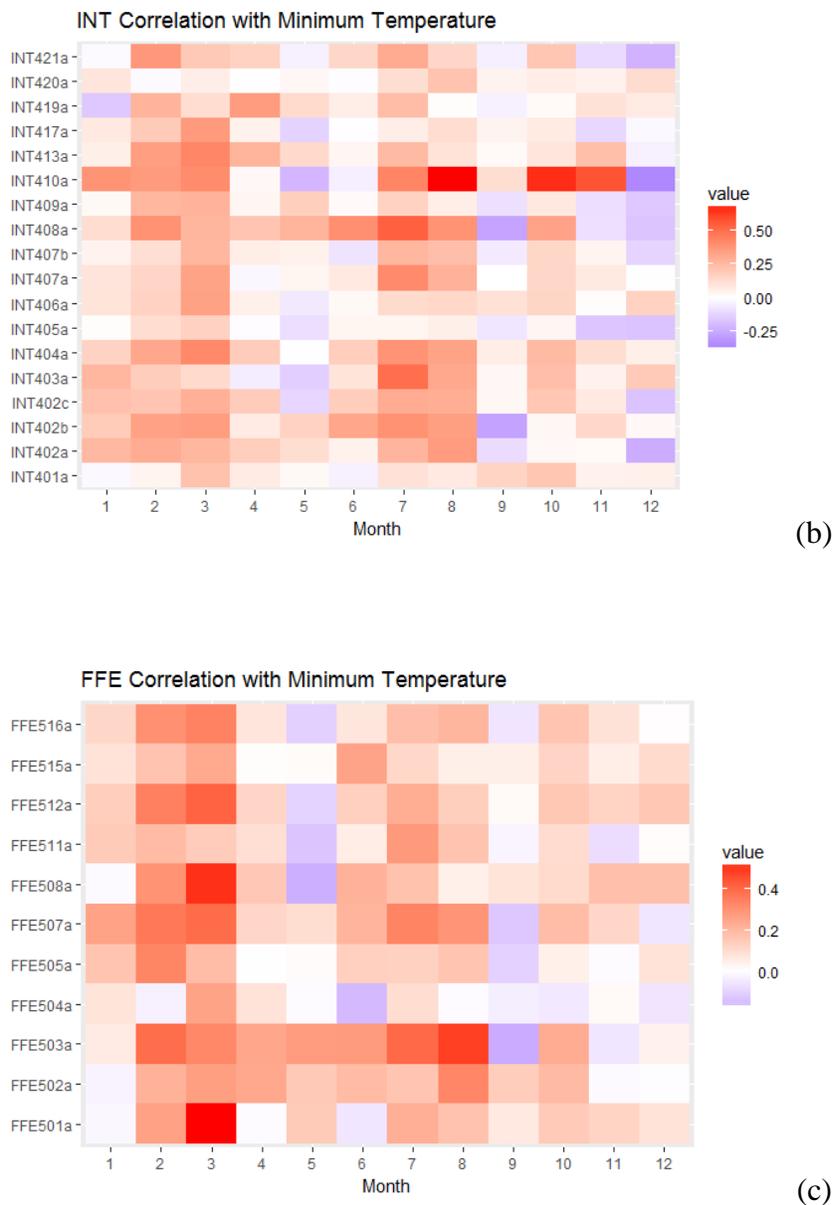
Figure 4: Correlation coefficients of ring width index (RWI) with minimum temperature in centigrade at the forest to lake edge site (LOW; a), the interior forest site (INT; b), and the forest to forest edge site (FFE; c). Across sites, the highest correlation values line up to occur in the month of March.
