The change of microclimate in riparian buffers following clearcutting of adjacent forest stands.

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Abstract

Streamside riparian zones are the interface between the aquatic and terrestrial ecosystem. They have a unique microclimate, differing from the microclimatic conditions in upland forest. This unique microclimate favours biota adapted to humid and cool conditions. The insufficient protection of riparian microclimate can decrease abundance of species sensitive to microclimate changes. In Sweden, it is common to leave narrow buffer strips (<5 m) along small streams during final harvest. These buffer strips are insufficient to protect the functions of riparian buffers, including the microclimate control. We need to gain better understanding of how different buffer management practices will affect microclimate.

Within my thesis I contribute to a better understanding on how different buffer management practices along a small stream affect microclimate after final harvesting in Sweden. I did this by examining mean solar radiation, maximum air temperature, minimum relative humidity and maximum water temperature in a case study consisting of a control site and three different treatment sites. I identified treatment specific differences in the response of riparian microclimate to harvest of the adjacent forest. Leaving a narrow buffer on one side of the stream will affect the microclimatic preconditions on the other side of the stream. Gap-Cutting treatment increased solar radiation and air temperature significantly. Further it decreased relative humidity significantly. Leaving variable retention tailored to a soil moisture map led to a significantly increased solar radiation and air temperature, but no significant differences in relative humidity. Water temperature decreased in two of the examined sites and increased in one, after final harvest. The riparian management showed subordinate influence on water temperature, in comparison to the influence of the hydrological regime. I further found small-scale heterogeneity of microclimate responses. Therefore, riparian management aimed at microclimate protection should consider within site heterogeneity and focus on areas were changes in microclimate result in adverse ecological consequences.

Keywords: riparian forest, forest management, microclimate, headwater streams

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Abbreviations

AT	Air temperature
C	Control site
GC	Gap-Cutting
OS	One-Sided
RH	Relative humidity
SR	Solar radiation
VR	Variable Retention
WT	Water temperature

1. Introduction

Streamside riparian zones are the interface between the aquatic and terrestrial ecosystem (Swanson et al., 1982). They have a unique microclimate, differing from the microclimatic conditions in upland forest. This unique microclimate favours biota adapted to humid and cool conditions (Rykken et al., 2007). The high heterogeneity of riparian zones allows for species-rich plant communities (Nilsson & Svedmark, 2002; Sabo et al., 2005). Especially poikilohydric species, that are reliant on the water status of the environment to survive, are sensitive to changes in air temperature and relative humidity. For example, Oldén et al. (2019) hypothesized that in particular increased maximum air temperature and decreased minimum relative humidity cause the drying out of sensitive mosses, such as *Pseudobryum cinclidioides*. Therefore, protection of riparian forests is detrimental. A frequent practice is the consideration of riparian buffers between production forest and stream edge during final harvest. This means leaving a row of trees unharvested. This practice was originally designed to protect the stream conditions, such as thermal and biochemical regimes but developed further to mitigate many functions of riparian zones, such as erosion prevention, methyl mercury leakage from clear-cuts and protection of the unique riparian microclimate (Bishop et al., 2009; Kreutzweiser et al., 2008).

In Sweden, it is common to leave narrow buffer strips of a no-drive zones with 1-2 rows of trees (<5 m width) along small streams (Kuglerová et al., 2020). These buffer strips are insufficient to protect the functions of riparian buffers, including the microclimate control (Chellaiah & Kuglerová, 2021; Kuglerová et al., 2020; Maher Hasselquist et al., 2021). Therefore, in 2013 the Swedish forest sector developed Strategic Management Objectives (SMOs) for environmental consideration during forestry operations, and protection of the thermal and light regimes (i.e., microclimate) is one of the objectives (Andersson et al., 2013). These objectives are lacking precise recommendations for how to apply them in practice (Kuglerová et al., 2024). Thus, we need to gain better understanding of how different buffer management practices will affect microclimate, so precise recommendations can be given to practitioners. Within my thesis I contribute to a better understanding on how different buffer management practices along a small stream affect microclimate after the final harvesting in Sweden, by examining a case study with a control site and three different treatment sites.

1.1 Microclimate in riparian zones

Within forest environments canopy cover and high moisture supply create buffered microclimate in comparison to microclimate outside the forest environment (De Frenne et al., 2021). The canopy cover reduces solar radiation, precipitation, and wind speed near ground level. But the forest environment increases longwave radiation received at the surface (De Frenne et al., 2021). This specific microclimate within forests is also influenced by other site-specific factors, such as topography, soil moisture and tree species composition (von Arx et al., 2012, 2013). Streamside riparian zones have a unique microclimate, differing from the microclimatic conditions in upland forest. This is due to the large interactive surface of the stream and its surrounding (Moore et al., 2005).

There will be four microclimate parameters, that I will survey in this thesis: solar radiation, air temperature, humidity, and water temperature.

Light regime and energy fluxes

Headwaters in managed boreal forest within Sweden are characterized by a high canopy coverage of about 70 % (Lundqvist, 2022). This means incoming solar radiation will be absorbed by the canopy cover and partially reflected. Some light will be transmitted. Transmitted light and light that is passing through gaps can be absorbed by understory vegetation, soil or streambed. Furthermore, it can be reflected by the stream water or absorbed. The absorption of radiation will cause an increase in soil temperature and stream water temperature (Moore et al., 2005). As water has a high specific heat capacity, the temperature increase will be slower in water then in soil.

The current forest management of riparian zones in Sweden is not promoting gaps (Chellaiah & Kuglerová, 2021). Thus, spatial heterogeneity of incoming solar radiation is low. Shading decreases incoming solar radiation, allowing for buffered air temperature in forest environments, with less extremes (De Frenne et al., 2021). Fewer temperature extremes will dampen changes of the relative air humidity. Furthermore, light is a limiting factor in primary production, setting boundary conditions for the aquatic ecosystem of the riparian zone (Keeton et al., 2007). This means, that while shading by the riparian canopy is vital, some light inputs through small canopy openings are desirable along the dark Swedish headwaters (Maher Hasselquist et al., 2021).

Air Temperature

Air temperature extremes from the macroclimate, above the canopy, are buffered in forest environments. Lower daily maximum air temperatures and higher daily minimum air temperatures can be found in a forest, with less seasonal and interannual variability (De Frenne et al., 2021). In riparian zones, evaporation from the stream water will have a cooling effect on air temperature (Swanson et al., 1982). Additionally, there is even more potential evaporation with increasing soil moisture closer to streams, which can have a further cooling effect on air temperature (Ploum et al., 2021). The water surface of the stream has less airflow resistance, creating a potential "wind channel". The movement of air masses along the stream can transport heat through convection and evaporation (Gurnell et al., 2007). In a study by Brosofske et al. (1997) air temperature in stream proximity was observed to be similar to upland interior forest conditions between 31 to 47 m from stream edge. The importance of air temperature for biota, such as bryophytes is often interconnected with relative air humidity and solar radiation, where frequent days with high temperatures, little rain and low humidity will influence the survival rate of bryophytes (Dahlberg et al., 2020; Koelemeijer et al., 2023; Man et al., 2022).

Humidity

Generally, increasing daytime air temperatures decreases relative humidity, as warmer air has more capacity to hold moisture. In forests, lower daytime air temperature, can lead to higher relative humidity compared to outside the forest environment (Chen et al., 1995). Open water proximity leads to increased water content in the air as water evaporates (Moore et al., 2005). Within riparian zones, relative air humidity is considered to be higher than in upland forests, due to higher soil moisture content and stream proximity. In Danehy & Kirpes (2000) they found enhanced relative air humidity up to 10 m from the stream (mountainous area). Riparian vegetation and dense understory vegetation can support high humidity due to transpiration and reduced solar radiation (Danehy & Kirpes, 2000; Pettit & Naiman, 2007). In a study by Brosofske et al. (1997) air temperature in stream proximity was observed to be similar to upland interior forest conditions between 31 to 62 m from stream edge. Poikilohydric species in riparian zones are especially dependent on the cool and humid conditions and have been found to be sensitive to changes in relative humidity (Oldén et al., 2019; Stewart & Mallik, 2006).

Water Temperature

Streams with a small water volume, such as headwater streams, are highly influenced by their riparian zone, but also by their catchment area (Moore et al., 2005). The riparian zone provides shading, which determines the incoming solar radiation and therefore warming of streams through direct sunlight and conductive

heat exchange from the streambed (Evans et al., 1998; Sinokrot & Stefan, 1993). The bank morphology of the riparian zone can also provide shading (Webb & Zhang, 1997). Together with the stream bedding, bank morphology and topography can change stream flow speed and surface turbulences, influencing warming and cooling of the stream (Olden & Naiman, 2010).
The catchment area affects headwater streams due to surface water input; upstream catchment area features as well as groundwater input (Oswood et al., 2006). These inputs control thermal, hydrological and biogeochemical characteristics of the stream (Sass et al., 2014). An upstream lake increases the average stream temperature during summer months, due to warming of the lakes surface water. Upstream wetlands also lead to warmer stream temperature (Rayne et al., 2008). As discussed in Moore et al. (2005) ground water inflow into a stream typically has a cooling effect during summer daytime. Additionally, in smaller streams the groundwater inflow has a higher ratio to the downstream flow than in bigger streams, making them more susceptible to catchment area changes. Understanding thermal responses in small streams is vital, as aquatic species, like the freshwater pearl mussel, have specific thermal tolerance levels that influence growth and reproduction chances (Wagner et al., 2024). Further, changes in water temperature affect metabolic rates in aquatic organisms (Demars et al., 2011).

1.2 Forest management

The predominant silvicultural system in Sweden is rotation forestry (Lundmark et al., 2013). This system promotes single-storied stands. During the end of a rotation cycle (i.e. final felling) these stands are usually clear-cut (Ekholm et al., 2023). Clear-cutting increases the habitat fragmentation by creating edges between forest stands and adjacent clear-cuts (Östlund et al., 1997). The abrupt transition between the forest stand and the clear-cut generates changes within the remaining forest, frequently termed as a "Forest-Edge-Effect" (Murcia, 1995).

Forest management and microclimate

The insufficiency of riparian zone protection is multifactorial. Microclimatic parameters are strongly influenced by the "Forest-Edge-Effect" along the riparian zone and water regime changes within the associated catchment area, due to management practices such as final harvest (Brosofske et al., 1997; Mellina et al., 2002; Moore et al., 2005; Oldén et al., 2019).

The forest edge adjacent to a clear-cut has a high exposure to solar radiation, leading to higher daytime temperatures and lower relative air humidity (Chen et al., 1995). Solar radiation will normalize at about one tree length distance to the edge in upland forests. Air temperature and humidity need greater distances to acclimate (Chen et al., 1995; Moore et al., 2005). When a forest edge is facing south- or southwest, the edge effect becomes stronger in the northern hemisphere (Chen et al., 1995; Moore et al., 2005). Oldén et al. (2019) found an increased effect of logging on humidity if the clear-cut was situated south or southwest. A small effect of a southern clear-cut was found on air temperature increase.

Within riparian buffers, forest edge effects on the microclimate can be mitigated to a certain extent due to the higher soil moisture and generally cooler microclimate (Rykken et al., 2007). In Finland, research found that riparian buffers of at least 30 m width on each side of the stream can, to a large degree, maintain riparian microclimate after clearcutting of adjacent stands (Oldén et al., 2019). In addition, in the Pacific Northwest the strongest stream effect on air temperature and relative humidity was found within 10 m of the stream (Rykken et al., 2007). As in Sweden, the average buffer widths along streams are far from 10-30 m retention on both sides of the stream, it is very likely that microclimate is severely changed after harvest. However, this has not been thoroughly studied in Sweden yet and therefore remains a presumption.

Stream water temperature is influenced by the catchment area and the riparian zone, thus changes of either of them can affect the water temperature (Martin et al., 2021; Moore et al., 2005). An increased exposure to radiation, due to canopy removal, can increase the water temperature (Moore et al., 2005). After forest harvesting, soil moisture and groundwater levels usually increase due to decreased interception and transpiration. Thus, more groundwater flow could lead to more cooling of streams (Kibler et al., 2013). On the other hand, heating of shallow groundwater due to increased solar radiation on a clearcut can lead to increases in stream water temperature (Bourque & Pomeroy, 2001; Johnson & Jones, 2000). Headwater streams with an initially lower temperature because of the subsurface origin, showed a warming with or without harvesting, suggesting that these are more sensitive to management interventions (Mellina et al., 2002; Zaidel et al., 2021). In a review study from Martin et al. (2021), they found positive effects of mitigating water temperature change with buffers of at least 30 m. The magnitude of water temperature change due to loss of shading was depended on multiple factors: geology, hydrology, topography, latitude, and stream azimuth (Martin et al., 2021). In Sweden, there are very few studies comparing the influence of various buffer designs on in stream water temperature after final harvest of an adjacent forest (Chellaiah & Kuglerová, 2021; Jyväsjärvi et al., 2020).

Historical riparian buffer management

In seven Nordic-Baltic countries, the protection of surface waters in forests has shown to be reliant on both legislation and voluntary commitments (Ring et al., 2017). Sweden’s approach to forest management is guided by the fundamental principle of “freedom with responsibility”, where the Swedish Forestry Act only provides baseline standards (Hasselquist et al., 2020; Ring et al., 2022).

More than 80 % of riparian forests in North America and Europe have already been disturbed or destroyed (Naiman et al., 1993). Hasselquist et al. (2020) published a case study, analysing the Krycklan Catchment Area in northern Sweden (Laudon et al., 2021). They found, that between 1965 and 1973, only 15% of the stream length in the catchment had a buffer (>10m) established after final harvest. Until 2004, 50% of stream length was protected by a buffer (>10m) after final harvest (Hasselquist et al., 2020). The establishment of riparian buffers was found to be more frequent on large streams with 90% having a buffer, than in small streams with 25% of their stream length being protected (Hasselquist et al., 2020). Kuglerová et al. (2020) also showed that small streams are commonly managed with narrow buffer strips, consisting of a no-drive zone with 1-2 rows of trees (<5 m width). These buffer strips are insufficient to protect the functions of riparian buffers, including the microclimate control (Chellaiah & Kuglerová, 2021; Kuglerová et al., 2020; Maher Hasselquist et al., 2021). In forested areas, small streams represent 70–80% of the total river network length (A. Ågren et al., 2015) and as such the insufficient buffer management affects the majority of our surface waters.

New buffer management objectives

Given the historical negligence of small streams and their riparian areas, in 2013 the Swedish forest sector developed Strategic Management Objectives (SMOs) for environmental consideration during forestry operations. This was, inter alia, an attempt to clarify the level of protection required for riparian zones. They defined six functions of a riparian buffer within the SMO: riparian buffers should 1) prevent sedimentation and erosion, 2) preserve biodiversity, 3) shade and regulate water temperature, 4) provide deadwood, 5) conserve biochemical cycling in riparian soils and 6) supply litter to serve as food for aquatic organisms (Andersson et al., 2013). As there was no detailed guidance provided of how exactly to protect these functions of a riparian buffer (Kuglerová et al., 2024), the MUST DEFINE Project (Using a MUltiple STakeholder Dialog and Experiments to reFINE the Swedish Strategic Management Objectives for forest buffers along streams) was initiated. A collaboration between SLU, the Swedish Forest Agency and SCA (forest company). For this research, different riparian management plans were made to compare how they will protect the riparian buffer functions. The providence of shade and water temperature regulation can be measured with microclimate indicators, such as air temperature, humidity, and radiation within the understory of the riparian buffer and the water temperature of the stream. This data will give a better insight into small scale processes in riparian buffers.

