Consequences of Alternative Forest Management in Different Widths of Riparian Buffer Zones: A GIS Analysis

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Abstract

With increasing pressure from policymakers and the general public to conduct alternative forest management throughout the European Union (EU), Sweden needs to find ways to best prioritize the implementation of this alternative management. Alternative management is a term used to describe alternative management methods to clear-cut rotation forestry and can include silvicultural methods such as continuous cover forestry, management increasing proportion tree diversity and presence of broadleaves, and extended rotation lengths. Riparian buffers are one possible location for this management that may provide a win-win solution for meeting EU goals of increasing conservation of productive forests and use of alternative management, as well as benefiting water quality and biodiversity. Riparian buffers can protect the ecological functioning of a stream, typically by leaving a strip of unharvested trees in place around the stream, but in Sweden these buffers are often narrow (5-7m) and are dominated by a single tree species. Implementation of alternative forest management that would promote a diversity of tree species in wide riparian buffers could benefit streams, as well as assist Sweden in meeting EU goals. To determine the amount of forest land contained within buffers under 5 m, 15 m, 30 m, and 60 m buffer width scenarios I conducted a GIS analysis of 11 study areas throughout Sweden. I also examined the current tree species composition in these potential buffer zones and analysed the area around both natural channels, and forest ditches. I found that there is a significant latitudinal gradient in species composition within the buffer zones from north to south, with total tree volume, deciduous tree volume, and spruce tree volume increasing from north to south, whereas the proportion of pine is highest in northern study regions. This latitudinal trend was not seen in terms of the proportion of forest land contained within the buffers that was productive forest land; however, there was a significant difference between the amount of productive forest land found around ditches versus streams. If ditches were to be buffered with wide 60 m buffers, it would require converting 5-6% of productive forestland. Buffering both ditches and natural channels, with 30 m buffers, would require about 20% of productive forestland. On a spatial scale, converting riparian buffers to alternative forest management appears to offer potential for maximizing protection of sensitive riparian zones, while minimizing economic losses in a way that meets EU goals for alternative management and conservation, although future studies are needed to examine the practical implementation of conducting alternative forest management within riparian buffer zones and the form that this management would take.

Keywords: riparian buffer zones, continuous cover forestry, CCF, hyggesfritt, geographical information system, ditch network maintenance, ditch, stream, natural channel

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Abbreviations

CCF	Continuous Cover Forestry
DEM	Digital Elevation Model
DNM	Ditch Network Maintenance
DOC	Dissolved Organic Carbon
DRIPs	Discrete Riparian Inflow Points
HPMF	High Pass Median Filter

1. INTRODUCTION

1.1 Importance of riparian zones

Riparian zones, or the forest surrounding both natural waterways and ditches, serve numerous ecosystem functions, for both the aquatic and the terrestrial environments. Because of this, a strip of uncut forest is often left in place, in the form of a riparian buffer following forest harvesting in the surrounding landscape. When planning these buffer zones, they should be designed in a way that the functionality of the riparian zone is preserved. The Swedish Forest Agency states that the functions that should be preserved within the riparian zones include:

Protect important ground chemical processes

Prevent sediment transport

Provide deadwood

Provide subsidies to aquatic organisms

Provide shade

Protect biological diversity. (Skogsstyrelsen, 2014).

These are all important aspects for the functioning and preservation of the habitat.

Some of the most important ecosystem services provided by riparian zones are those that buffer the stream from detrimental effects of forest management on adjacent land. One of the functions of riparian buffers is to filter excess nutrients. When an adjacent forest area is clearcut, it can result in a large influx of available nutrients in the area (Kreutzweiser et al., 2008). By creating a riparian buffer, the buffer can filter out these excess nutrients, preventing them from reaching and infiltrating the waterways.