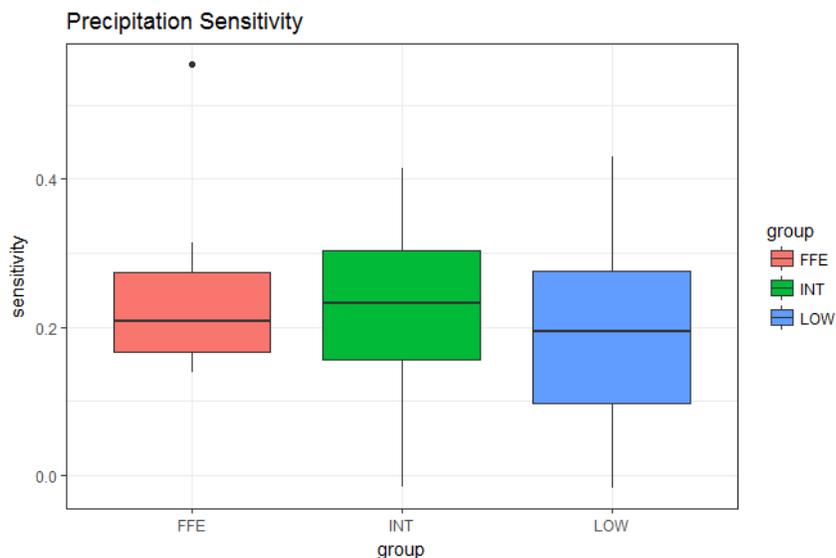
Figure 5: Sensitivity to annual precipitation (measured in mm) in May across sites. No significant differences between the interior, forest-forest, and forest-lake edges were found.
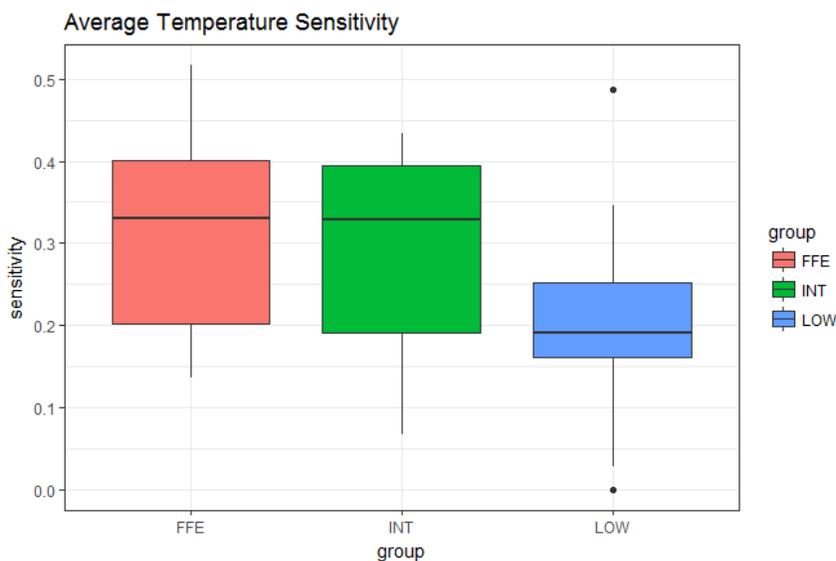