1.3 Aim and research questions

In Sweden there is a lack of research focusing on potential riparian buffer designs to protect riparian microclimate. Within this thesis I will survey three different treatment sites and one untreated site to provide better understanding of microclimatic changes before and after the final harvesting of an adjacent forest. I will be answering the following questions:

1) How did riparian microclimate change in general from 2022 to 2023? Was the change associated to harvest treatment or annual differences in weather? (Q1)

For this question, I used data on air temperature and humidity, water temperature and light collected during July 2022 (pre-treatment year) and July 2023 (post-treatment year) from 4 sites. Three of the sites were harvested in the winter of 2023 (i.e., before the collection of 2023 data) while one site served as untreated control. All treated sites received a riparian buffer, but the buffer designs varied (see methods).

I anticipate an increase in solar radiation and air temperature of all treatment sites, but a decrease in relative air humidity and water temperature. Furthermore, the fluctuation in solar radiation, air temperature and relative air humidity will increase, seen in an increased standard deviation.

2) What were the site-specific responses of microclimate to the harvesting treatment? (Q2)

For this question, I used data on air temperature and humidity, water temperature and light collected during July of 2022 and 2023. I used descriptive statistics to evaluate within site variability (differences across multiple loggers situated at each site) and compared specific sites before and after treatment. I also investigated how are the specific site-responses associated to the type of treatment they received (site-specific buffer configuration).

I anticipate more extreme changes from the Gap-Cutting treatment on solar radiation, air temperature and relative air humidity, than in the Variable-Retention treatment (see methods for details on buffers). I further anticipate the smallest treatment effect on the microclimate parameters in the Variable-Retention treatment. The One-Sided treatment might already be pre-effected from a previous final harvest, nonetheless the final harvest during 2023 will assumingly still affect the microclimate. I anticipate an increase in solar radiation and air temperature and a decrease in relative air humidity. The water temperature changes might be largest within the Variable-Retention treatment as the final harvest area was the largest.

Water temperature in the Gap-Cutting treatment might increase, due to more light exposure further downstream.

3) Based on the observations in Q1 and Q2, are there conclusive recommendations that can be implemented into riparian buffer management? (Q3)

To answer this question, I looked specifically how microclimate reacted to the treatments in vicinity to each logger, for example buffer width at each plot level and consequences of wind felling. Are there plots showing very specific changes, different from other plots?

I anticipate that plots located in narrower strips of the installed buffers, or locations where severe wind-felling occurred after harvest, will have more solar radiation and increased air temperature. Within the Variable-Retention treatment plots situated in the widest part of the buffer should show less variation over time in air temperature and relative humidity.

2. Material and methods

2.1 Study area and project structure

Within the MUST DEFINE project, four sites were chosen together with an industry partner (forest company SCA). On these demonstration (DEMO) sites, final harvests were planned, and the researcher team, together with forest planner, designed buffers along the streams situated in the stands. The stands are primarily dominated by Norway Spruce (*Picea abies*) with variable proportions of Scots Pine (*Pinus sylvestris*) and deciduous trees, such as Birch (*Betula spec.*) and Alder (*Alnus spec.*). For each site different riparian buffer management was planned, that was adapted to local conditions and needs (see further below). This also enabled to compare different buffer designs in how they protect the streams. All four stands and streams were monitored 1 year before and 1 year after harvest, with 3 streams being harvested and one serving as a control.

Table 1: Site characteristics per treatment site. Age in years, HS – harvest size, CO - Canopy openness pre-treatment; Wetness - averages of the recorded values for wetness (4 point scale, dry-wet), CS – catchment size, Upstream source – upstream distance in m, BW – bankful width

	Age	HS [ha]	CO [%]	Wet-ness	CS [km²]	Upstream source [m]	BW [cm]
Control (C)	110	No harvest	27.20	mesic	0.72	Wetland upstream	77.50
Gap-Cutting Treatment (GC)	141	15.14	20.43	mesic	0.61	Lake (250 m)	47.67
One-Sided Treatment (OS)	89	3.79	22.20	dry	2.51	Lake (280 m)	136.50
Variable-Retention Treatment (VR)	125	22.51	17.41	moist	1.00	Lake (150 m)	50.33

Note. Adapted from Hofman, R. B. (2023). Riparian vegetation ecology: An observational study into the effects of forest management on understory vegetation communities along boreal headwaters. In *Master's thesis in Forest Science at the Department of Forest Ecology and Management*.

Per site, the researcher team established eight plots along the stream in 2022 before the final harvest of the adjacent forest. Plot 1 is the most downstream and plot 8 the most upstream. They are organized in a zig-zag pattern, and situated at equal distances from each other, and the researchers randomly chose on which site to start with Plot 1 (Figure 1B). An exception is the One-Sided treatment site, as one side of the stream was already harvested in 2018 and left with retained 5 m riparian buffer. There, only 6 plots were placed on the side harvested for this trial, north-east of the stream. In my thesis, plots function as replicates for each other for Q1 (Figure 6). The number of plots per parameter can be seen in Table 2.

All microclimatic parameters were continuously measured from 21 of June until 16th of October 2022, before the adjacent forest was harvested. Several additional parameters were measured in each plot (soil chemistry, deadwood, aquatic biodiversity) which will not be considered in this thesis.

During winter 2022/2023 three of the four sites got harvested, so that the effects of the final harvest could be measured continuously from 21 of June until 16th of October 2023. Additionally, a second tree inventory was conducted in 2023. The final harvest of the fourth DEMO site (control in this thesis) was finished during the beginning of August 2023. Therefore, in Q1 and Q2, this site is functioning as a control site during the month of July 2023. The post-harvest measurements for this site are available from August until October but are not used in this thesis. The four sites got assigned different harvest treatments:

- Control Site (C): No treatment. (Figure 2)
- Gap-Cutting Site (GC): A riparian buffer was established as an at least 10 m wide intact buffer (on each side of the stream). At three places, ca. 20 m long canopy gaps were created. The canopy gaps were harvested all the way to the stream edge, in areas where a lot of understory trees occurred (Figure 3).
- One-Sided Site (OS): This site had a previous clearcut on the south-west side of the stream with a riparian buffer of 5 m left. On the other side of the stream an improved retention was designed (to compensate for the narrow buffer from the previous harvest on the other side) as 10+10 m width. In the 10m buffer closer to the stream, no harvest was allowed. In the adjacent 10-20 m strip, partial harvest was allowed and ca 50% of the trees were removed from this outer strip. Retention of on average 20.3 m was left (Figure 4).
- Variable-Retention Site (VR): The riparian buffer was tailored to a soil moisture map, leaving wider retention in areas with high soil moisture content and smaller retention in areas with less soil moisture content. This meant that at some locations, the buffer was more than 20 m wide but at some places, trees were cut nearly all the way to the stream (Figure 5).

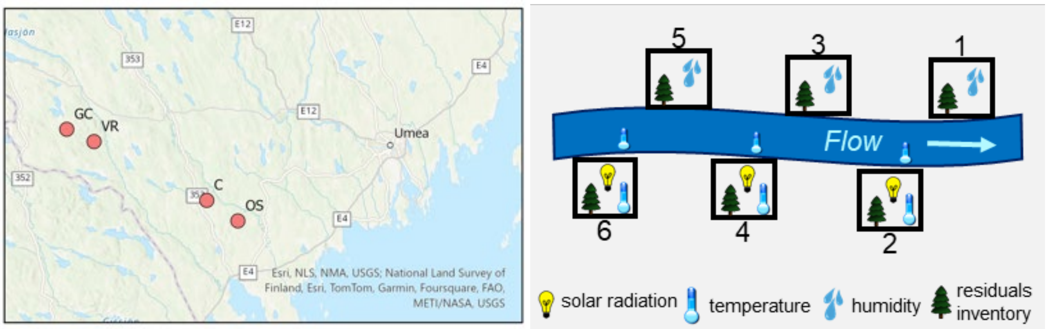

Figure 1: [A] Left figure shows the location of the treatment sites and the control site within Sweden.(Source: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community)
[B] Right figure shows an exemplary illustration of the study set-up at each of the four sites (in reality usually 1-8 plots). The symbols represent the measurements that were carried out related to each plot 1-6 (excluding measurements unimportant for this thesis).

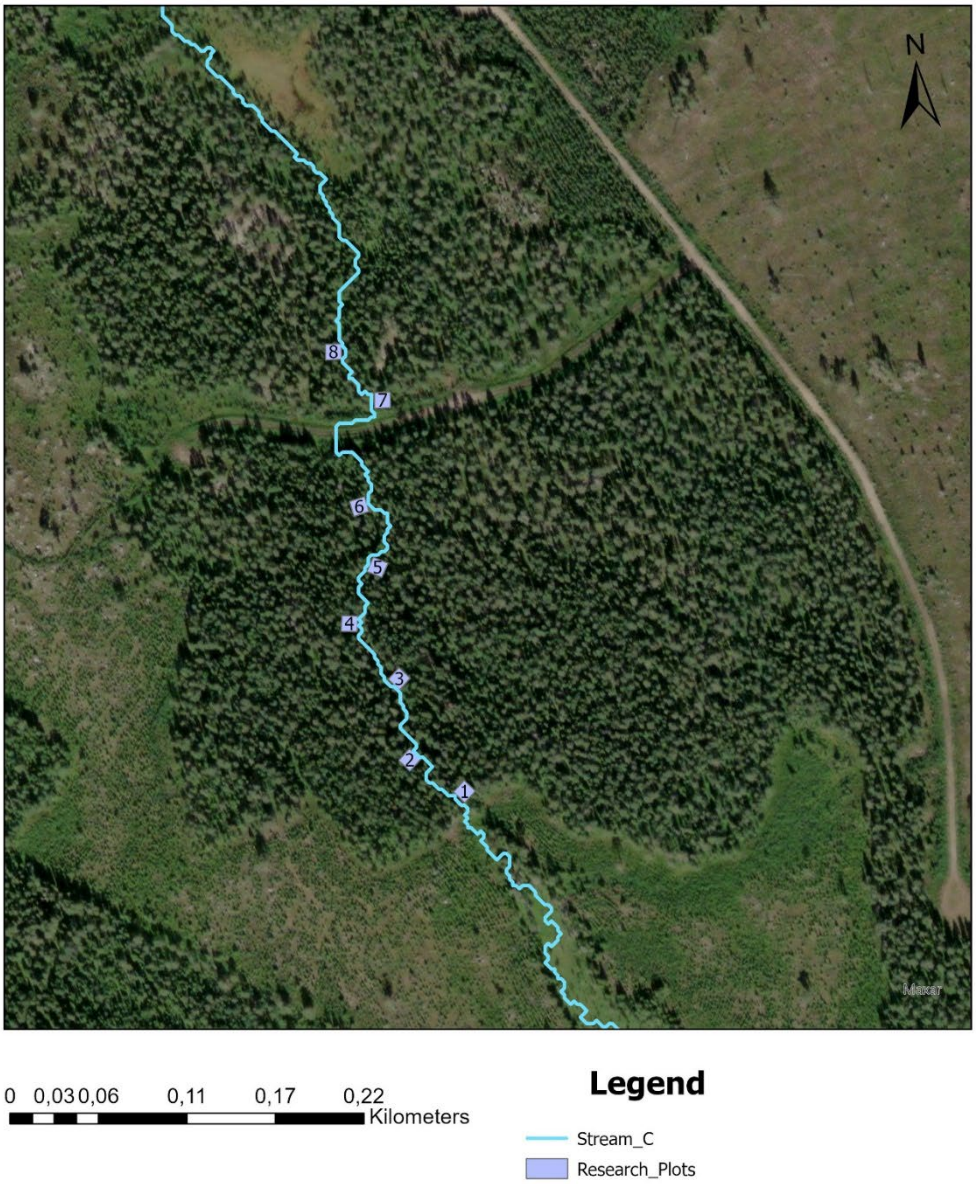

Figure 2: Map control site (C). (Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community)

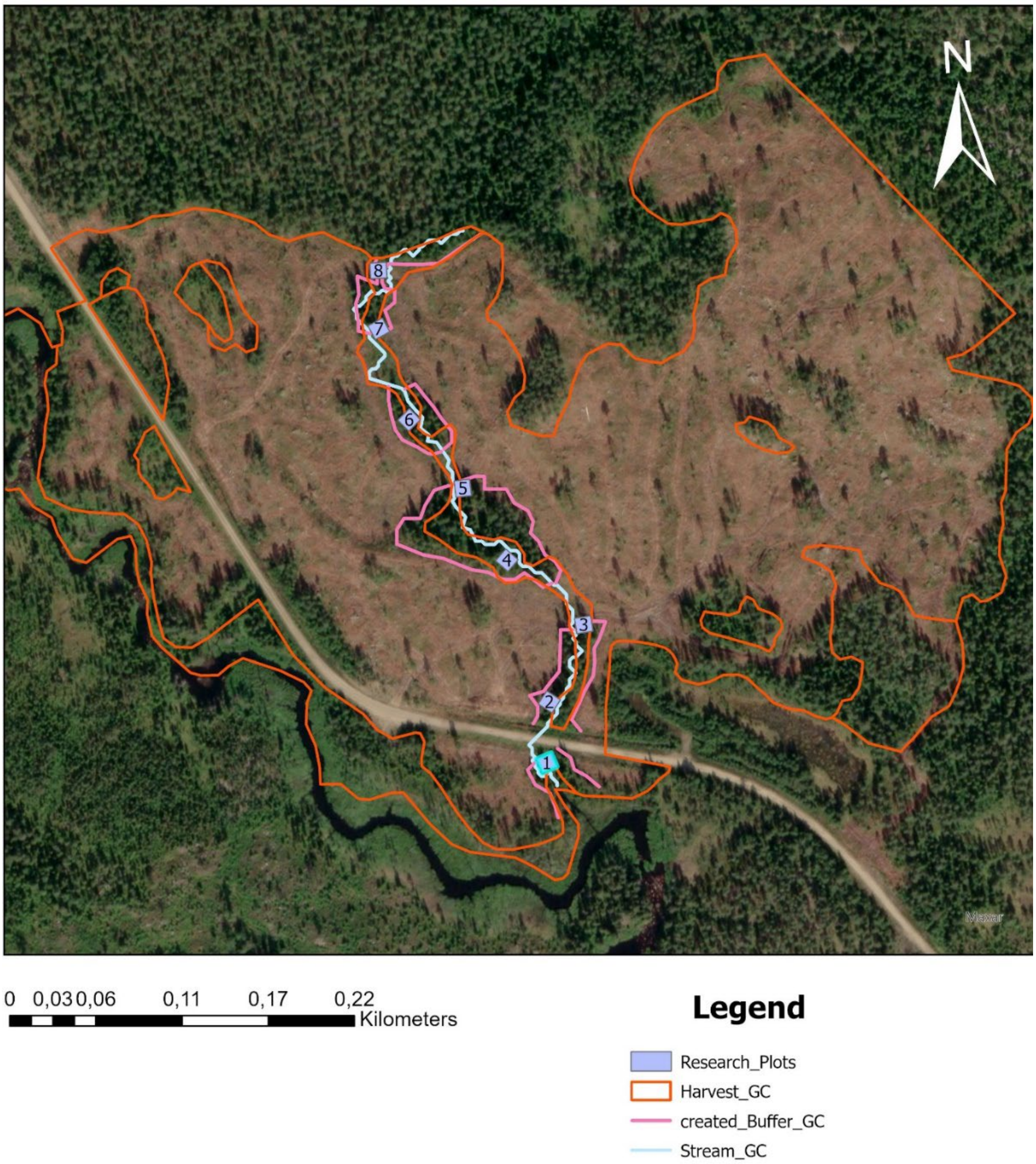

Figure 3: Map Gap-Cutting Treatment (GC). The red boundaries (Harvest_GC) were obtained directly from SCA and show their harvest planning. The pink boundary of the buffer (created_Buffer_GC) is the buffer marked in the field by the researchers and thus this can differ from the buffer planned by SCA (red). (Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community)