Riparian zones can also stabilize the streambank, trap sediments, and prevent excess erosion from occurring in the area (Polvi et al., 2014). Some erosion and sediment input into forest streams can be essential for the health of the stream by providing a substrate for habitat creation, maintaining diverse structure, and modulating changes in the morphology of the stream (Florsheim et al., 2008). However, due to human activities such as logging, sediment input, and erosion, sediment levels can often be greater than what is ideal for the aquatic environment. This can negatively affect many fish and aquatic species (Mikołajczyk, and Nawrocki., 2019). Riparian buffer zones are a great means to mitigate these negative effects on the riparian habitat.

Riparian zones also act as an important source of deadwood for the waterways. This deadwood can provide an important habitat for many fish and aquatic organisms, while also providing decomposing organic material (Gurnell et al., 1995). Deadwood as a component of the stream can also function to change the geomorphology and hydrology of the stream through the formation of eddies and pools (Montgomery, 1995). However, the amount of deadwood provided to a stream by a riparian buffer, and the duration of provision, can vary based on the size and structure of the riparian buffer zone (Kuglerová et al., 2023).

Additionally, riparian zones provide subsidies to streams in the form of leaf litter and invertebrates. Leaf litter subsidies provide an important source of carbon, phosphorus, and nitrogen to the aquatic environment. As with many aspects of riparian zones, the vegetation composition in the riparian zone is incredibly important. Conifer species, of which much of Sweden's riparian zones are currently composed, offer only low-quality subsidies to aquatic environments. This is due to conifer needles with thick waxy cuticles being more difficult for microbial processes to break down (Duan et al., 2014). As a result, they contribute few high-quality inputs such as nitrogen and phosphorus, and more dissolved organic carbon (DOC) to the streams. This high level of DOC inputs from coniferous trees is likely a contributor to the brownification of Sweden's boreal streams (Kritzberg et al., 2020). A higher proportion of broadleaves within the riparian zones would lead to higher quality inputs, and thus healthier overall riparian and aquatic ecosystems.

Riparian zones also help regulate both the light environment of the stream, and the temperature within the stream, through shading (Bowler et al., 2012). This is important for both many aquatic species like fish, that can often only live in a narrow temperature window (Jonsson and Jonsson, 2009), but also for regulating the biological, chemical, and physical processes within the waterway (Caissie, 2006).

A final function of preserving riparian zones, is to protect biological diversity in the area, when the surrounding area is cut. While harvesting surrounding forest can negatively impact biodiversity, leaving retention buffers can help to mitigate these losses, in the areas where the zones are left (Hylander, 2004). In addition, Olden et al., 2019, found that a 30 m buffer preserved vascular plant communities. Riparian buffers can help to protect biological diversity within a managed landscape.

Riparian buffers perform myriad functions, from buffering against input of sediments and nutrients from nearby logged areas, to preserving biodiversity and providing the aquatic ecosystem with deadwood. They can be a crucial component of managed forest landscapes, for preserving ecological functioning.

1.2 Implementation and spatial arrangement of riparian buffers

Throughout the world there are numerous means of implementing and managing riparian buffers (Ring et al., 2017; Luke et al., 2019; Kampf et al., 2021). These alternative methods can vary greatly in spatial arrangement and can affect ecological management. Some of the most common spatial arrangements of riparian buffers are fixed width buffers, variable width buffers, and buffers that emulate natural disturbance.

In a fixed width buffer, a predetermined distance around the riparian zone, such as 15 m, is left unharvested on either side of the stream. Fixed width buffers are commonly used as they are both easy to plan and to implement in the field (Richardson et al., 2012).

Another method is hydrologically adapted buffers (Kuglerová et al., 2014). Hydrologically adapted buffers are increasingly championed as a way to increase the functioning of the buffer zone, while at the same time reducing the costs associated with riparian buffers. In a hydrologically adapted buffer, depth to groundwater maps are commonly used to delineate an area surrounding the riparian zone. In this method, the more ecologically sensitive wet areas, or Discrete Riparian Inflow Points (DRIPS) (Ploum et al., 2018) can be protected, while buffers do not need to be as wide in drier areas. Because wet areas are often less productive from a forestry standpoint, these methods can also be more economically sensible (Tiwari et al., 2016).