Figure 6: Average temperature sensitivity (measured in centigrade) in March across sites. Average temperature sensitivity at the forest-lake edge (LOW) was 33.9% lower than at the interior (INT) and 69.8% lower than at the forest-forest edge (FFE). The interior and the forest-forest edge were comparable in average temperature sensitivity.
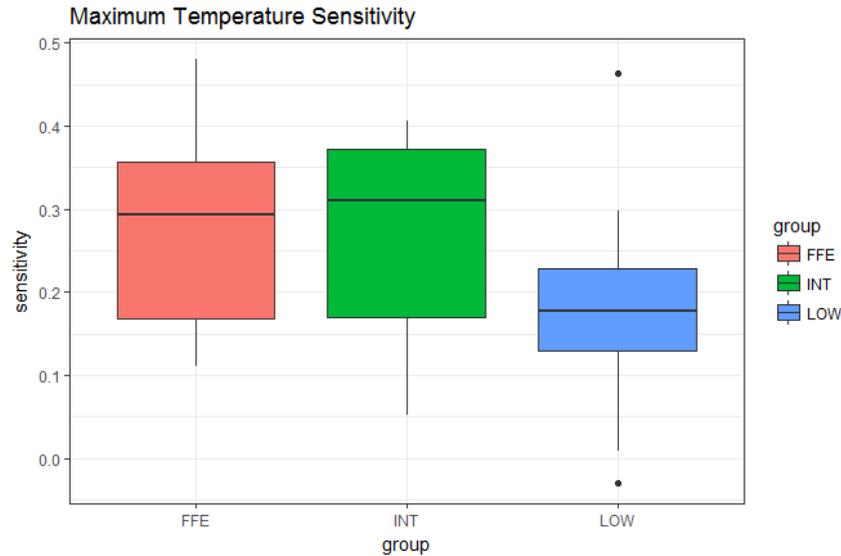
Figure 7: Maximum temperature sensitivity (measured in centigrade) in March across sites. Maximum temperature sensitivity at the forest-lake edge (LOW) was 60.4% lower than at the interior (INT) and 34.3% lower than at the forest-forest edge (FFE). The interior and the forest-forest edge were not significantly different.
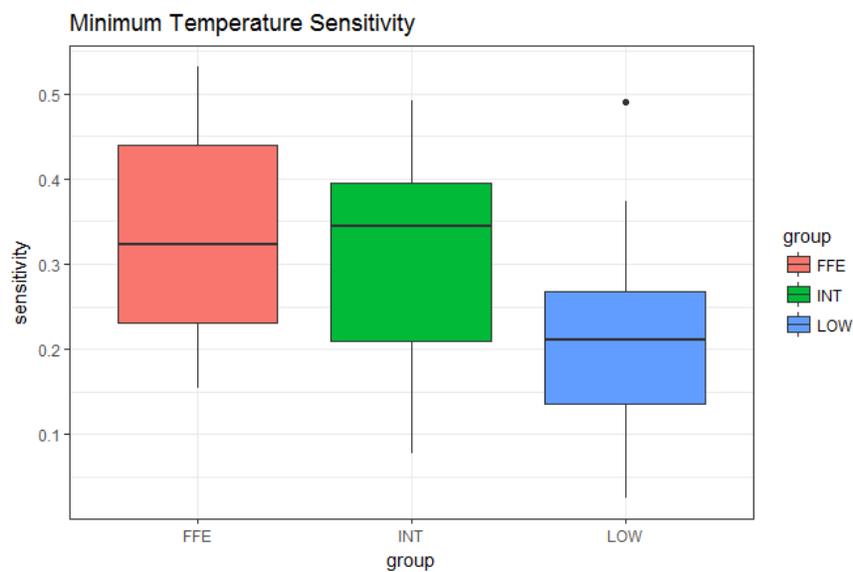