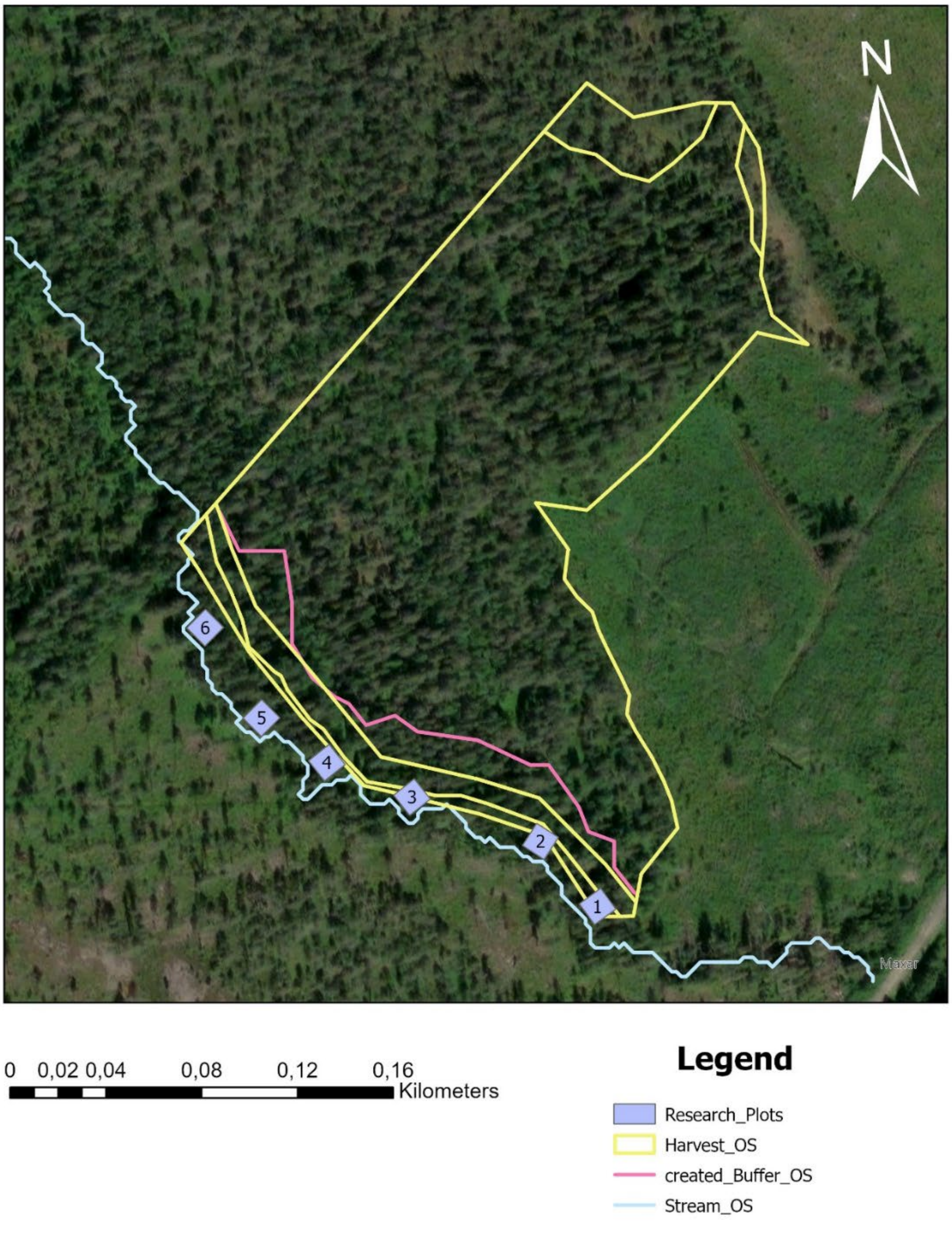

Figure 4: Map One-Sided Treatment (OS). Note that aerial image from post-harvest is not available so image from before-harvest is used here. The forest within the yellow boundary (harvest OS) is now harvested. The yellow boundaries (Harvest_OS) were obtained directly from SCA and show their harvest planning. The pink boundary of the buffer (created_Buffer_OS) is the buffer marked in the field by the researchers and thus this can differ from the buffer planned by SCA (yellow). (Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community)

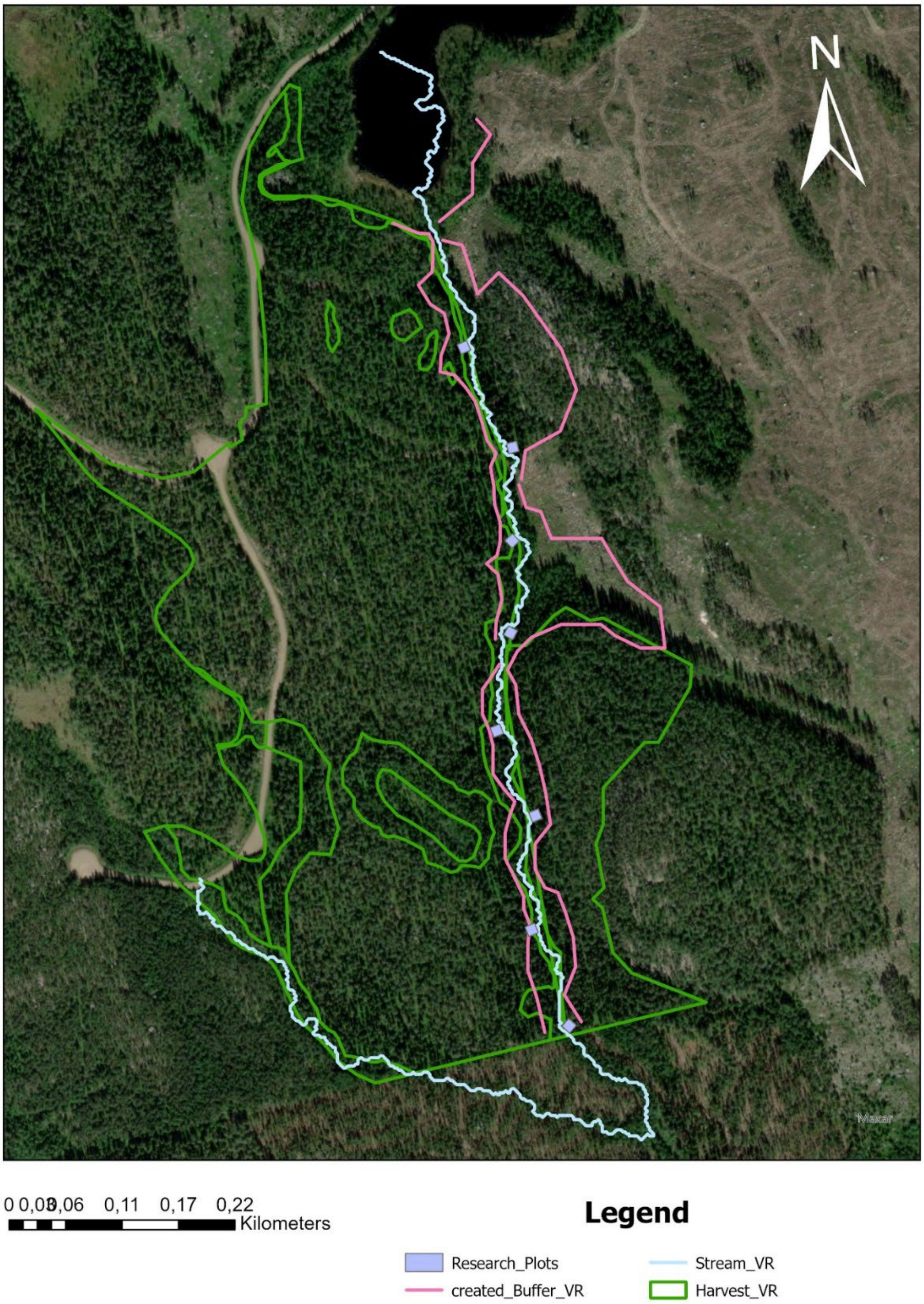

Figure 5: Map Variable-Retention Treatment (VR); most southern plot is number 1; most northern plot 8. Note that aerial image from post-harvest is not available so image from before-harvest is used here. The forest within the green boundary (harvest VR) is now harvested. The green boundaries (Harvest_VR) were obtained directly from SCA and show their harvest planning. The pink boundary of the buffer (created_Buffer_VR) is the buffer marked in the field by the researchers and thus this can differ from the buffer planned by SCA (green). (Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community)

2.2 On-site data

Within my thesis, I analysed the following microclimate parameters: air temperature, water temperature, relative humidity, and solar radiation. I choose to compare the month July for all microclimate parameters, as the highest potential for change can be seen during the warmest months of the year (Moore et al., 2005).

Table 2: Overview of number of measurements per parameter and site; T – temperature (air and water), SR – solar radiation, RH – relative humidity

	Abbreviation	Zig-zag layout	T & SR 2022	T & SR 2023	RH 2022	RH 2023
Control Site	C	True	4	4	2	2
Gap-Cutting Treatment	GC	True	4	4	3	3
One-Sided Treatment	OS	False	3	3	3	3
Variable-Retention Treatment	VR	True	4	4	2	3

Solar radiation

In four plots at each site, HOBO pendant loggers were used to measure light (Onset Computer Corporation, Bourne, MA, USA) 40 cm above ground and 3 m away from the stream edge. The light meter measures luminous flux per unit area (illuminance), in this case units of lumens per square meter, known as lux (lx). Direct outdoor sunlight on a clear day has been measured to be approximately 130000 lx (Norton & Siegwart, 2013). Values exceeding this limit were classified as outliers and removed for the subsequent analysis. The standard unit for quoting solar radiation is units of watts per square meter (W/m^2). In literature there is no homogenous conversion for lux into solar radiation. For the wavelengths 400 – 700 nm under daylight conditions Thimijan & Heins (1983) suggest dividing the LUX measurements with 54 as a conversion factor to convert into photosynthetically active radiation [W/m^2]. In Michael et al. (2020) they suggest 122 ± 1 lx for outdoor natural sunlight as a conversion factor from irradiance to illuminance in 1 W/m^2. They also refer to an engineering rule of thumb, where 120 lx equal 1 W/m^2.

I decided to use the conversion from Li et al. (2023) where they compared measurements from a pyranometer in an automatic weather station (Weatherhawk 232; WeatherHawk Inc., Logan, UT, USA) and a light meter (HOBO MX2202; Onset Computer Corp., Bourne, MA, USA). This resulted in the following equation:

$$\mathbf{(SR) = 0.009 * (lx) - 1.360}$$ SR- Solar Radiation; lx – LUX

After converting, I choose to aggregate the hourly solar radiation into daily mean radiation per plot (exemplary: Figure 6). Within this thesis solar radiation measurements are functioning as an approximate for light regime change.

Therefore, the average solar radiation will give an insight of the average change in light regime.

Air temperature

Within four plots at each site HOBO pendant loggers were used to measure air temperature (Onset Computer Corporation, Bourne, MA, USA) 40 cm above ground and 3 m away from stream edge. Air temperature was measured in °C every hour. I choose to aggregate the hourly air temperature into daily maximum air temperature per plot (exemplary: Figure 6). In an environment that is associated with a cool and humid climate, I was interested in the possible changes in extremes due to final harvesting (Rykken et al., 2007). The daily maximum air temperature in combination with a low daily minimum humidity could be detrimental to especially poikilohydric species (Oldén et al., 2019).

Relative air humidity

Within three plots at each site, EL-USB-2 - Data Loggers were used to measure relative air humidity (Lascar Electronics Ltd.) at an average height of 1.3 m and in 3-5 m distance from the stream edge. The relative air humidity was measured in %. As explained in On-Site data: Air Temperature, I was interested in the changes of minimum relative humidity, therefore, I aggregated the hourly relative air humidity into daily minimum humidity per plot (exemplary: Figure 6).

Water temperature

In the stream channel bordering four riparian plots at each site, HOBO pendant loggers were used to measure water temperature (Onset Computer Corporation, Bourne, MA, USA) 10 cm above stream bottom. Water temperature was measured in °C. I aggregated the hourly water temperature into daily maximum water temperature per plot (exemplary: Figure 6). Generally, increases in water temperature can have a lethal effect on aquatic biota with thermal thresholds, like salmonids (Sullivan et al., 2000). As boreal headwater streams are mainly cool water systems, I was mostly interested in the maximal warming of the stream that can occur. Aquatic species, like the freshwater pearl mussel, have an upper thermal tolerance that decreases summer survival during warmer periods (Wagner et al., 2024). Further, increase in water temperature can accumulate downstream, as stream flows through the clearcut (Swartz et al., 2020).

Additional information

A residuals inventory was done in 2022 and 2023, where stumps and rootwads (uprooted trees) were counted in all plots. Further site-specific information (Table 1) was acquired from the master's thesis of Hofman (2023). He collected information about canopy openness, wetness, catchment area size and bankful width. He calculated canopy openness by taking a picture of the canopy and then using a fish-eye lens for mobile phones and the GLAMA mobile app (Tichý, 2014). Wetness of the soil was assessed on a 4-point scale (dry, mesic, moist, and wet) by touch. The catchment area size was calculated using the flow accumulation raster derived from digital elevation models in ArcGIS and Whitebox software (A. M. Ågren et al., 2014).

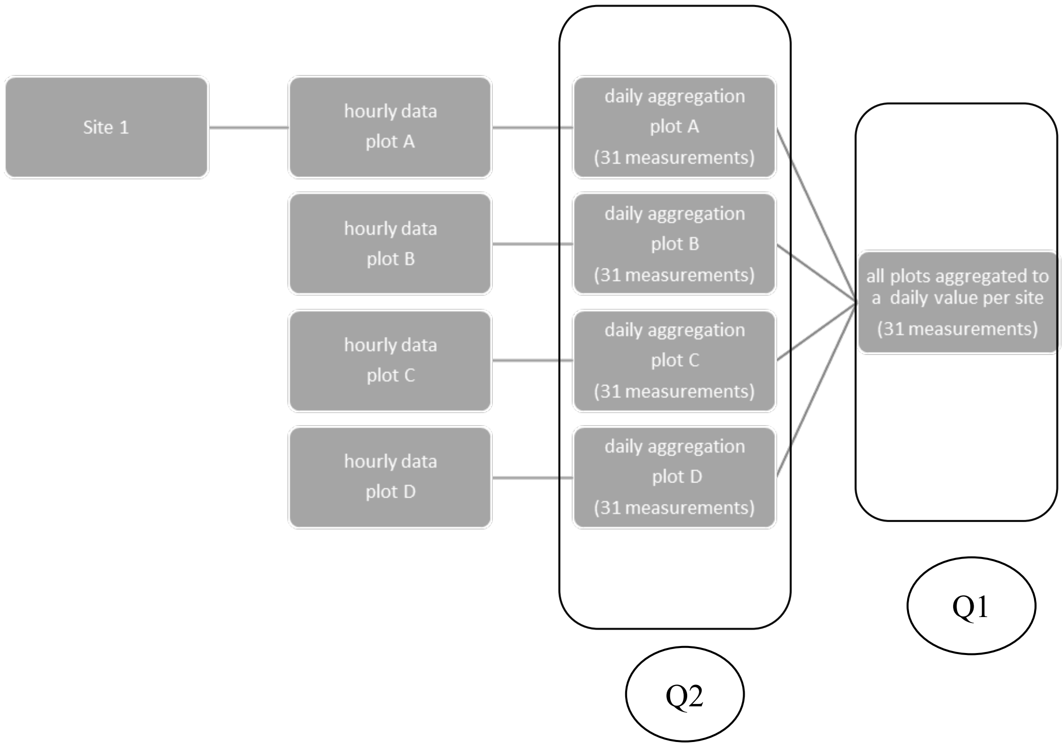

Figure 6: Schematic visualization of the data aggregation for question 1 and 2.