Buffers that emulate natural disturbance are another buffer management method, which has gained increased attention recently (Swartz et al., 2020; Sibley et al., 2012; Kreutzweiser et al., 2012). This method could contain sections with a fixed width buffer around much of the stream, with some areas logged all the way to the stream. These open areas can emulate patch dynamics seen in a natural ecosystem through windfalls or fires.

While there are many different buffer arrangements, proponents often debate how wide buffer zones around waterways should be to provide the necessary ecosystem services, and as a result, buffer widths can vary greatly. Some studies have shown that buffers should be as wide as 30 m (Olden et al., 2019), but in Swedish forestry, the buffers are often much smaller (Ring et al., 2022; Kuglerová et al., 2020). The width of riparian buffers can vary greatly, and in wider buffer zones, they may even extend beyond the riparian zone of the stream. However, the goal remains to buffer the riparian zone, which may just be a small part of the riparian buffer size, even if the entire area is no longer riparian forest. Within a Swedish perspective, riparian buffers have an average width of between 5 m and 7.2 m (Ring et al., 2022). However, Swedish riparian buffer zone management relies largely on voluntary processes such as forest certification standards such as those provided by the Forest Stewardship Council (FSC). FSC certification only states that the ecological function of riparian buffer zones should be maintained, and that the form of the buffer zone is planned and based off the natural value of the stream and the buffer zone's forest natural values and sensitivity (Forest Stewardship Council, 2020). The FSC does not prescribe any minimum width or other minimum considerations. In addition, when consideration is given to watercourses, large waterways often see more protection in the form of wider buffers, even though small headwater streams make up a large proportion of the total stream network and can have large impacts on downstream conditions in larger streams (Wipfli, et al., 2007). This lack of stipulation and knowledge on riparian buffer width can lead to both large variation in the forms buffers take and the function that they can provide.

1.3 Management within riparian buffers

There is a long history of research into the ideal spatial arrangement of riparian buffers, but very little about the management of riparian buffers to increase their hydrological, biogeochemical, and ecological functioning over the long term. Riparian buffers have typically been thought of as conservation areas that should be left untouched. But in the case of Swedish riparian forests, in which fire suppression and forest management have promoted even-aged conifer stands right up to the stream edge, there could be some benefit to promoting a diversity of tree species and ages in the riparian zone (Hasselquist et al. 2021). In addition, continuous cover forestry (CCF) has been a hot topic in the European Union (EU) and in Sweden and may be an optimal possibility for management of riparian zones.

Various proposals have been put forward to utilize alternative management methods within buffer zones in Sweden (Hasselquist et al. 2021). Alternative management is a term that describes silvicultural methods other than even-aged clear-cut forestry. Some examples of management that can help to support biodiversity and ecosystem resilience are continuous cover forestry, and an increase in species diversity and broadleaf presence (European Commission, 2021), as well as methods such as longer rotation periods.

CCF is a form of alternative forest management and is a silvicultural method in which subsets of trees are harvested on short intervals, while continuously maintaining tree cover within the stand (Pommerening and Murphy, 2004). Continuous cover forestry or "hyggesfritt skogsbruk," as it is called in Swedish, can come in several forms. Some of the most common methods of CCF include management systems such as strip cutting, gap cutting, shelterwoods, or single tree selection. Single tree selection, while the most extreme form of CCF is also likely what most people think of when CCF is discussed. A single tree selection system is conducted on full storied stands, with a reverse J shape size distribution curve. It entails selectively removing individual trees to maintain the reverse J shape (Lundqvist, 2017). Strip cutting and gap cutting are both similar with the spatial arrangement being the differing factor. It is a method wherein narrow strips or either uneven or even structure in a forest landscape are clear-cut, leaving other strips unharvested (Stenberg et al., 2022). Shelterwoods, are characterised by regenerating a new cohort of trees, under a small remaining crop of trees from the previous stand (Pommerening and Murphy, 2004). Which method to choose, would rely on evaluating the individual forest stand, and the current structure and species composition of the stand.