Figure 8: Minimum temperature sensitivity (measured in centigrade) in March across sites. Minimum temperature sensitivity at the forest-lake edge (LOW) was 58.2% lower than at the interior (INT) and 31.1% lower than at the forest-forest edge (FFE). No significant difference was found between the interior and the forest-forest edge.

(a)

(b)

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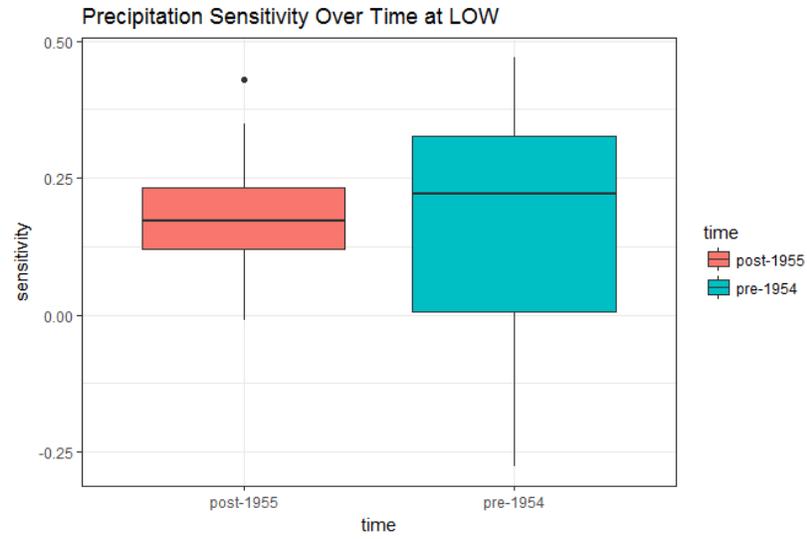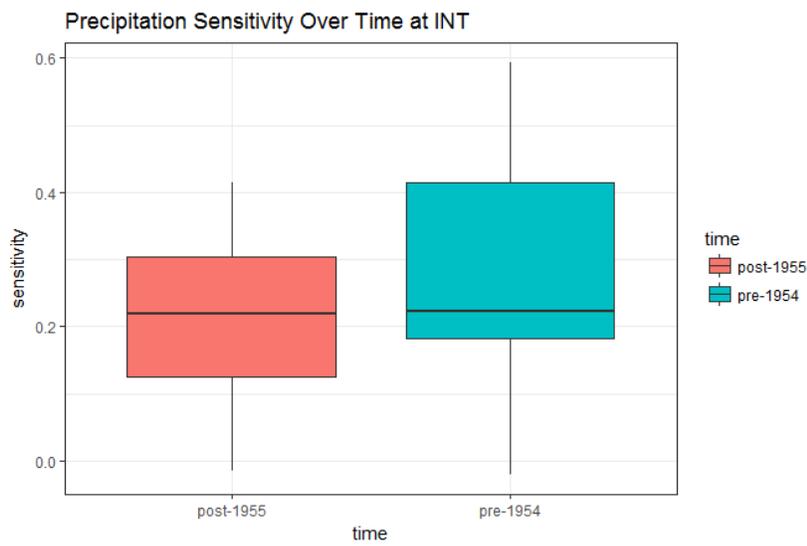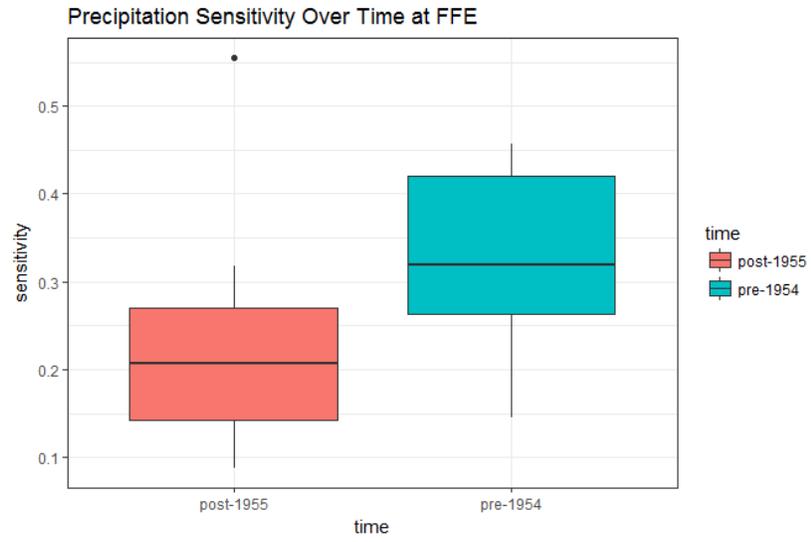
Figure 9: May precipitation sensitivity (measured in mm) for the time periods 1895-1954 and 1955-2017. No significant differences were found for the forest-lake edge (LOW; a), the interior (INT; b), or the forest-forest edge (FFE; c).


(a)

(b)