2.3 Analysis

This thesis is derived from the analysis of the before-after, control-impact (BACI) study design (Wauchope et al., 2021). Nonetheless, the MUST DEFINE project is a trial study, leading to a study layout with unconventional replicate and treatment parameters. For a standard BACI study design the control and treatment times series should show similar trends before the treatment takes place, a so-called parallel trend assumption (Linden, 2018). Furthermore, more control and treatment sites would be necessary to have a sufficient number of replicates. With this in mind, during my thesis, I will have a BACI-like comparison, analysing the trends of the control site against the trends of the treatment sites before and after the final harvest. I will also look at each site individually to aim for a better understanding of site-specific processes, predetermining microclimate and its response to management.

The data analysis was performed using R studio (R Core Team, 2023), the packages “dplyr”, “readXl”, “ggpubr”, “lubridate”, “patchwork”, “superb” and “ggplot2” for data manipulation and plotting (Cousineau et al., 2021; Grolemund & Wickham, 2011; Kassambara, 2023; Pedersen, 2024; Wickham, 2016; Wickham et al., 2023; Wickham & Bryan, 2023).

Question 1) How did riparian microclimate change in general from 2022 to 2023? Was the change associated to harvest treatment or annual differences in weather? (Q1)

To answer the first question, I used the daily aggregated timeseries per plot (= 4 logger) of each site (Table 2). I further aggregated them into daily averages per site (Figure 6). This resulted in:

- Average daily mean solar radiation
- Average daily maximum air temperature
- Average daily minimum humidity
- Average daily maximum water temperature

meaning I had one value per day (31 days in July) for each site and each microclimate parameter. Then, I needed to assess, whether the effects of “Year” and “site” are significant for each microclimatic parameter and thus have an effect. Therefore, I build a linear mixed model using the lmer() function from the “lme4” package (Bates et al., 2015).. Example for radiation:

```
lmer.SR <- lmer( SR.mean ~ Year * site + (1|Day), data = df )
```

Then I used the Anova() function from “car” package (Fox & Weisberg, 2019). Thus, I know how significant the effect of the explanatory variables “Year” and “site” and their interaction was. The explanatory variable “Year” is not equivalent to the effect of the weather difference between these years but used to compare the before and after of each site, i.e., year 2022 is before and year 2023 is after harvest. The comparison of the control site 2022 vs. 2023 provides me with an estimate of how big the weather differences and the impact of the weather differences on each microclimate parameter were, without any treatment. This information can then be considered when I compare each treatment site with the control site. I added the random effect of “Day”. As each “Day” will have a specific weather condition, it can influence the daily microclimate variable. This can lead to a unhomogenised grouping of the response variable. With setting the “Day” as a random effect I overcame this problem.

To analyse whether the control and treatment sites differ, I used the emmeans() function from the “emmeans” package (Lenth, 2023). Using the pairwise specification and interaction between Year and site. For analysing whether the microclimate measurements changed significantly from before to after treatment. I used the same Linear Mixed Models I build previously. This time I only compared the two levels of "Year" within each level of "site". This allows for a lower p-value adjustment and therefore more precise results. I looked at the following comparisons for question one:

- Control site 2022 vs. control site 2023
- Each treatment site 2022 vs. control site 2022 (to see if they already differed significantly before treatment)
- Each treatment site 2023 vs control site 2023 (to see if they are now significantly different after treatment)

Question 2) What were the site-specific responses of microclimate to the harvesting treatment? (Q2)

In contrast to Q1, where I calculated site averages from the 4 (or 3 for humidity) loggers for each parameter, in Q2, I used each logger separately to depict within-site variations. Thus, I had up to four timeseries per year, one for each plot (logger) per site and microclimate parameter (Table 2 & Figure 6).

Then, I constructed a linear mixed model, for each microclimate parameter. Example of the solar radiation:

```
lmer.SR <- lmer(SR.mean ~ Year * site + Year * plot + (1|Day) + (1|site/plot),
data = df)
```

I added the random effect of "Day" (explained in Q1). As the plot layout is non-randomised, but grouped instead, it needs to be accounted for. So, I added the random effect plot per site, as each site contains multiple plots.

To analyse whether the plots changed from before and after treatment, I used the emmeans() function from the "emmeans" package. Using the pairwise specification and no interaction between Year, site and plot. Therefore, I got the results separately, comparing the before and after for each plot within each site.

Additionally, I visually analysed the daily aggregated timeseries for each plot within each site.

Question 3) Based on the observations in Q1 and Q2, are there conclusive recommendations that can be implemented into riparian buffer management? (Q3)

For the results of this question, I chose to only compare the changes of solar radiation, air temperature and relative humidity with the implementation of the plot-wise buffer management. These microclimate parameters have shown to be highly linked with buffer management, while water temperature is additionally influenced by overall changes of the catchment area (and cannot be directly linked to plot-scale changes related to management).

Further, based on the results from Q1 and Q2 I chose to take a deeper look at GC and VR treatments only, in Q3. Since at OS significant differences from the control site before treatment were identified, due to prior management practices and no significant changes of air temperature and relative humidity were observed after treatment, OS was excluded from the comparison. Within these sites I compared plots with significant changes to plots with unsignificant changes of the microclimate. This will help understanding the small-scale processes and influences on microclimate. I combined the microclimate results with measurements of buffer width and residual inventory of the buffer conditions. The buffer width was measured at plot location and on both sides of the stream. The residuals inventory added information about uprooted trees and stump count in both years separately. This gave insight into additional tree extraction during the final harvest or increased wind felling after treatment.

3. Results

3.1 Question 1) Control vs. treatment site changes

Solar radiation

The Anova () of the LMM shows that the explanatory variables “Year” and “site”, as well as their interaction have a significant effect (p-value < 0.001) on average of daily mean radiation (further only radiation). The control site shows a greater range of radiation in 2022 within the 25 and 75 percentiles than in 2023. Comparing the variation of the control site to the treatment sites, the control site has a lower standard deviation both years (Table 3). The difference of the average daily mean radiation in 2022 (36.0 W/m²) and 2023 (37.7 W/m²) at the control site is not significant (p-value > 0.6). The median of all treatment sites is higher, than of the control site during 2022 and further increased in all treatment sites in 2023 (Figure 7A). In 2022, GC (Gap-Cutting Treatment) and VR (Variable-Retention Treatment) are not significantly different from the control site (p-values > 0.1). But the solar radiation at OS (One-Sided Treatment) is significantly higher from the control site in 2022 (p-value < 0.05). In 2023, light increased significantly at all treatment sites in comparison to the control site (Table 3, Figure 7A). The solar radiation at VR and GC doubled, while the solar radiation at OS increased by 13 %. All treatment sites have a significantly changed light regime (p-value < 0.05) compared to their before state (Table 3). Additionally, the range of solar radiation increased at both VR (36 %) and GC (44 %).

During 2022 all sites show similar variability over time in solar radiation with OS and VR having the more extreme variations (Figure 7B & Table 3). During 2023, there are clear differences visible between the treatment sites and the control site. While the control site shows very little variability over time, the treatment sites have more variation (Figure 7B).

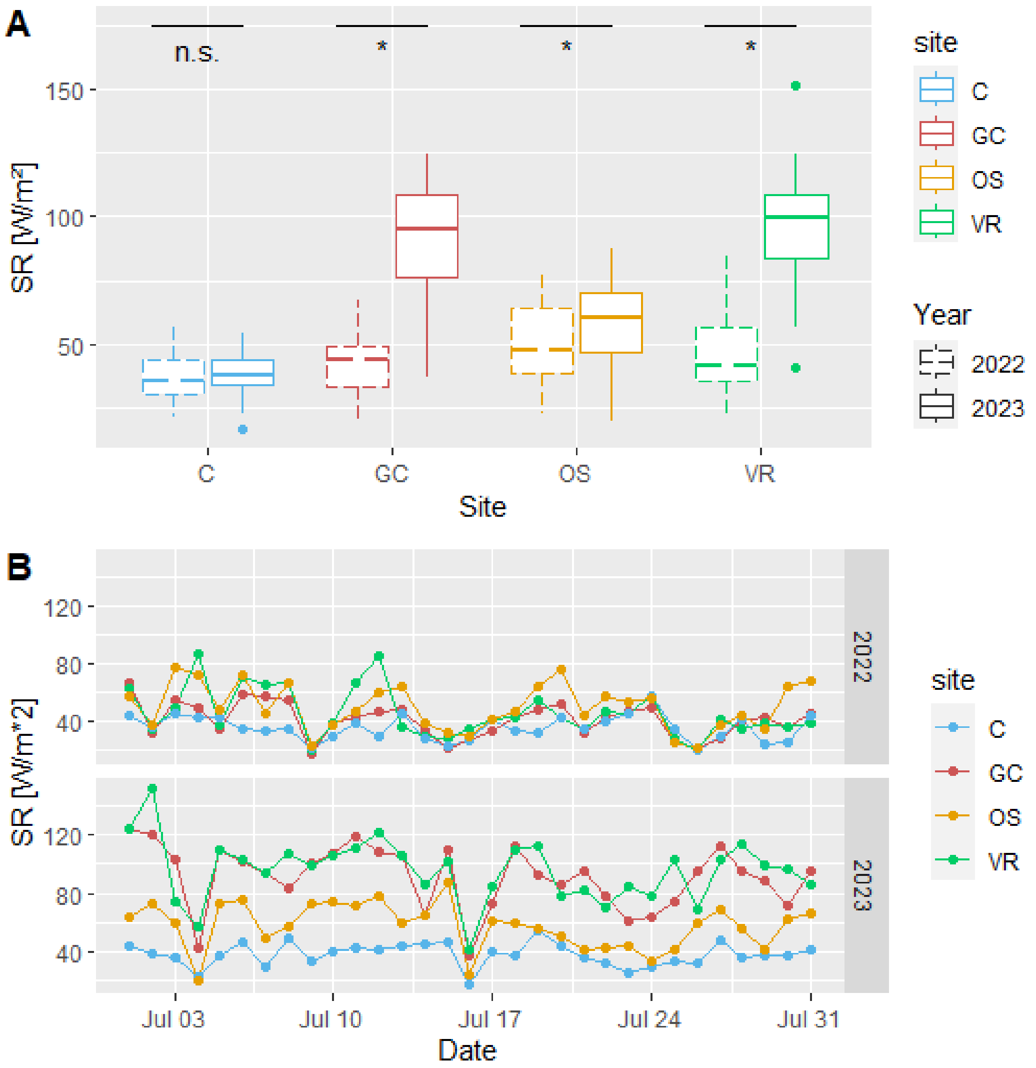

Figure 7: C – Control Site; GC – Gap-Cutting Treatment; OS – One-Sided Treatment; VR – Variable-Retention-Treatment.
*[A] Boxplots representing average daily mean solar radiation (SR) per site and year. Above symbols indicate whether the difference between before- treatment in 2022 and after-treatment/ no treatment in 2023 is significant. Codes: n.s. - not significant; * - significant.*
[B] Timeseries of the average daily maximum solar radiation per site and year.

Air temperature

The Anova () of the LMM shows that the explanatory variables "Year" and "site", as well as their interaction have a significant effect (p-value < 0.001) on average of maximum daily air temperature (further only air temperature).

Within the control site, there is a marginal increase in median average daily maximum air temperature from 2022 to 2023 (Figure 8A). The mean average daily maximum air temperature in 2023 was 0.2 °C higher at 20.1 °C than in 2022 with 19.9 °C. The difference between the two years 2022 and 2023 at the control site is not significant (p-value ~ 1). In 2022, the median at VR and OS are visibly higher than the controls site median (Figure 8A). Nonetheless, in 2022 only the air temperature at OS was significantly higher (p-value < 0.01) compared to the control site. In 2023 all treatment sites air temperature was significantly higher (p-value < 0.05) compared to the control site. At VR and GC, the maximum air temperature increased by 4 °C on average in 2023, which was a significant (p-value < 0.0001) change, compared to the before-treatment state. The decrease of –0.05 °C in 2023 at OS was not significant.

OS shows the highest peaks of average daily maximum air temperature during 2022 (Figure 8B). The standard deviation of GC and OS is highest with 4.6 °C in 2022. C has an SD of 3.6 °C and VR 3.0 °C. In 2023, all the treatment sites show similar variability over time with a SD ranging from 4.0 °C at OS and 4.5 at VR. The control site has the lowest average daily maximum air temperature with less variability and a SD of 2.9 °C (Figure 8B).

Figure 8: C – Control Site; GC – Gap-Cutting Treatment; OS – One-Sided Treatment; VR – Variable-Retention-Treatment.
*[A] Boxplots representing average daily maximum air temperature per site and year Above symbols indicate whether the difference between before-treatment in 2022 and after-treatment/ no treatment in 2023 is significant. Codes: n.s. - not significant; * - significant*
[B] Timeseries of the average daily maximum air temperature per site and year.

Humidity

The Anova() of the LMM shows that the explanatory variable "site", has a significant effect (p-value < 0.001) average minimum humidity in July (further only humidity). The variable "Year" and their interaction with "site" has no significant effect (p-value > 0.08).

Within the control site, there is a marginal decrease in median average daily minimum relative humidity from 2022 to 2023 (Figure 9A). The mean average daily minimum relative humidity in 2023 was 0.5 % lower at 64.7 % relative humidity than in 2022 at 65.2 %. The difference between the two years, 2022 and 2023, on the control site is not significant (p-value ~ 1). The median in 2022 of all treatment sites is lower than the median of the control site (Figure 9A). In 2022, the mean relative humidity at VR and GC is not significantly different (p-value > 0.5) compared to the control site. OS is on the edge of being significantly different, with a p-value of ~0.05. In 2023, only GC is significantly different from the control site (p-value < 0.01). In 2023, after treatment, the relative humidity at VR has decreased by 3.3 %. At GC, the decrease of 8.3% was significant (p-value < 0.01). The relative humidity at OS has increased by 2% after treatment (Table 3).

Both years, all sites show the same variability over time, with the control site having some more extreme peaks in 2022 and 2023 (Figure 9B). The standard deviation lowest at OS with 13.4 % both years. SD increased at C and VR in 2023 around 2% (Table 3).

Figure 9: C – Control Site; GC – Gap-Cutting Treatment; OS – One-Sided Treatment; VR – Variable-Retention-Treatment.
*[A] Boxplots representing average daily minimum relative air humidity per site and year. Above symbols indicate whether the difference between before-treatment in 2022 and after-treatment/ no treatment in 2023 is significant. Codes: n.s. - not significant; * - significant*
[B] Timeseries of the average daily minimum relative air humidity per site and year.

Water temperature

The Anova () of the LMM shows that the explanatory variables “Year” and “site”, as well as their interaction have a significant effect (p-value < 0.01) on the average of maximum daily water temperature in July (further only water temperature).