To maximize the benefits riparian buffers could provide, CCF management ideally would result in a greater proportion of broadleaved trees. A review by Hasselquist et al., 2021, discusses different possible methodologies for maximizing the benefits from riparian buffers with CCF management using predominately broadleaved species. Riparian buffers within Sweden are typically only considered and managed at the final felling stage, where when conducting a clear cut, a small strip of trees can be left around the waterway.

Management of this riparian zone is seldom considered throughout the forest rotation period; however, Hasselquist et al., 2021 recommend managing the riparian buffer throughout the entire rotation period. They recommend starting management at the final felling stage, by saving all broadleaves within the riparian zone and selectively cutting conifers to increase the light availability for broadleaf regeneration. Throughout the rotation period, and in line with normal stand management prescriptions such as pre-commercial thinning, thinning, and the second final felling, foresters can selectively cut conifers to increase habitat for more broadleaves and to increase overall stability and heterogeneity of the stand. As the riparian stand ages, further selective cuttings can be done to maximize heterogeneity of the stand for biodiversity and other purposes, and to increase the amount of available deadwood within the ecosystem (Hasselquist et al., 2021). Practicing this sort of CCF management maximizing broadleaves may, in theory, allow the riparian buffer to function ideally, and to function over the entirety of the rotation age, rotation after rotation, compared to only providing benefits at the final felling stage. In addition, selective cutting of conifers, and eventually broadleaves, will help minimize the economic burden of this type of management, and allow ongoing economic harvesting within the riparian zones.

Continuous cover forestry has the additional benefit of helping to maintain a lower water level throughout the landscape. This can be especially beneficial in heavily ditched landscapes. Historically, ditches were dug throughout much of Sweden to lower the water table to promote forest growth on previously wet soils. Overtime, these ditch networks can be clogged and begin to fill in. While ditch network maintenance is commonly used to control the water level following clear cut harvesting (Sikström and Hökkä, 2016), CCF can be an alternative to ditch maintenance, as a continuous tree cover in the area works to maintain a lower water table and eliminate the need for ditch cleaning (Leppä et al., 2020). This lower water table can allow for tree growth and regeneration. However, there can be some variation in change in groundwater levels depending on the peat type (Laudon and Hasselquist, 2023). CCF can help to minimize the expensive economic impacts of ditch cleaning, but also prevent the negative ecological impacts of ditch maintenance, such as an increase in export of sediments and nutrients (Nieminen et al., 2018).

Management within riparian buffers, and the idea of how to maximize their functionality has been an overlooked component of dealing with riparian zones. However, CCF management that promotes multi-species stands is a promising management method for boosting the ecological functioning of the stand, while also minimizing negative effects of ditch cleaning due to CCF’s ability to keep the water table down.

1.4 The amount of ditches and waterways in Sweden

Sweden has a long and extensive history of constructing forest ditches. Throughout the 1930s the Swedish government granted financial incentives to private landowners, paying by the meter of ditch dug (Päivänen and Hånell, 2012). Ditches were intended to help drain wet soils and mires to aid in tree growth. Today, ditch network maintenance (DNM) is carried out within these systems to clear out old ditches that have filled in. DNM can have subsequent large effects on downstream habitat through increased suspended sediment loads and nutrient export (Niemenin et al., 2018). In addition to digging ditches for drainage purposes, many natural channels were straightened, and had obstructions removed to facilitate timber floating down the waterways (Helfield et al., 2007).

In addition to ditches dug for drainage purposes related to forestry, Sweden also has many ditches dug for agriculture purposes, as well as along roadsides to keep the roads clear of water (Kalantari and Folkeson, 2013). Currently, the best maps show only 0.4 million kilometres of waterways throughout Sweden (Laudon et al., 2022). However, a recent study by Laudon et al., 2022, which mapped waterways throughout Sweden using new technology and deep learning models, found approximately 1.2 million kilometres of waterways (Laudon et al., 2022). This recent work showcases the lack of knowledge and understanding of how extensive the water networks throughout Sweden are, and the need to better understand the implications of managing them in different ways.