(c)
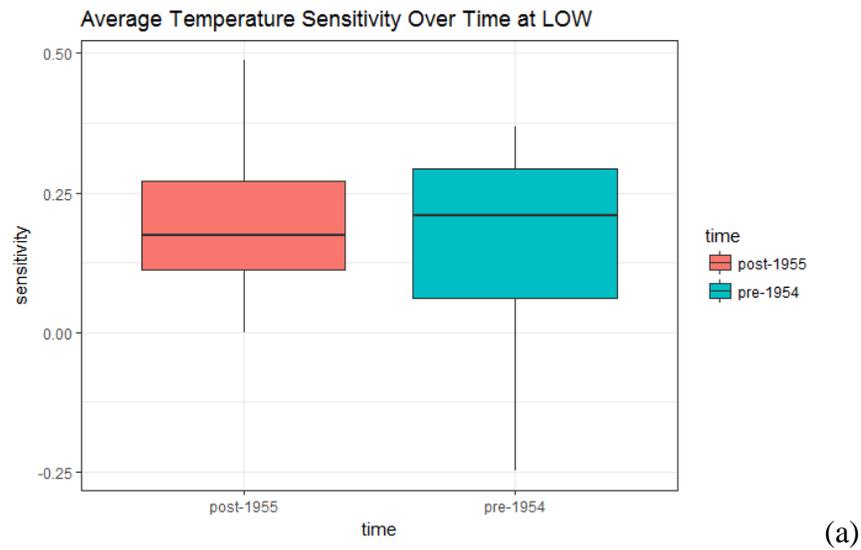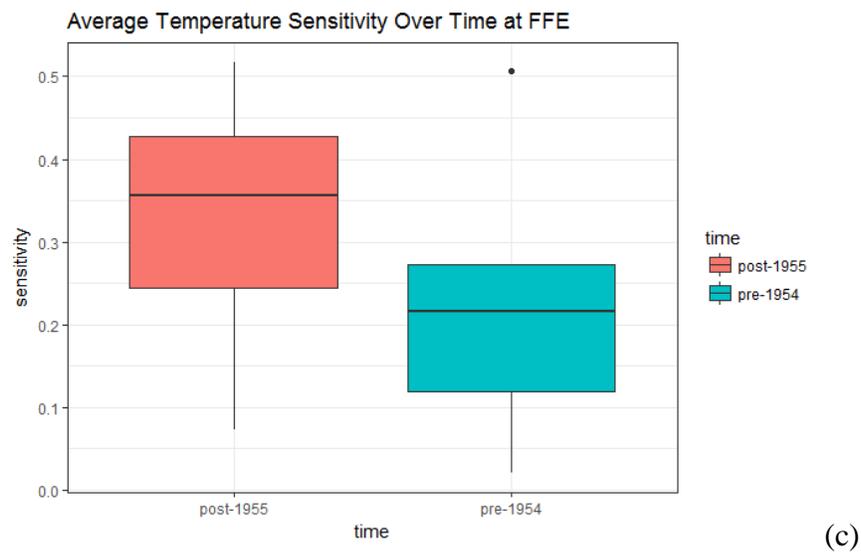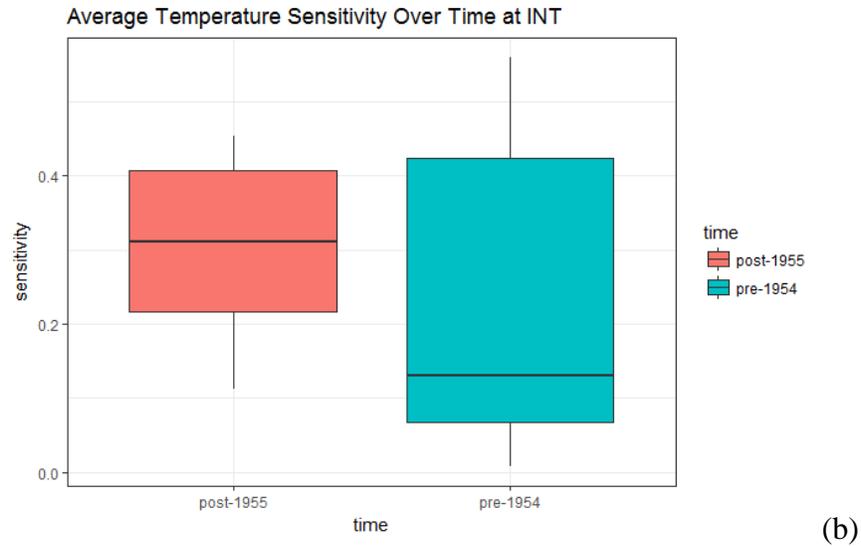
Figure 10: March average temperature sensitivity (measured in centigrade) for the time periods 1895-1954 and 1955-2017. No significant differences were found for the forest-lake edge (LOW; a), the interior (INT; b), or the forest-forest edge (FFE; c).

Maximum Temperature Sensitivity Over Time at LOW

(a)

Maximum Temperature Sensitivity Over Time at INT

(b)