The control site shows a greater range of water temperature in 2022 within the 25 and 75 percentiles than in 2023 (Figure 10A). Furthermore, the water temperature range from the control site is lower than the range of the treatment sites in both years (Table 3). At the control site, there is a slight decrease in median average daily maximum water temperature from 2022 to 2023 (Figure 10A). The average maximum water temperature in July 2023 was 12.1 °C; 0.6 °C lower than in 2022 at 12.7 °C. The difference between the two years, 2022 and 2023, on the control site is not significant (p-value > 0.7). During 2022, the median at all treatment sites is higher, than at the control site (Figure 10A). Looking at the mean water temperature in 2022 all treatment sites have significantly higher water temperature than the control site (p-values < 0.001). Comparing the water temperature in 2023, VR is not significantly different (p-value > 0.3) from the control site. OS and GC are significantly different (p-value < 0.0001) from the control site. In 2023, OS shows an increase of the water temperature by 1.6 °C. The water temperature at VR decreased the most after treatment, by 1.9 °C, while the temperature at GC decreased by 1.2°C. The water temperature at all treatment sites changed significantly (p-value < 0.01) post-harvest.

When comparing the timeseries, C, VR and GC have little variation over time in 2022 (Figure 10B). During 2023, OS undergoes a sudden increase of the water temperature, not observable at other sites (Figure 10B). In 2023, OS has the warmest water temperature, followed by GC. C and VR have similar water temperature during the first two thirds of July. In the last third the water temperature at VR increases, while the control site preserves stable water temperatures. The standard deviation decreases at GC and OS by around 0.8 °C. At VR standard deviation increases slightly by 0.1°C (Table 3).

Figure 10: C – Control Site; GC – Gap-Cutting Treatment; OS – One-Sided Treatment; VR – Variable-Retention-Treatment.
*[A] Boxplots representing average daily maximum water temperature per site and year. Above symbols indicate whether the difference between before-treatment in 2022 and after-treatment/ no treatment in 2023 is significant. Codes: n.s. - not significant; * - significant*
[B] Timeseries of the average daily maximum water temperature per site and year.

Table 3: Comparison of average daily max/ mean/ min of each parameter, together with its standard deviation (SD). C – Control Site; GC – Gap-Cutting Treatment; OS – One-Sided Treatment; VR – Variable-Retention Treatment; SR – solar radiation. The significance results from the Linear Mixed Model are displayed as p-values. The ones displayed as bold are classified as significant (< 0.05). In column 3-6 the p-values are indicating the difference between before (Year 2022) and after/ no treatment (Year 2023) per site and parameter. Column 7-10 the p-values display the difference of before and after treatment measurements to the before and after measurements of the control site

site	*Year*	*Mean of average daily SR in W/m² (SD)*	*Mean of avg. daily max Air Temp. in °C (SD)*	*Mean of avg. daily min Humidity in % (SD)*	*Mean of avg. daily max Water Temp. in °C (SD)*	*Mean SR*	*Max Air Temp.*	*Min Humidity*	*Max Water Temp.*
C	2022	36.0 (13.1)	19.92 (3.6)	65.19 (14.5)	12.68 (1.0)	Below p-value displayed, comparing the difference of each parameter to the control site per year and site			
	2023	37.7 (14.4)	20.08 (2.9)	64.69 (16.6)	12.07 (0.6)				
	Difference	1.67 (p-value ~ 0.64)	0.16 (p-value ~0.86)	-0.50 (p-value ~0.8)	-0.61 (p-value ~ 0.11)				
GC	2022	41.3 (20.7)	20.52 (4.6)	61.01 (14.5)	16.38 (1.8)	0.8134	0.9978	0.8518	**<.0001**
	2023	91.2 (36.9)	24.55 (4.3)	52.68 (14.1)	15.22 (1.0)	**<.0001**	**<.0001**	**0.0018**	**<.0001**
	Difference	**49.97 (p-value < 0.0001)**	**4.03 (p-value < 0.0001)**	**-8.33 (p-value < 0.01)**	**-1.16 (p-value < 0.01)**				
OS	2022	50.1 (21.6)	23.19 (4.6)	56.19 (13.4)	16.09 (2.6)	**0.0024**	**0.0083**	0.0541	**<.0001**
	2023	57.6 (19.6)	23.14 (4.0)	58.18 (13.4)	17.71 (1.7)	**<.0001**	**0.0180**	0.3591	**<.0001**
	Difference	**7.51 (p-value ~ 0.03)**	-0.05 (p-value ~ 0.95)	1.99 (p-value ~ 0.05)	**1.62 (p-value < 0.0001)**				
VR	2022	45.8 (22.8)	20.83 (3.0)	59.27 (14.5)	14.83 (1.5)	0.1047	0.9727	0.4874	**<.0001**
	2023	95.8 (35.4)	24.70 (4.5)	56.00 (16.1)	12.90 (1.6)	**<.0001**	**<.0001**	0.0717	0.3790
	Difference	**49.97 (p-value < 0.0001)**	**3.87 (p-value < 0.0001)**	-3.27 (p-value ~ 0.3)	**-1.93 (p-value < 0.0001)**				

3.2 Question 2) Microclimate responses plot-wise

For the results of this question, I am presenting everything site-wise not per microclimate parameter, to get a better understanding of the effect of each treatment and site-specific processes. Most of the microclimate parameters are interacting with one other, so they are presented together.

The Anova () of the LMM shows that the explanatory variable "Year" and the interaction of "Year" with "site" or "plot" have a significant effect (p-value < 0.01) on daily mean radiation and daily maximum air temperature. The Anova () of the LMM's from daily maximum water temperature and daily minimum relative humidity show a significant effect of the explanatory variable "Year", as well as the interaction of "Year" with "site" (p-value < 0.01).

Control site

Plot-wise, the daily mean solar radiation did not change significantly from 2022 to 2023 (p-value < 0.05). The solar radiation in 2022 ranged from 28.1 W/m² in plot 2 to 46.3 W/m² in plot 8. In 2023, the lowest solar radiation was in plot 4 with 26.3 W/m² and the highest in plot 8 with 53.6 W/m² (Table 4). Both years plot 2 shows the lowest variation over time (SD = 7.7). In 2022, all plots show similar variation over time, while in 2023 plot 8 is more divergent in comparison to the other plots (Figure 11).

The mean daily maximum air temperature did not change significantly from 2022 to 2023 in any plot. All plots show similar variation over time, both years (Figure 11). All plots show higher standard deviation in 2022 than 2023 (Table 4).

During the humidity measurements there have been multiple logger failures at this site. Plot-wise comparison is therefore not available for plot 3 and 7. Plot 5 has no significant changes of the mean daily minimum relative humidity. The minimum relative humidity increased in 2023 as well as the standard deviation (Table). Both years the variation over time of all plots shows similar patterns (Figure 11).

In the water temperature timeseries, plot 2 is located the most downstream and plot 8 the most upstream. In 2022, plot 8 has the highest daily maximum water temperatures, followed by plot 6, 4 and 2, indicating downstream cooling (Figure 11 & Table 4). In 2023, plot 6 has a marginally lower water temperature than plot 4 (0.2 °C). Both years, all plots start into July with a relatively high water temperature, that decreases throughout the course of the month (Figure 11).

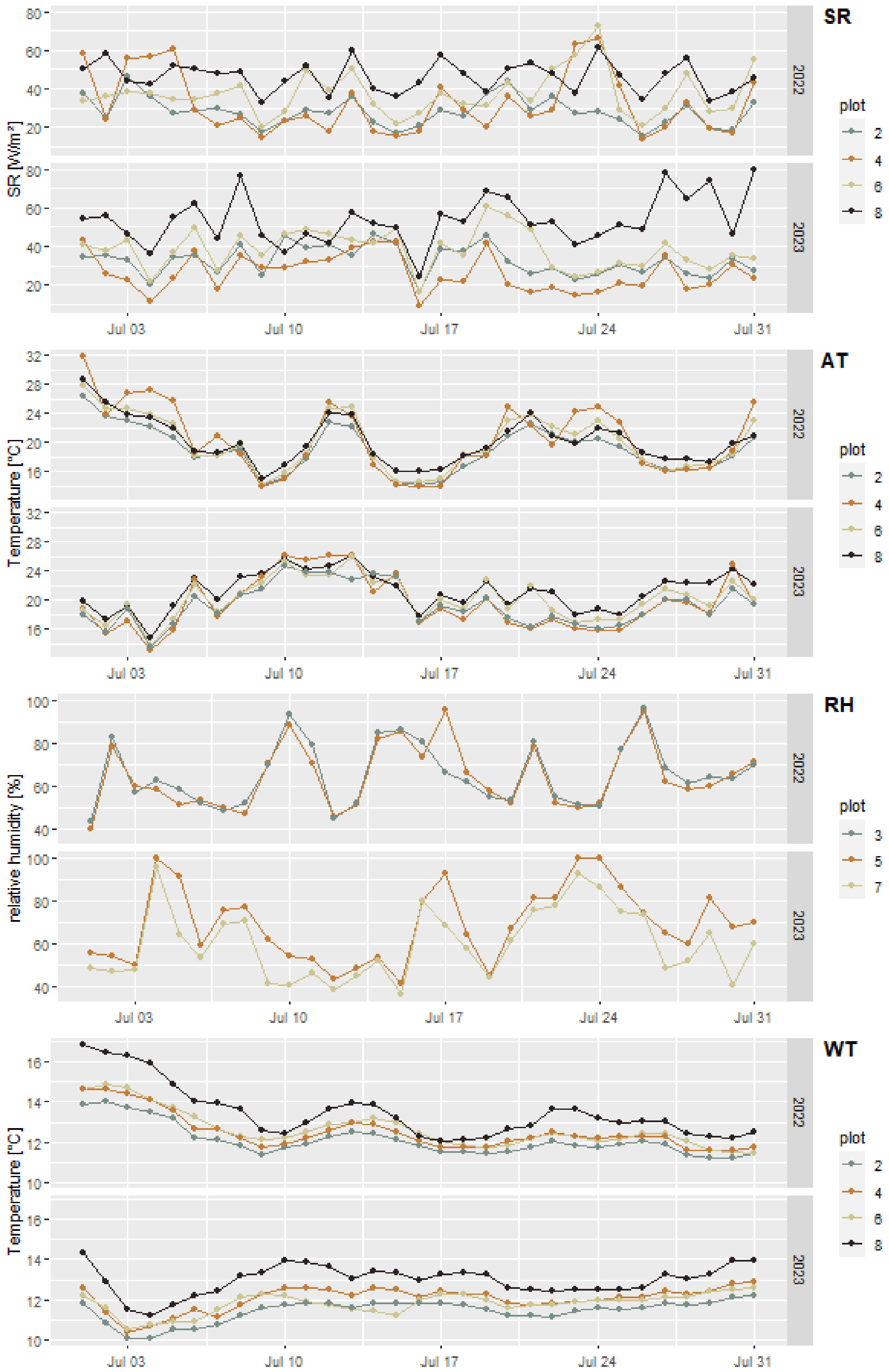

Figure 11: Timeseries of all four microclimate parameters at the control site per plot. SR - daily maximum solar radiation; AT – daily maximum air temperature; WT – daily maximum water temperature; RH – daily minimum relative humidity

Gap-Cutting Treatment

The daily mean solar radiation increased significantly (p-value < 0.0001) in all plots from before to after treatment. In plots 4, 6 and 8 also the air temperature increased significantly (p-value < 0.01). The largest increase in daily maximum air temperature is found in plot 4 (7.4 °C), where the solar radiation changed by over 40%. The largest solar radiation increase was 4.7 times in plot 8 (Table 4). Plots 6 and 8 had an increase in maximum air temperature by 4 °C. The overall variation over time in solar radiation is more divergent in 2023 (Figure 12). All plots show an increased standard deviation of solar radiation in 2023, while only plot 4 and 6 have higher standard deviation of air temperature (Table 4). The variation over time in air temperature is more similar in 2022 and more divergent in 2023 between plots (Figure 12).

The mean daily minimum relative humidity decreased significantly in plot 3 and 7 (p-value < 0.001). Plot 5 showed a smaller decrease (Table 4). The plots variation over time is more divergent in 2023 (Figure 12).

In the water temperature timeseries, plot 2 is located the most downstream and plot 8 the most upstream. Both years, plot 8 has the highest daily maximum water temperatures, followed by plot 6, 4 and 2, indicating downstream cooling (Figure 12 & Table 4). All plots had decrease (i.e., higher cooling) in mean daily maximum water temperature, with plots 2 and 4 being significantly different (p-value < 0.05). The magnitude of temperature decrease, increases the further downstream the plot is situated, meaning plot 8 shows the least decrease in water temperature, while plot 2 shows the most.

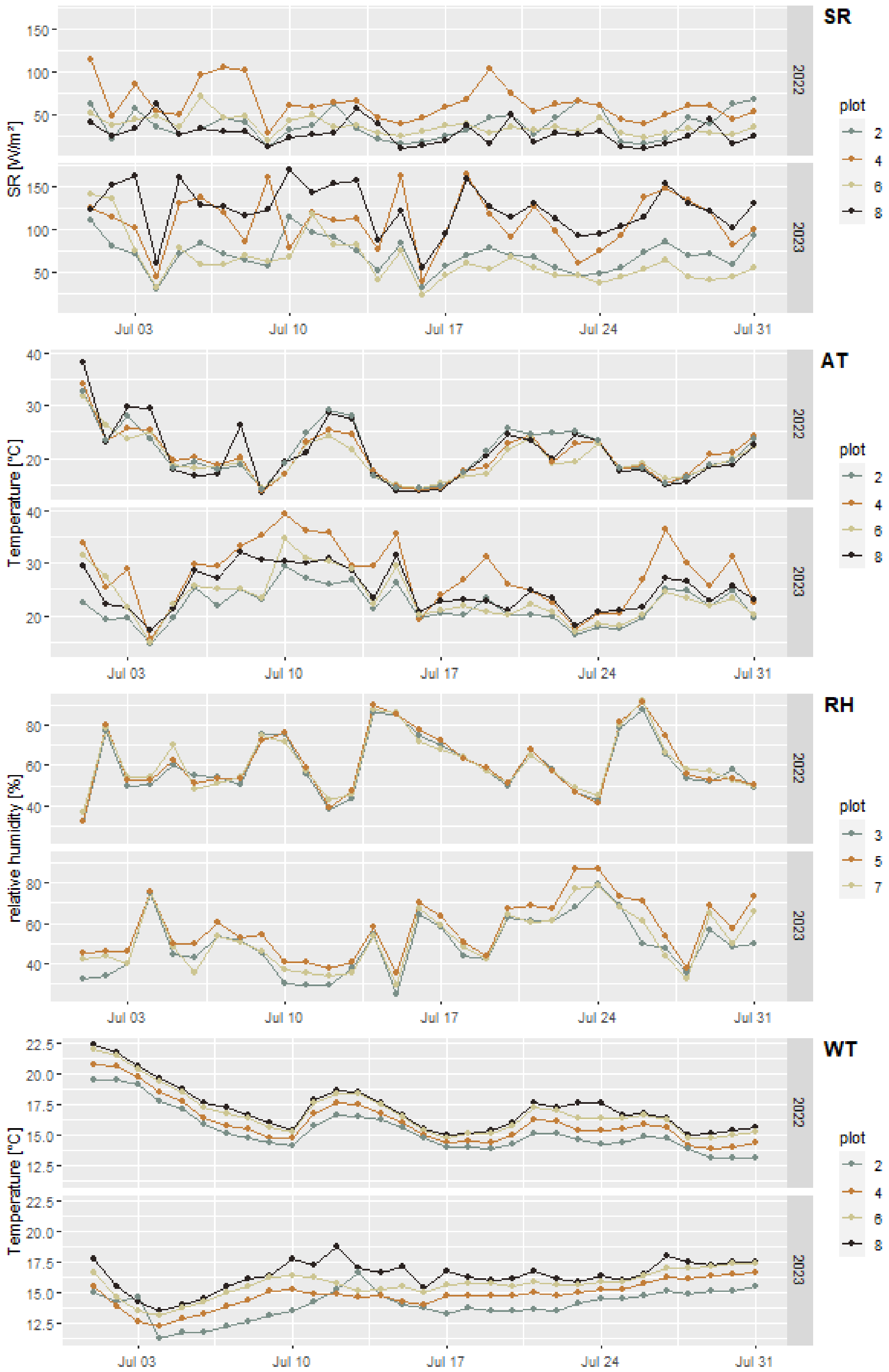

Figure 12: Timeseries of all four microclimate parameters at the Gap-Cutting Treatment per plot. SR - daily maximum solar radiation; AT – daily maximum air temperature; WT – daily maximum water temperature; RH – daily minimum relative humidity.