1.5 Aims of the study

With the European Commission focusing on blue green infrastructure, different uses and implementations of blue green infrastructure will affect forest management in Sweden. Blue Green infrastructure is defined by the European Commission as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (European Commission). In addition, the EU Forest Strategy for 2030 has a target of protecting at least 30% of the EU land under a current forest management regime (European Commission, 2021) By utilizing blue green infrastructure to meet this goal of 30%, it could help to maintain and improve ecological functioning of riparian zones, while still allowing for some economic harvest in riparian zones. To understand the effects that different buffer management scenarios could have on the broad-scale forest landscape, utilizing existing mapped networks of natural channels and forest ditches throughout Sweden, this study addresses the following research questions:

1. Does the productive forest land and tree species composition within different buffer width scenarios vary between northern and southern Sweden?

2. What percentage of forest land would be transitioned to alternative forest management under 5, 15, 30, and 60 m buffer width scenarios around natural channels?
    a. How much additional land would be converted if buffers around forest ditches were included?

3. What is the species composition of the forest land that would be transitioned to alternative forest management?
    a. Is there potential for alternative forest management to improve riparian buffer conditions?
    b. Are there patterns that make this transition more or less feasible?

2. MATERIALS AND METHODS

2.1 Background information on Sweden

Sweden is a northern boreal country with a latitude ranging from 55-70 degrees north and a longitude ranging from 11-25 degrees east (Figure 1). Sweden is primarily dominated by forest land. 68.7% of the land area is forested (The World Bank). Of this forest land, approximately 84% is productive, and 16% is unproductive (SCB, 2023).

The climate in Sweden is largely temperate, despite its northern location. A prevailing south westerly to westerly wind originating over the Atlantic keeps the climate relatively mild during the winter months, although winter climate is still characterized by long dark winters.

Furthermore, there is a precipitation and elevation gradient from north to south within Sweden, with precipitation ranging from 400 to 2100 mm (Paul et al., 2023). North-south variation in terms of botany is often defined by Limes Norrlandicus. Limes Norrlandicus divides the northern and southern distribution of many plants in Sweden, and runs at approximately 60 degrees north (Gullefors, 2008).

2.2 Background information on the 11 study areas

This paper studied 11 regions throughout Sweden. These 11 areas were sites digitized in a previous study by Paul et al., 2023. This study was conducted to accurately map the dense network of ditches within Sweden. By carefully digitizing the existing ditches, Paul et al., 2023 compared the historical level of natural ditches with the current level of man-made and natural ditches. Of the channels within the study area, 87% were ditches. Thirteen percent of the channels were strictly natural channels. Looking closer at the human modified ditch network within the study area, 6% of the ditches were agricultural ditches, 25% were road ditches, and the vast majority, at 56%, were forest ditches. It is these forest ditches, and the natural channels, that were analysed for this study. The location of the 11 study areas is shown in Figure 1.