(c)
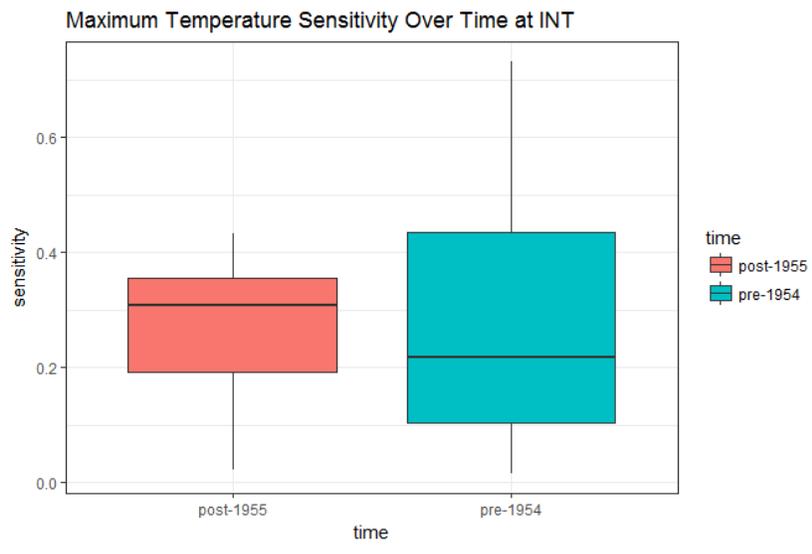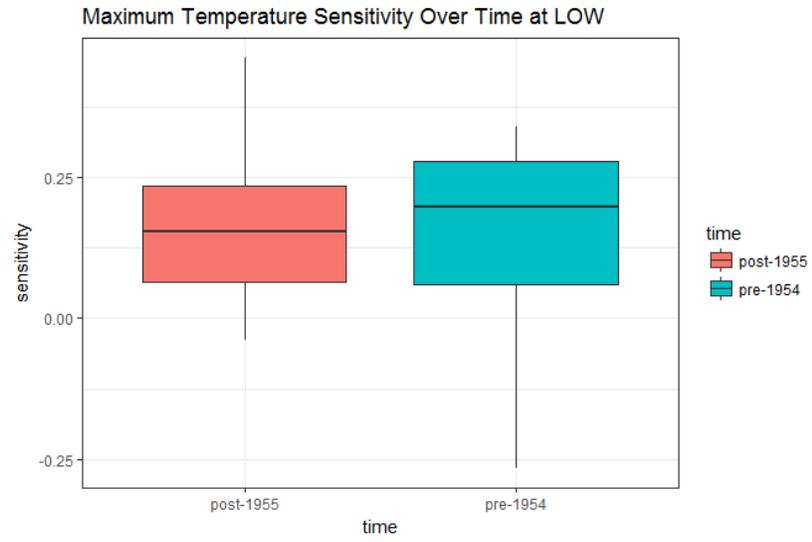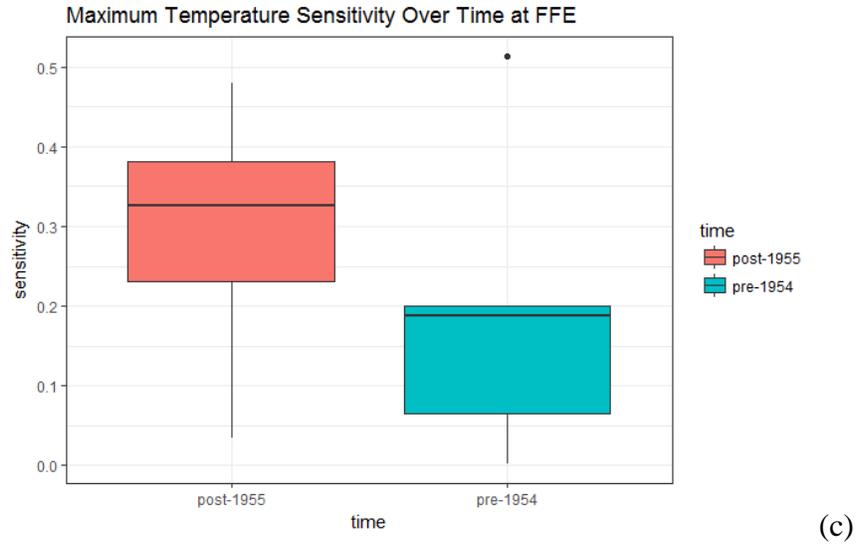
Figure 11: March maximum temperature sensitivity (measured in centigrade) for the time periods 1895-1954 and 1955-2017. No significant differences were found for the forest-lake edge (LOW; a), the interior (INT; b), or the forest-forest edge (FFE; c).


(a)