One-Sided treatment

At OS the variation over time in solar radiation and air temperature shows similar relations between the plots both years (Figure 13). This means plot 4 shows the highest solar radiation with 65 W/m^2 on average and highest air temperature with 25°C on average. Plot 4 is followed by plot 6 with 52 W/m^2 and 22°C on average and then plot 2 with 45 W/m^2 and 22°C on average. Solar radiation has increased in plot 2 and 6 and marginally decreased in plot 4. The changes of solar radiation, air temperature and relative humidity are not significant.

In the water temperature timeseries, plot 2 is located the most downstream and plot 6 the most upstream. In 2022, plot 6 has the highest daily maximum water temperatures followed by plot 2 and then plot 4, being only marginally cooler (Figure 13 & Table 4). In 2023, plot 6 has the highest water temperatures, followed by plot 4 and 2. Plots 2 and 6 had a significant increase in mean daily maximum water temperature ($p\text{-value} < 0.01$). The largest increase of 2.3 °C is in plot 4, followed by plot 2 with 1.5 °C increase and plot 6 with 1.1 °C. The steep increase in water temperature between July 20th and 21st 2022, already seen in Figure 10, is observable in all plots (Figure 13).

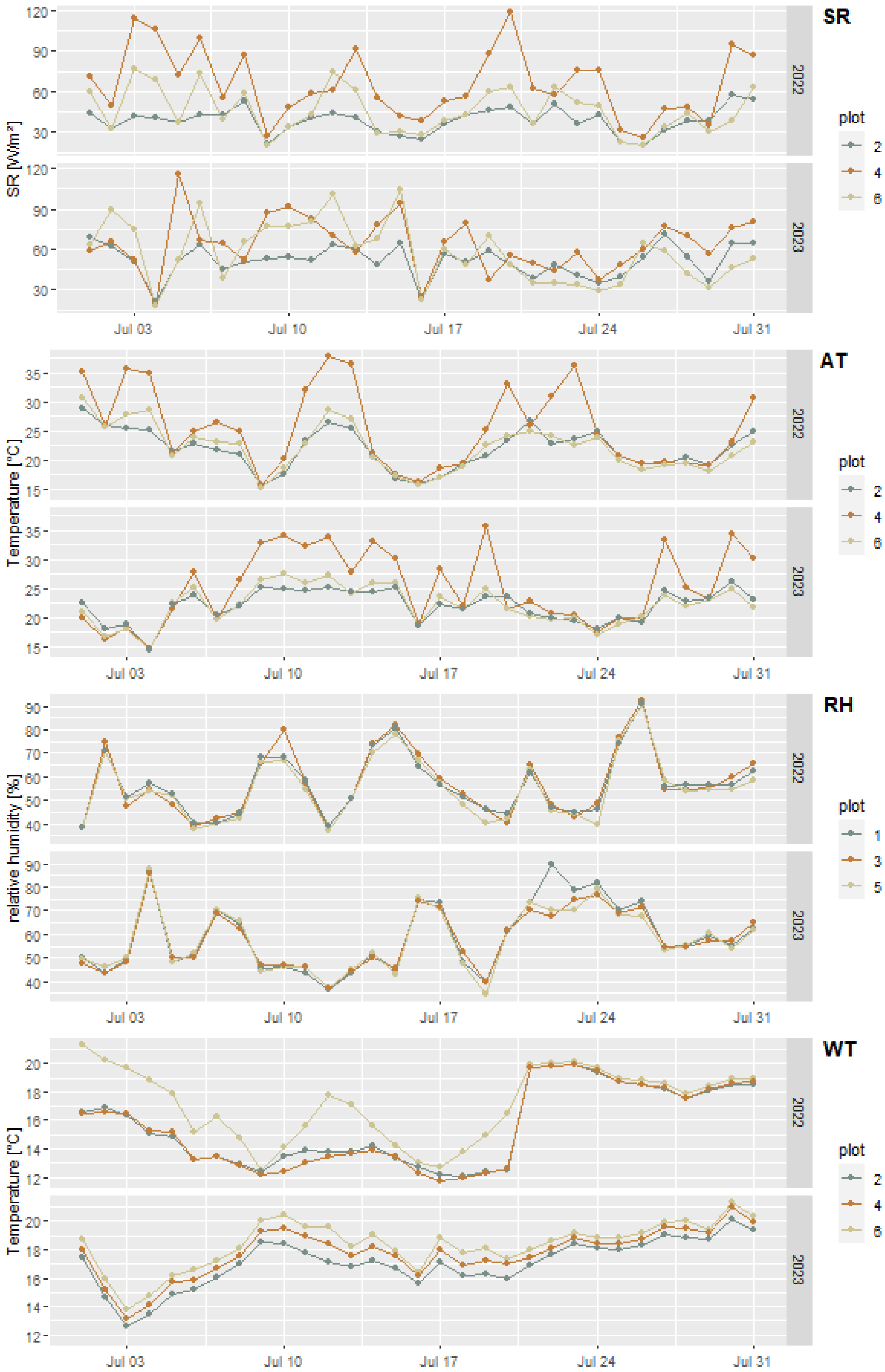

Figure 13: Timeseries of all four microclimate parameters at the One-Sided Treatment per plot. SR - daily maximum solar radiation; AT – daily maximum air temperature; WT – daily maximum water temperature; RH – daily minimum relative humidity

Variable-Retention treatment

The daily mean solar radiation increased in all plots significantly (p-value < 0.0001). The mean daily maximum air temperature increased significantly (p-value 0.01) in plot 2 and 4. The increase in plots 6 and 8 were marginal. The largest increase was in plot 2 for both radiation (80.8 W/m^2) and temperature (8.9 °C). Following is plot 4 with 43.0 W/m^2 radiation increase and 3.5°C temperature increase (Table 4). Plot 6 has an increase of 39.4 W/m^2 and 2.5°C. Plot 8 shows only a marginal temperature increase (0.7°C) with a radiation increase of 36.6 W/m^2. The plots variation over time is more divergent in 2023 (Figure 14).

During the humidity measurements there has been a logger failure in 2022 at plot 5. Plot-wise comparison is therefore not available for plot 5. Plot 3 has a significantly decreased mean daily minimum relative humidity (p-value < 0.05). The standard deviation increased marginally in plot 3 and 7. The variation over time is similarly divergent both years (Figure 14).

In the water temperature timeseries, plot 2 is located the most downstream and plot 8 the most upstream. Both years, plot 8 has the highest daily maximum water temperatures, followed by plot 6, 4 and 2, indicating downstream cooling (Figure 14 & Table). Plots 4, 6 and 8 had a significant decrease in mean daily maximum water temperature (p-value < 0.001), while the decrease in plot 3 was not significant. The magnitude of temperature decrease, decreased from plot 6 (upstream) to plot 2 (most downstream). The water temperature decreased from 1.2 °C in plot 2 up to 2.6 °C in plot 6. The magnitude of temperature decrease is marginally lower in plot 8 (2.1 °C) than plot 6 (Table 4).

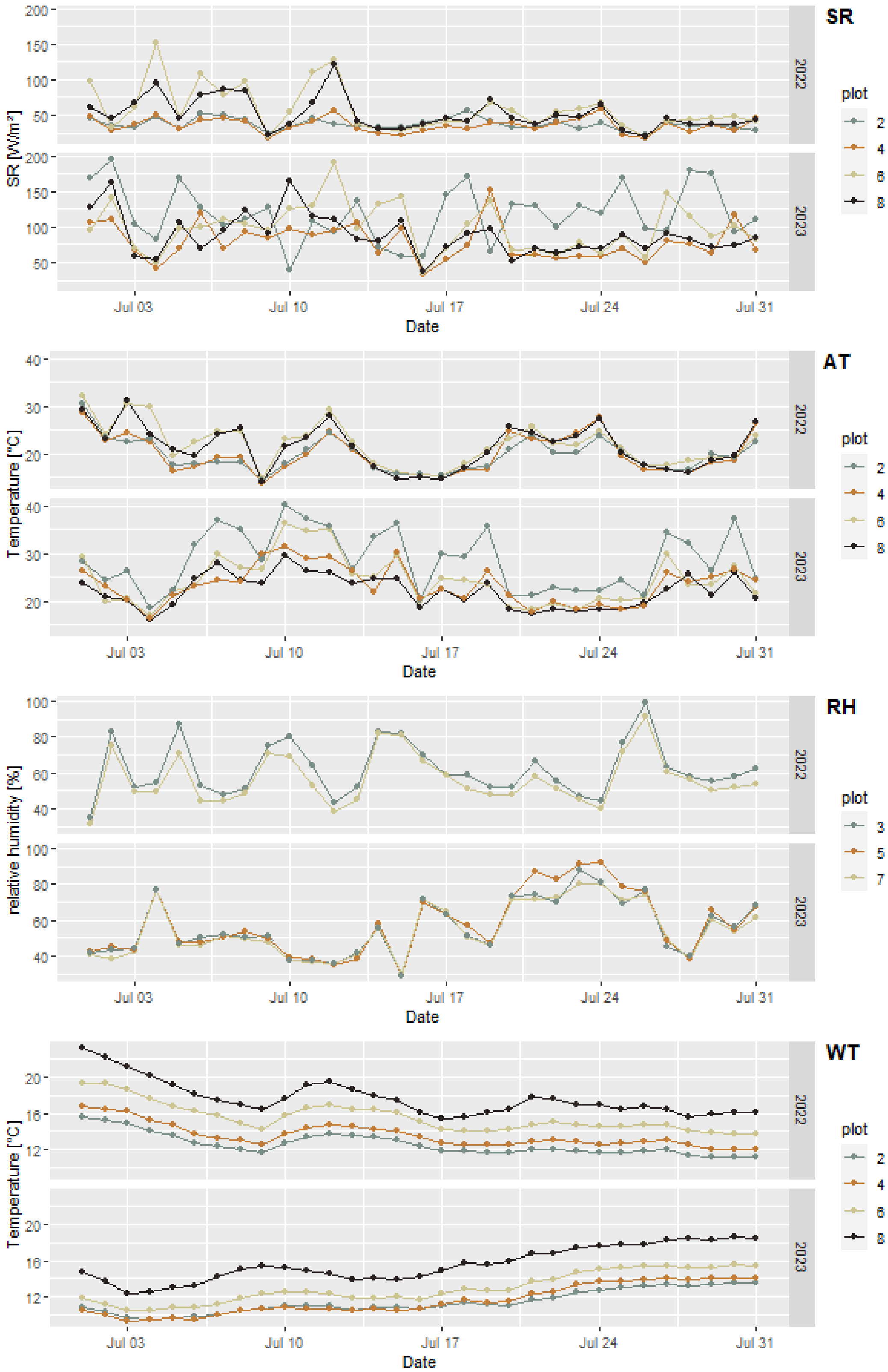

Figure 14: Timeseries of all four microclimate parameters at the Variable-Retention Treatment per plot. SR - daily maximum solar radiation; AT – daily maximum air temperature; WT – daily maximum water temperature; RH – daily minimum relative humidity.

Table 4: Plot-wise comparison of daily mean/ max/ min of each parameter before and after treatment per plot. C – Control Site; GC – Gap-Cutting Treatment; OS – One-Sided Treatment; VR – Variable-Retention Treatment. SR - solar radiation; AT – air temperature; WT – water temperature; RH – relative humidity. The significance results from the Linear Mixed Model are displayed as p-values. The ones displayed as bold are classified as significant (< 0.05).

site	*Plot*	*Year*	*Mean of daily mean SR[W/m²]*	*(SD)*	*Difference (p-value)*	*Mean of daily max AT [°C]*	*(SD)*	*Difference (p-value)*	*Mean of daily max WT [°C]*	*(SD)*	*Difference (p-value)*	*Plot*	*Mean of daily min RH [%]*	*(SD)*	*Difference in pp (p-value)*
C	2	2022	28.1	(7.6)	4.5	19.04	(3.12)	0.26	12.09	(0.78)	-0.65				
		2023	32.6	(7.7)	(0.9998)	19.30	(2.83)	(1.0000)	11.44	(0.55)	(0.9118)				
	4	2022	32.2	(16.1)	- 5.9	20.46	(4.76)	- 0.92	12.50	(0.89)	- 0.47	3	65.60	(14.67)	NA
		2023	26.3	(9.8)	(0.9966)	19.54	(3.66)	(0.9997)	12.03	(0.61)	(0.9954)				
	6	2022	37.5	(11.7)	0.8	19.98	(3.71)	0.21	12.63	(0.93)	- 0.81	5	64.79	(15.01)	4.4
		2023	38.2	(10.2)	(1.0000)	20.21	(2.82)	(1.0000)	11.82	(0.51)	(0.6878)		69.19	(17.39)	(0.1268)
	8	2022	46.3	(8.0)	7.3	20.20	(3.17)	1.06	13.48	(1.33)	- 0.51	7			NA
		2023	53.6	(12.8)	(0.9736)	21.26	(2.67)	(0.9985)	12.97	(0.73)	(0.9908)		60.19	(16.59)	
GC	2	2022	37.8	(16.9)	**32.6**	20.93	(4.92)	1.02	15.33	(1.75)	**- 1.34**				
		2023	70.4	(19.7)	**(<.0001)**	21.94	(3.50)	(0.9991)	13.99	(1.21)	**(0.0271)**				
	4	2022	63.0	(21.4)	**45.2**	20.50	(4.45)	**7.4**	16.09	(1.85)	**- 1.29**	3	60.29	(14.54)	**- 11.26**
		2023	108.3	(32.0)	**(<.0001)**	27.90	(6.08)	**(<.0001)**	14.80	(1.09)	**(0.0409)**		49.03	(14.27)	**(0.0001)**
	6	2022	36.4	(10.7)	**26.7**	19.82	(3.95)	**3.68**	16.89	(1.90)	- 1.21	5	61.48	(15.29)	- 4.27
		2023	63.1	(27.1)	**(<.0001)**	23.49	(4.58)	**(0.0086)**	15.68	(1.05)	(0.0783)		57.21	(14.60)	(0.1383)
	8	2022	27.8	(13.4)	**95.4**	20.83	(5.75)	**4.04**	17.21	(1.92)	- 0.81	7	61.26	(14.02)	**- 9.47**
		2023	132.2	(28.4)	**(<.0001)**	24.86	(4.11)	**(0.0018)**	16.40	(1.22)	(0.6861)		51.79	(14.26)	**(0.0011)**
OS	2	2022	38.7	(9.5)	12.9	21.92	(3.40)	0.14	15.59	(2.75)	**1.46**	1	56.50	(12.86)	2.52
		2023	51.5	(12.4)	(0.3282)	22.06	(2.81)	(1.0000)	17.05	(1.72)	**(0.0082)**		59.02	(14.74)	(0.3826)
	4	2022	65.6	(25.5)	- 1.9	25.56	(6.85)	- 0.28	15.50	(2.88)	**2.26**	3	57.06	(14.30)	0.77
		2023	63.8	(20.5)	(1.0000)	25.28	(6.35)	(1.0000)	17.76	(1.72)	**(<.0001)**		57.84	(12.55)	(0.7881)
	6	2022	45.9	(16.9)	11.5	22.10	(3.98)	- 0.01	17.18	(2.54)	1.14	5	55.02	(13.34)	2.68
		2023	57.4	(22.9)	(0.5207)	22.09	(3.36)	(1.0000)	18.33	(1.70)	(0.1311)		57.69	(13.27)	(0.3529)
VR	2	2022	37.5	(8.2)	**80.8**	19.79	(3.41)	**8.88**	12.58	(1.21)	- 1.16				
		2023	118.3	(40.0)	**(<.0001)**	28.67	(6.30)	**(<.0001)**	11.42	(1.30)	(0.1168)				
	4	2022	35.8	(10.7)	**43.0**	19.98	(4.07)	**3.49**	13.56	(1.31)	**- 1.94**	3	61.90	(14.94)	**- 6.11**
		2023	78.8	(25.7)	**(<.0001)**	23.48	(4.03)	**(0.0176)**	11.62	(1.64)	**(<.0001)**		55.79	(15.58)	**(0.0342)**
	6	2022	58.5	(32.4)	**39.4**	22.00	(4.52)	2.45	15.54	(1.60)	**- 2.57**	5			NA
		2023	97.9	(34.0)	**(<.0001)**	24.46	(5.16)	(0.3640)	12.97	(1.69)	**(<.0001)**		57.65	(17.75)	
	8	2022	51.6	(23.0)	**36.6**	21.53	(4.57)	0.66	17.66	(1.96)	**- 2.06**	7	56.65	(14.22)	- 2.08
		2023	88.2	(29.1)	**(<.0001)**	22.19	(3.48)	(1.0000)	15.60	(1.91)	**(<.0001)**		54.56	(15.16)	(0.4703)

3.3 Question 3) Management differences plot-wise

For the results of this question, I chose to only compare the changes of solar radiation, air temperature and relative humidity with the implementation of the plot-wise buffer management. These microclimatic parameters have shown to be highly linked with buffer management, while water temperature is additionally influenced by overall changes of the catchment area (and cannot be directly linked to plot-scale changes related to management). Based on Q1 and Q2, I chose to analyse GC and VR. OS has shown no significant changes of air temperature and relative humidity. C, as the control site, has been untreated. Within GC and VR, I will compare plots with significant changes to plots with unsignificant changes of the microclimate. This will help understanding the small-scale processes and their influences on microclimate.