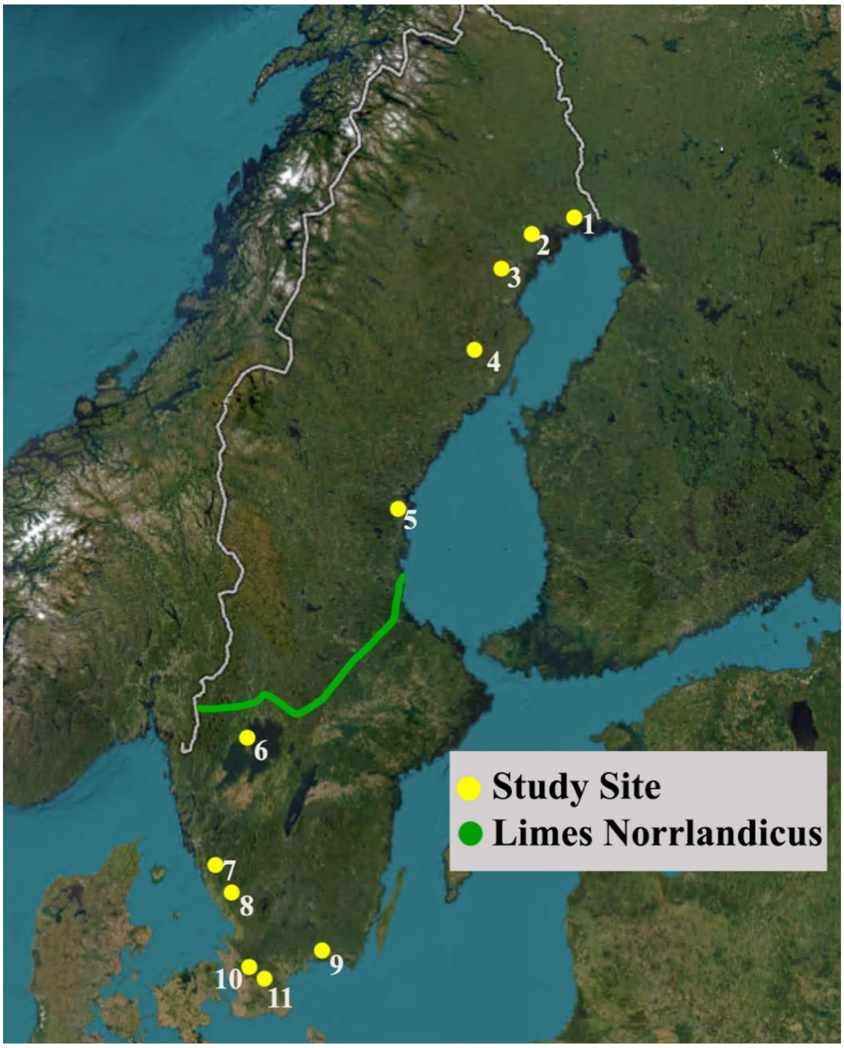


Figure 1. Overview map of the 11 study areas spread throughout Sweden. The 11 areas are divided into northern and southern study regions based off Limes Norrlandicus or the Biological northern border.

2.3 Digitization of ditches and natural channels

The original study by Paul et al., 2023, digitized ditches using 55 LiDAR 2.5 km by 2.5 km images. This area totalled 344 square kilometres, plus the Krycklan catchment study area, which was an additional 68 square kilometres. The Krycklan study area is a research site that has been maintained over a long term by the Swedish University of Agricultural Sciences (Laudon et al., 2020). The scanning was conducted at 3000 m with a scanning angle of plus/minus 20 degrees. Up to 7 echoes were registered during scanning, and a digital elevation model of ground surface with a resolution of 0.5 m x 0.5 m was created from the final echo. The ditch networks throughout the study area were then manually digitized by the Swedish Forest Agency. By using national property maps, the channels were sorted into forest, natural channel, agricultural, or road ditch (Paul et al., 2023). The ditch data can be found at Ågren et al., 2022.

The natural channels were digitized by first detecting all natural channel heads. Paul et al., 2023 utilized a Digital Elevation Model (DEM) and followed the incised natural channel to the point where it was no longer detected. This could either be a natural channel head, or where it met an upstream ditch network at a transition point. This natural channel head was then snapped to the closest nearby flow accumulation cell, and then the algorithm trace downstream flow path was used to map the natural channels (Paul et al., 2023). Both the original study and the study here counted and studied only streams narrower than 6 m wide.

2.4 Editing of the natural channels in GIS

When working with analysis of the natural channels, for some of the natural channels, the base data of the natural channel location could be slightly off. Therefore, a PhD student working with these data split the task with me to manually examine all natural channels within the 11 zones. This was done utilizing both an orthophoto with 0.25 m resolution, and a High Pass Median Filter (HPMF). The high pass median filter worked to emphasize short range topographic variability. It was implemented using the HPMF algorithm from the Whitebox tools and works by taking the value at the grid cell centre and subtracting that from the median value in the surrounding neighbourhood with a kernel of eleven cells (Lindsay, 2014).

By using both layers, we were able to get a clearer vision of the proper route of the natural channels. Using QGIS, we then manually edited the vertices of the existing natural channels, to match the natural channels as seen in the Orthophoto and the HPMF. Photos from this process showing both the orthophoto and the high pass median filter can be seen in Figure 2.