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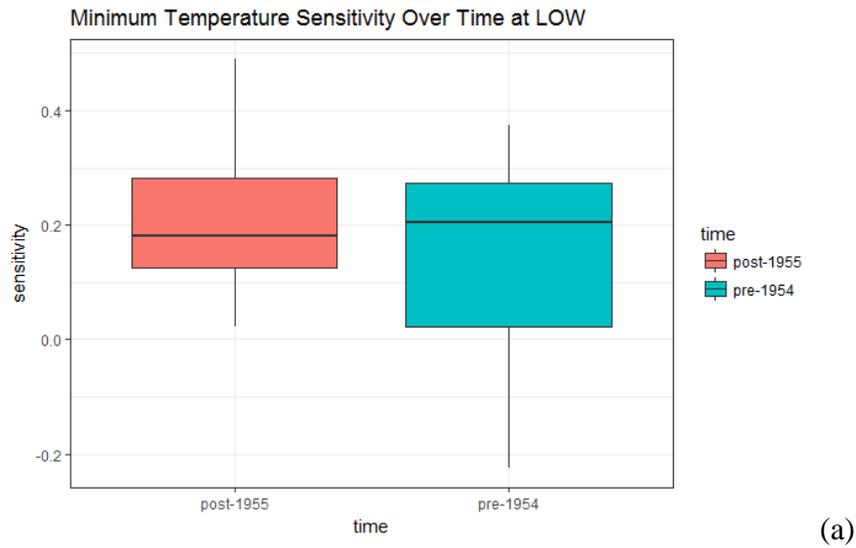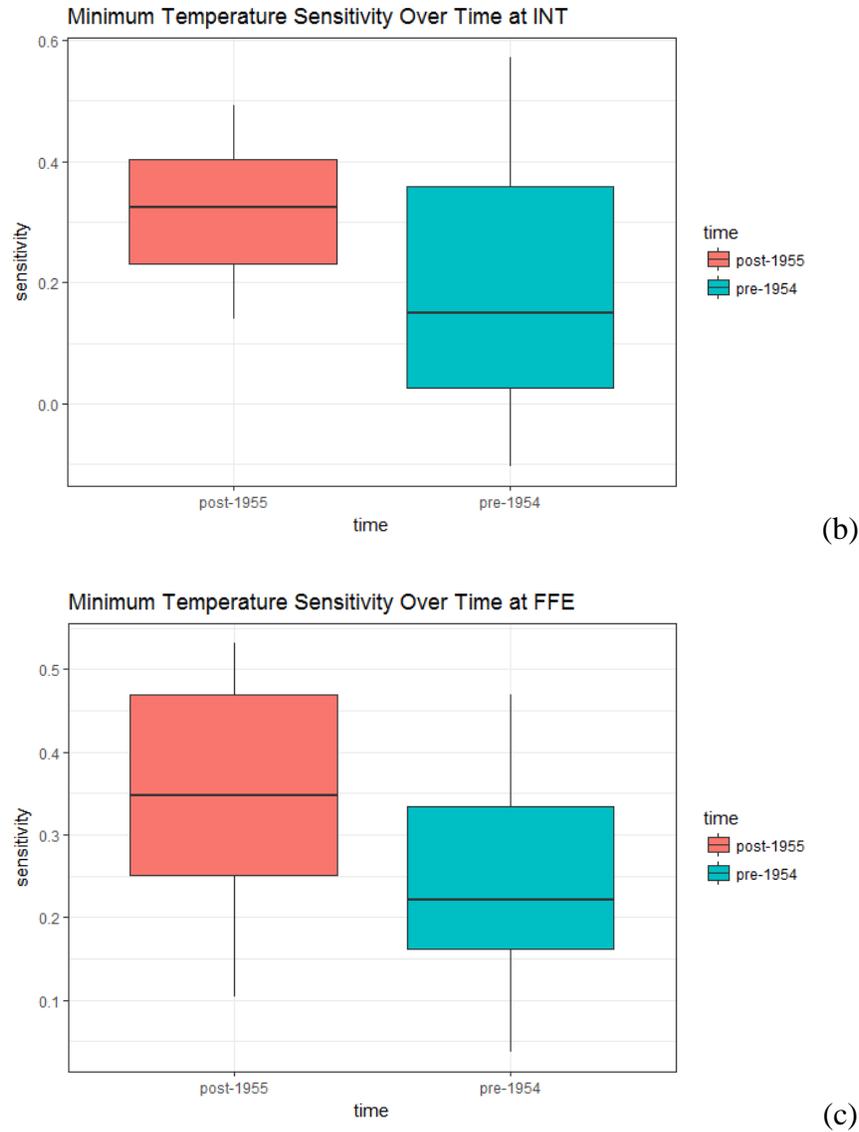
Figure 12: March minimum temperature sensitivity (measured in centigrade) for the time periods 1895-1954 and 1955-2017. No significant differences were found for the forest-lake edge (LOW; a), the interior (INT; b), or the forest-forest edge (FFE; c).

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