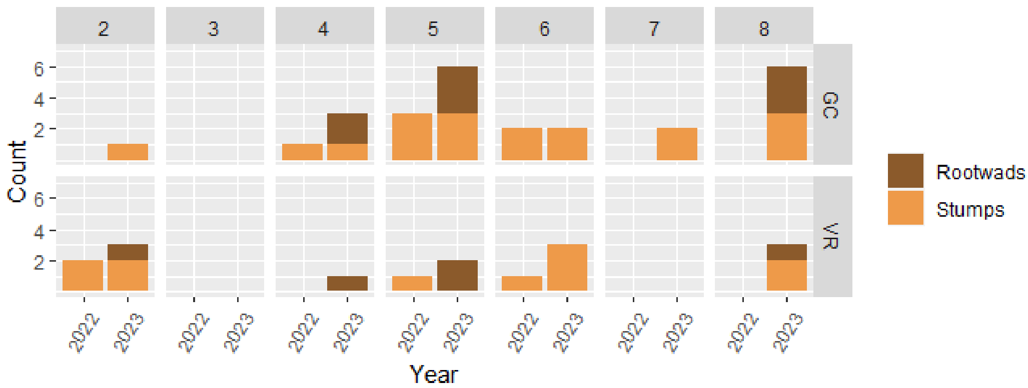

Figure 15: Changes in stump and rootwad count at GC - Gap-Cutting Treatment and VR - Variable-Retention Treatment per plot and year. Note: at GC, plot 3 does not show changes in stumps and rootwads but this plot was partially harvested to accommodate construction of a bridge to cross the stream. All the stumps were buried under the bridge. Thus, this plot experienced a large change in buffer treatment that cannot be seen in the stump and rootwad data.

Gap-Cutting Treatment

The average buffer width is 9 m on the west side and 8.4 m on the east side of the stream (Figure 3). The total (both sides combined) average buffer width is 17.4 m. The largest buffer is at plot 4 with a total of 27 m and the smallest buffer at plot 8 with no buffer on the westside and a 5 m buffer on the east side (Table 5). Generally, GC is the treatment site with the most rootwads, indicating that wind-felling occurred post-harvest. The largest increase of 3 stumps and 3 rootwads is seen at plot 8 (Figure 15). Followed by plot 5 with 3 additional rootwads and plot 4 with 2. Plot 3 is an exception regarding change, as the foresters had to build a bridge for stream crossing at that plot. Half of the 10x10 m plot was left with a 10 m buffer, while the other half was completely harvested. Plot 6 is the only plot experiencing no changes in the plot.

Variable-Retention Treatment

The average buffer width is 12.6 m on the west side and 27 m on the east side of the stream (Figure 5). The total average buffer width is 39.6 m. The largest buffer is at plot 8 with a total of 90 m and the smallest buffer at plot 7 with 6 m buffer on the westside and 18 m buffer on the east side (Table 5). The largest increase of 2 stumps and 1 rootwads is seen at plot 8 (Figure 15). Plots 2, 4 and 5 had one additional rootwad in 2023. Plot 3 and 7 experienced no changes.

Table 5: Aggregation of total differences between the two years, positive values indicate an increase; negative values indicate a decrease. SR - daily mean solar radiation; AT – daily maximum air temperature; WT – daily maximum water temperature; RH – daily minimum relative humidity. Bold numbers – parameter had a significant change (see Table 4 for more information). Bold and underlined plot number – at least one microclimate parameter changed significantly. Even plot numbers are located on the westside of the stream, uneven numbers on the east side.

site	*Plot*	*SR [W/m²]*	*AT [°C]*	*RH [pp]*	*Buffer-width, west side [m]*	*Buffer-width, east side [m]*	*Total [m]*	*Riparian buffer changes*
GC	**2**	**32.6**	1.02		10	11	21	+1 stump
	3			**- 11.26**	5	5 *	10	* Stream crossing was built, one half of plot has 10 m buffer, the other 0 m
	4	**45.2**	**7.4**		12	15	27	+2 rootwads
	5			- 4.27	15	10	25	+3 rootwads, situated at northern gap edge
	6	**26.7**	**3.68**		10	8	18	No changes
	7			**- 9.47**	6	10	16	+2 stumps, situated at southern gap edge
	8	**95.4**	**4.04**		5	0	5	+3 stumps and +3 rootwads, very small buffer
VR	**2**	**80.8**	**8.88**		8	24	32	+1 rootwad
	3			**- 6.11**	20	19	39	No changes
	4	**43.0**	**3.49**		12	15	27	+1 rootwad
	5			NA	14	18	32	+1 rootwad
	6	**39.4**	2.45		18	15	33	+2 stumps,
	7			- 2.08	6	18	24	No changes
	8	**36.6**	0.66		10	80	90	+2 stumps and +1 rootwad

4. Discussion

4.1 General microclimate changes

In this thesis, I aimed to fill a knowledge gap about microclimate changes as a result of final harvest of forests adjacent to riparian buffers, which were treated with different management approaches. Comparing the differences between 2022 and 2023 in microclimate of the control site, where no treatment was applied in July, can indicate the impact in “macro” weather outside the forest environment changing microclimate of the riparian zone.

The control site did not show significant changes in solar radiation, air temperature, relative humidity, and water temperature between the two years. This suggests that changes at the treatment sites occurred due to final harvesting and buffer management. Nonetheless, it needs to be mentioned that microclimate did show variation over time.

Solar radiation and air temperature

In 2022, GC (Gap-Cutting Treatment) and VR (Variable-Retention Treatment) showed no significantly different solar radiation and air temperature, compared to the control site. OS (One-Sided Treatment) was already significantly different in temperature and radiation, from the control site before treatment. In 2018, OS was harvested on the south-western side of the stream and left with an average riparian buffer of 5 m. Previous research has shown that buffers of 5 m width are not enough to protect the riparian and aquatic ecosystems (Chellaiah & Kuglerová, 2021). All the study sites are in the same region, have similar forest condition before the harvest and are small headwater streams, thus their starting conditions were assumed to be very similar. But at OS, the higher radiation and temperature already in 2022 indicates that even though forest was still intact on one side of the stream after the harvest in 2018, from my results it is obvious that the application of such narrow buffer on one side did cause substantial changes in the microclimate on the side of the stream where forest was retained. This is in line with findings of Oldén et al. (2019) where mean and maximum air temperature increased in the riparian buffer, due to harvesting on opposite stream side.

After treatment, all treatment sites, including the previously impacted OS site, showed a significantly increased radiation, compared to before. The solar radiation in VR and GC doubled, while solar radiation in OS increased by 13 %. Harvesting in adjacent forests has shown to increase solar radiation of the remaining forest towards the edge (Chen et al., 1995). In a Norway Spruce dominated forest in Västerbotten (Northern Sweden), Renhorn et al. (1996) found a 38 % higher solar radiation at the forest edge (2 m) than in the interior forest.

Increased light availability can lead to higher species richness in forests with a high canopy cover (Schmiedinger et al., 2012). Hofman (2023) described that a higher species richness in nature reserves in northern Sweden was partially explained by more light availability. Complementary, Oldén et al. (2019) found an increase in the moss *Polytrichum commune* with more light availability as the growth of *P. commune* is limited by light availability (Callaghan et al., 1978). More light availability can additionally increase primary production in aquatic ecosystem, which in production forests are often limited by light not nutrient availability (Myrstener et al., 2023; Warren et al., 2017). On the other hand, a sudden increase of light directly on the stream can cause growth of unwanted filamentous algae (Myrstener et al., 2023). Further, a change in exposure to sunlight can decrease the growth of poikilohydric organism at the edge (Hylander, 2005).

The increase in solar radiation can lead to higher daytime air temperature towards the edge (Chen et al., 1995). This research is supported by my findings, where the clearcut of the adjacent forest caused a significant increase of maximum air temperature during July at VR and GC of approximately 4°C. These results are comparable with the findings from Rykken et al. (2007) in the Pacific Northwest, where in a 30 m riparian buffer both sides of the stream, they observed an increase over 3°C of maximum air temperature in the first 10 m from the stream. Oldén et al. (2019) noted even greater maximum air temperatures increases of 5.6°C, when a 15 m buffer was additionally selectively harvested. It needs to be considered, that these extreme values may not be directly comparable to average values reported in other studies, such as Brosofske et al. (1997) where they found an average increase by 3°C, after final harvest, or Renhorn et al. (1997), where the edge-interior temperature gradient was usually less than 1°C.

The importance of air temperature for biota, such as bryophytes is often interconnected with relative air humidity and solar radiation, where frequent days with high temperatures, little rain and low humidity will influence the survival rate of bryophytes (Dahlberg et al., 2020; Koelemeijer et al., 2023; Man et al., 2022). Further, air temperature is one of the factors that affects the upper soil layers and their soil temperature (Jungqvist et al., 2014). Soil temperature controls biogeochemical processes such as mineralization rates or forest productivity (Haei et al., 2013; Rustad et al., 2001; Stromgren & Linder, 2002).

Humidity

VR and GC were not significantly different from the control site in 2022. OS was close to being significantly different (p-value ~ 0.05) from the control site. OS showed a lower minimum relative humidity than the other sites before treatment. Similar to the air temperature, Oldén et al. (2019) found a decrease of mean and minimum humidity from harvesting on the opposite site of the stream. At OS, a marginal increase (1.99 pp) of humidity was noted. After final harvest, soil moisture and groundwater levels usually increase due to decreased interception and transpiration, leading to possible higher evaporation and relative humidity (Ploum et al., 2021). This could be a partial explanation for a minimum relative humidity increase.

Only the Gap-Cutting design led to a significant decrease of minimum humidity by 13.6% (8.3pp) after the treatment, but VR also experienced a decrease (by 3.3pp; 5.5%). The buffer at VR was designed as a hydrologically adapted buffer, leaving wider strips in areas with higher moisture content and narrower strips in drier areas. Thus, moist areas were better protected at VR, and this probably prevented more pronounced changes in air humidity (Hide, 1954; Vargas Zeppetello et al., 2019). Because of the buffer design at GC, the riparian buffer strips left will have a higher interior forest-to-edge ratio than the buffer left at VR. These differences in buffer design likely explain the greater impact on microclimate at GC. Decreases in relative air humidity due to higher daytime temperature in a forest adjacent to a clearcut have been found in earlier studies (Brosofske et al., 1997; Chen et al., 1995; Oldén et al., 2019). A similarly strong decrease was reported by Rykken et al. (2007) in a 30m buffer on both sides of a stream, where they observed a humidity decrease of 15% within 10 m of the stream edge. Other studies reported a decrease between 9-11% (Brosofske et al., 1997; Welsh et al., 2005). Oldén et al. (2019) found a significant decrease in daily minimum humidity in 15m buffers but did not find a significant decrease in daily minimum humidity in a 30 m buffer. The mean humidity was 8.1% lower after harvest and the minimum humidity 19.0% lower.

Relative humidity changes are especially problematic for poikilohydric species. For example, the mosses *Hylocomium splendens* and *Pseudobryum cinclidioides* have no internal water conducting system and dry out due to decreases in relative humidity, potentially even if the soil moisture content is high (Callaghan et al., 1978; Oldén et al., 2019; Perhans et al., 2009; Stewart & Mallik, 2006).

Water temperature

The results have shown, that generally in both years, the longitudinal course of the four streams show a decrease in water temperature from the most upstream logger (plot 8) to the most downstream logger (plot 2), i.e., downstream cooling. This trend is aligned with the findings of Leach et al. (2017), who found that headwater streams with an upstream lake experience longitudinal cooling. Interestingly, the 3 treatment sites in my thesis had all an upstream lake, and the control site had an upstream wetland (also acting as a source of warmer water during the warmest month). As such, the results of the water thermal regimes before and after treatment have to be taken with consideration of the upstream source. As the downstream cooling trend is seen both years in my study, the effect of the upstream source, but also the catchment area and groundwater inflow, are considered to have superordinate impact on the water temperature, in comparison to the impact of the riparian management (Martin et al., 2021; Moore et al., 2005). Therefore, I describe all the findings for water temperature in the following segment and will not focus on water temperature in the buffer treatment-specific section.

All treatment sites had significantly higher maximum water temperatures than the control site in 2022. This indicates pre-existing site differences. The control site shows the lowest range of variation in water temperature both years. Additionally, the site has the lowest maximum water temperatures 2022 (12.1 °C) and 2023 (11.4°C). The control site is originating from a wetland. The treatment sites are all originating from lakes. The surface runoff from lakes and wetland is considered to increase the average water temperature in downstream streams during summer months (Leach et al., 2017; Rayne et al., 2008). Nonetheless, the water temperatures at the treatment sites originating from lakes are 2-4°C higher before harvest, compared to the control site, which originated from wetlands.

Wetlands typically have a higher latent heat flux, than open water bodies such as lakes, as they lose energy from evaporation as well as transpiration and water under emergent vegetation is partially shaded (Semadeni-Davies, 2009). This could partially explain, why the control site with an upstream wetland has lower maximum water temperatures. Further, the runoff from wetlands is considered to be low and steady, due to a slow water release ability (Fossey et al., 2016). Especially the occurrence of several wetlands in smaller sizes has shown to decrease base flow variation. This could possibly decrease energy fluctuations into downstream streams (McLaughlin et al., 2014).

The water temperature in all treatment sites changed significantly after the final harvest. The water temperature at VR decreased by 1.9°C after treatment, while the temperature at GC decreased by 1.2°C. At OS water temperature increased by 1.6°C. This suggests that all treatments had a significant impact on the water temperature. A decrease in water temperature is associated with increased inflow of cooler groundwater after final harvest (Kibler et al., 2013; Moore et al., 2005). Kibler et al. (2013) observed a temperature decrease up to 1.5 °C. The larger decrease at VR could be due to the bigger clear-cut size (22.51 ha), than at GC (15.14 ha). Interestingly, at GC the magnitude of temperature decrease, increases the further downstream the plot is situated, meaning plot 8 shows the least decrease in water temperature, while plot 2 shows the most. This could mean at GC the inflow of cooler groundwater increased within flow direction longitudinally.

Previous studies found an association between increased water temperature after harvest (as observed at OS) and increased solar radiation and warming of shallow groundwater in clearcuts. (Bourque & Pomeroy, 2001; Johnson & Jones, 2000). Furthermore, an increased exposure to radiation, due to canopy removal, can increase the water temperature (Moore et al., 2005). It needs to be considered, that the daily extreme values measured in this thesis, may not be directly comparable to observations in other studies, where they calculated mean weekly maximum and weekly mean temperatures. Nonetheless, in other studies they found an increase in water temperature after final harvest ranging from 0.3 - 0.7°C weekly mean temperature to 5.4-6.4°C mean weekly maximum temperature (Bourque & Pomeroy, 2001; Johnson & Jones, 2000).

Although the final harvest had varying effects on the water temperature at all sites, the downstream cooling effect continued after treatment. This finding supports previous research, where streams with a lentic source are less susceptible to harvest influences, as they continuously experience downstream cooling, whereas cooler streams with a lotic source have more capacity to heat up after harvest (Leach et al., 2022; Zaidel et al., 2021). Longitudinal increases in water temperature due to harvest are more critical for species with an upper thermal threshold further downstream (Swartz et al., 2020; Wagner et al., 2024).

Additional information about groundwater levels in the clearcut, groundwater temperature at the clearcut and in the riparian zones, as well as the temperature of the runoff from the upstream lentic sources would be necessary to understand water temperature dynamics of the catchment area.

4.2 Treatment specific changes and management implications

All sites experienced wind felling, identified by an increase in uprooted trees. The probability of wind damage is dependent on local conditions, as well as tree and stand characteristics (Maher Hasselquist et al., 2021). In Sweden, 70% of sites harvested 2-8 years prior to an inventory, were partly influenced by wind felling (Kuglerová et al., 2020). Most stands in this study were dominated by Norway spruce and large Norway spruce trees are especially susceptible to wind throw (Zeng et al., 2004). The risk of wind damage should be considered during buffer design planning. To a certain extent wind throw has a positive impact on the function of riparian zones to provide deadwood (Andersson et al., 2013; Kuglerová et al., 2023). Nonetheless, frequent and excessive wind throw could counteract microclimate mitigation efforts and increase sediment inputs into the stream (Kuglerová et al., 2023).

Gap-Cutting treatment

The solar radiation increased significantly in all plots from before to after treatment. In plots 4, 6 and 8 also the air temperature increased significantly. A 10 m buffer was left at plot 2, with additional 11m on the opposite side of the stream. The orientation of the clear-cut towards the north of the plot could decrease the exposure of the plot to solar radiation and changes in air temperature from the clear-cut, leading to a low, albeit significant change of solar radiation (32.6 W/m²) and no significant change in air maximum air temperature (1°C). Plot 4 showed the highest increase in air temperature (7.4°C). The 12m buffer on the plots side and the total buffer of 27m was not enough to prevent microclimate changes. Plot 4 is additionally situated in the middle of the clearcut, so the furthest away from the surrounding forest, and relatively close to one of the gaps. The buffer strip around plot 4 is therefore exposed to increased radiation from all directions. This could partially explain the strongest microclimate changes. The buffer width at plot 8 (5 m) and plot 6 (18 m) were also insufficient to protect local microclimate. Additionally, plot 8 had three rootwads more in 2023, indicating wind felling and thus loss of tree cover (Kuglerová et al., 2023). Plot 3 and 7 showed a significant decrease in humidity. At plot 3 half the plot was harvested to build a stream crossing, exposing half of the plot to solar radiation. This is the strongest decrease in humidity found in all sites and plots. Plot 7 is situated directly on the southern edge of the buffer strip, next to the gap. The combination of the southern aspect of the edge and an insufficient buffer width of 16 m total could explain the significant humidity decrease. Plot 5 has not decreased significantly, although three more rootwads occur after treatment. The plot is situated on the northern edge of the left buffer strip. The combination of the northern aspect of the edge and the total buffer width of 25m could explain this smaller decrease.

The Cap-Cutting design increases edge to interior forest ratio, especially, if the gaps are not surrounded by riparian forest, but more so dividing buffer strips from each other. This design was inappropriate to prevent significant microclimate change. However, gap cutting approaches are often used to promote light variability and structural heterogeneity, simulating disturbance regimes in late-successional forests (Parker et al., 2002; Van Pelt & Franklin, 1999). This form of disturbance is often supressed by management (Chellaiah & Kuglerová, 2021). If the objective is to promote heterogeneity and retain some microclimate refugia the size and placement of the gaps might be relevant as diversity of riparian forests is spatially heterogeneous (Kuglerová, Jansson, et al., 2014; McClain et al., 2003). Further, retention patches with dense understory vegetation experience a dampened edge effect (Heithecker & Halpern, 2007). Thus, it could be suggested to additionally tailor gap placement accordingly.

Another possibility to enhance light variability would be selective logging (removal of e.g., 30% of the tree basal area) in the buffer, that has shown to have less impact on air temperature and humidity, than halving the buffer width (Oldén et al., 2019). Further, even small gaps created through the extraction of a few trees can have a collective influence on forest structure (Spies & Franklin, 1989). Generally, the partial harvest of the riparian zone by single tree selection or gap cutting, can compensate for an economical loss from wider retention left (Kuglerová et al., 2020, 2023).

One-Sided treatment

The changes of solar radiation, air temperature and relative humidity are not significant. There is overall a marginal increase in radiation and humidity but decrease in air temperature. The site has an average buffer width of 25.3m. OS has been harvested on the south-western side of the stream in 2018 and left with an average 5 m buffer. The solar radiation and air temperature had been significantly different from the control site in 2022, before treatment (discussed above). The average buffer of 20.3m left, after treatment, on the north-eastern side of the stream has potentially prevented further air temperature and humidity changes. However, from a microclimate perspective, this raises a question, whether species sensitive to microclimate changes might have already declined or even disappeared, and the implementation of a generous buffer possibly has been uneconomic and unfit to this particular site (Oldén et al., 2019). On the other hand, it needs to be mentioned that the retention of wider buffer serves several other functions that shouldn't be neglected (Kreutzweiser et al., 2008; Kuglerová, Ågren, et al., 2014).

The fact that some plots with a one-side buffer width of 10 – 18m did not experience any solar radiation and air temperature increase, but others with similar width did, suggests that width alone is not necessarily the "one and only" important variable to prevent microclimate changes. So other influences should be considered as well, when designing a buffer concept. Frequently discussed influences are main wind direction, wind speed, aspect of the edge, topography, tree species composition, forest density and understory vegetation (Brosofske et al., 1997; Chen et al., 1995; Oldén et al., 2019; Rykken et al., 2007).

Variable-Retention treatment

The daily mean solar radiation increased in all plots significantly. The mean daily maximum air temperature increased significantly in plot 2 and 4. The increase in plots 6 and 8 were marginal. The largest increase was in plot 2 for both radiation (80.8 W/m²) and temperature (8.9 °C). Although the total buffer width is 32 m, the outer 2 m of the plot were harvested, leaving an 8 m buffer and therefore allowing for solar radiation to penetrate far into the plot. Thus, entailing an air temperature increase. The buffer width of 12 m (total 27 m) at plot 4 was also insufficient to mitigate maximum air temperature increases of 3.5°C. Plot 6 had an additional 5 m, so 18 m on the plot side of the stream and only experienced a temperature increase of 2.5 °C. Plot 4 and 6 experienced a similar radiation increase of approximately 42 W/m². Interestingly, plot 8 had no significant air temperature change, although the buffer surrounding the logger on the westside is only 10 m wide and there was an increase of two stumps and one rootwad (indicating decrease in forest cover in the plot). The total buffer is 90 m wide. This does not necessarily align with the assumption, that southwest facing riparian edges will have an increased edge effect (Chen et al., 1995; Moore et al., 2005). Plot 3 has a significantly decreased mean daily minimum relative humidity. The 19 m buffer width on the plots side of the stream was not wide enough to avert humidity changes, although the total buffer width is 39 m. Plot 7 a marginally decreased humidity.

Interesting to note is that especially at VR buffer widths were created considerably wider than what is commonly seen in practice (<5 m width), but nonetheless were insufficient to mitigate maximum air temperature and minimum humidity changes (Kuglerová et al., 2020). Possibly a wider minimum buffer width than 6 m would have been necessary as a baseline for this design to protect microclimate.

Nonetheless it needs to be considered, that the plots experiencing no significant changes of air temperature or humidity have a buffer width ranging from 10-18 m on the plot side (total 24-90 m). Plots with significant changes range from 8-19 m on the plot side (total 27-39 m). These inconsistent results emphasise, that buffer width is an ill-fitted guideline that is administratively simple to recommend, but scientifically not fully supported (Richardson et al., 2012).

The Variable-Retention design was based on the approach of hydrologically adapted buffers. These are designed to take into consideration groundwater discharge areas, where riparian forests are extending further from the stream into the upland forest (Kuglerová, Ågren, et al., 2014). Groundwater discharge areas are recognised to support erosion control, removal of groundwater transported nitrogen as well as phosphorus and possibly increase carbon sequestration (Hickey & Doran, 2004; Kuglerová, Jansson, et al., 2014; Olsson et al., 2009). Further, groundwater discharge areas have been found to host higher plant species richness (Kuglerová, Jansson, et al., 2014; McClain et al., 2003). Thus, it would be interesting to compare the findings of microclimate changes with vegetation surveys to evaluate the ecological consequences of air temperature increase and relative humidity decrease in groundwater discharge areas.

4.3 Study limitations and implications for future research

Overall, this thesis has studied small headwater streams in boreal forest, which means conclusions can not necessarily be applied in other riparian forests. Further, when interpreting the results the limitations of the study design have to be considered. The temperature logger simultaneously measured radiation and therefore was not shielded from direct sunlight. Sun shields can prevent overheating of the logger capsule, and non-shielding led probably to inaccurate measurements. The solar radiation measurements give a high temporal resolution of changes in light availability over a small, point-based location. This data can be used to understand energy fluxes. Nonetheless, for interpreting changes in habitat structure due to harvest treatments additional measurements with a camera to calculate canopy openness over a broader area might be insightful.

Evaluating vegetation surveys will help understanding the ecological consequences of microclimate changes. Additionally, in-depth analysis can improve the interpretation of plot-wise microclimate responses. Measurements of wind direction, edge aspect and understory vegetation density are main drivers of microclimate changes due to “Edge-Effect” (Brosofske et al., 1997; Chen et al., 1995; Oldén et al., 2019; Rykken et al., 2007). Further contributing factors are species composition, precipitation, soil moisture and macroclimate (Davis et al., 2019; De Frenne et al., 2019; Greiser et al., 2024). Microclimate buffering in forest environments is described by lower daytime temperatures and higher nighttime temperatures (De Frenne et al., 2019, 2021; Greiser et al., 2018). In further studies daily fluctuations, before and after treatment can be analysed to showcase changes in buffering capacities for both daytime maximum and nighttime minimum temperatures. A decrease in nighttime temperatures due to reduced buffering capacity of the riparian zone could increase the risk of frost damage of re-foliating leaves (Augspurger, 2011). Moreover, analysing microclimate responses during spring and autumn time would be relevant. The focus on microclimate changes would differ as seasons with frequent temperatures below 0°C have other effects on biota than frequent warm and dry days.

5. Conclusion

This thesis has presented a case study, showing the influences of final harvesting on riparian zone microclimate due to different buffer management approaches during the month of July 2023.

I identified treatment specific differences in the response of riparian microclimate to the harvest of the adjacent forest. The Gap-Cutting treatment increased solar radiation and air temperature significantly. Further it decreased relative humidity significantly. Leaving variable retention tailored to a soil moisture map led to a significantly increased solar radiation and air temperature. The site that was harvested on one side prior to this research project and left with a narrow buffer (5 m), showed differential prerequisites as higher solar radiation and air temperature. Water temperature decreased in two of the examined sites and increased in one after final harvest. The riparian management showed subordinate influence on water temperature, in comparison to the hydrological regime.

Plot-wise comparisons revealed small scale heterogeneity of microclimate responses. Aspect of the edge, location of the plot within the clearcut and buffer width on the opposite side of the stream seemed to influence the magnitude of microclimate change. Nonetheless, buffer width alone was an insufficient parameter to explain changes in microclimate.

This led to the conclusion that small scale heterogeneity of the microclimate response derives not only from variation within each treatment but additionally from small scale heterogeneity that is site-specific. Therefore, riparian management aimed at microclimate protection needs to consider within site heterogeneity and focus on areas were changes in microclimate result in unwanted ecological consequences.

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Popular science summary

Streamside riparian forest is a type of forest that grows along a stream and differs from the forest further away from the stream. Often these riparian forests have cooler and more humid air. This special climate in a small area can be referred to as microclimate. The unique microclimate conditions favour plants and animals that thrive in cooler daytime temperatures and more humid air. If the surrounding forest further away from the stream is now harvested, it influences the riparian forest. In Sweden, commonly a narrow strip (<5 m) of forest is left along the stream, so called buffer. A buffer that is too narrow will experience changes in the microclimate amongst other things due to increased solar radiation from the forest edge. Therefore, narrow buffers are insufficient to prevent microclimate changes. Which, as a result can minder the biodiversity in the riparian forest. Therefore, we need to know more about what management approaches can provide better protection of the riparian forests.

In my study, I contributed to a better understanding of how different management approaches affect microclimate after final harvesting in Sweden. Light, air temperature, relative humidity and water temperature can be measured to describe the microclimate of the riparian forest. I studied these four parameters in a control site, where no harvesting took place and three site with different management approaches each.

The results of the study showed that each approach had a different effect on the microclimate. Cutting gaps increases the exposure of the riparian forest to the surrounding weather. This approach had the biggest effect on light, air temperature and humidity. Light and air temperature in the riparian forest increased, while humidity decreased. Leaving wider forest along the stream, especially in areas with higher soil moisture only caused an increase in light and air temperature. The third approach showed, that if there was already one side of the stream harvested and the buffer left was 5 m wide, the riparian forest on the other side of the stream will be affected already. I further found variability in changes of microclimate within each approach. This suggests high heterogeneity within each site. Therefore, riparian management aimed at microclimate protection needs to consider within site heterogeneity.

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2024:02 Författare: Rasmus Staaf
Riparian plant biodiversity and community composition of ditches and straightened streams. Identifying Key Environmental Drivers in a Boreal Forest Setting

2024:03 Författare: Noel Wieser
Diversity of wood-inhabiting fungi across managed and wildfire boreal Scots pine forest chronosequences

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– A chronosequence analysis between burnt and managed forests

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Gap-edge Effects on Seedling Growth, N Uptake and Associated Ectomycorrhizal Fungi

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Measurement of water content in green stems using thermal properties

2024:13 Författare: Jonas Laurens Kappen
Tree species mixture under drought stress: results of results of *Quercus gambelii* – *Pinus ponderosa* stands in the Southwestern US

2024:14 Författare: Dorothea Milena Jentzsch
The change of microclimate in riparian buffers following clearcutting of adjacent forest stands.