Figure 2. Maps from QGIS showing the manual digitization process of natural channels. The photo shows an orthophoto with a 0.25 m resolution. The blue line is the originally digitized natural channel, and the yellow line shows the edited natural channel, to match the orthophoto and HPMF.

The sites used for this study, and the Paul et al., 2023 study range from southern to northern Sweden. The sites were chosen based on several criteria: the land cover type was predominately forest; the site comprised a wide variety of species, soil types, topography, and soil runoff; and the sites lie within the ongoing national Swedish laser scan for high resolution DEM (although this area has now expanded since the original study) (Paul et al., 2023). This high resolution 12.5 m x 12.5 m resolution data is currently only available for southern Sweden and more coastal areas of northern Sweden. The area in which this data exists can be seen in Figure 3.

Figure 3. Overview map showing the range of SLU Skogskarta 2015. This was the layer used for volume analysis, with a 12.5 m x 12.5 m resolution. (SLU Forest Map, 2015).

Having a north-south range of study sites allows a comparison of potential differences between northern and southern Sweden. Laudon et al., 2022 used a deep learning model to map channels throughout all of Sweden and compile a channel density map throughout the country. Comparing this map with the 11 study sites used in this study shows that the southern study regions were representative of the average channel density, whereas the northern study regions along the coast may have had a slightly higher overall channel density than the average.

2.5 GIS analysis

I used several publicly available land cover maps from the Swedish Environmental Agency, and SLU Skogskarta as base layers to conduct analysis of tree species volumes, areas in different buffer widths, and productivity status. National land cover maps had a resolution of 10 m x 10 m, and forest data from SLU Skogskarta had a resolution of 12.5 m x 12.5 m. One site (Krycklan) was excluded from future analysis data only existed with a resolution of 25 m x 25 m. I then conducted the GIS analysis using ArcGIS Pro Version 2.5.0 from Esri.

2.5.1 Base maps

To determine the extent of forest land, and specifically productive forest land that would be utilized for alternative management under the European Union Forest Strategy for 2030 Proposal, I used national land cover data from the Swedish Environmental Protection Agency (Naturvårdsverket). The national land cover map (NMD) utilizes 10 m x 10 m pixels based on a combination of LiDAR data and satellite data collected from satellites Sentinel 2. The data used in the creation of the map layer had an age range from 2015-2018 for the satellite data, and 2009-2019 for laser data, meaning that there is some variation when the data was captured between study zones, although I do not expect this to affect the results. Land cover throughout the country is divided into 25 different classes based on cover type. The base categories include “forest, open wetland, arable land, other open land, artificial surfaces, and water.” However, these categories also include subcategories of division. For example, “forest” is further divided into Forest on Wetland, and Forest not on Wetland, with subsequent subcategories for different tree cover types.

Within the National Land Cover Dataset, there is a sublayer of forest productivity. This layer divides forest land into productive forest, unproductive forest, and non-forest land. Productive forest is defined as forest land with growth being greater than or equal to 1 m^3/ha/year. Unproductive forest land is forest land with growth less than 1 m^3/ha/year at 100 years old. These data were then further compared with data from SLU Riksskogstaxeringen to classify the quality of data (Naturvårdsverket, 2020). This comparison showed a 95-98% agreement in boundaries of productive and unproductive forest between the NMD data and the field data, with productive forest boundaries having the highest level of accuracy, and boundaries of unproductive forest land slightly less. One difficulty with the layer is that the area of unproductive forest land can be slightly overestimated in heavily ditched areas. This layer will be utilized for determining the amount of productive forest land contained within different riparian buffer scenarios.

2.5.2 Buffer width scenarios

When creating riparian Buffer Zones within Arc GIS Pro, I used the ‘Multiple ring buffer’ tool in the Analysis Tools toolset to create 5 m, 15 m, 30 m, and 60 m buffers surrounding the streams. This distance is buffered on either side of the stream, i.e., a 5 m buffer has 5 m on either side of the stream. An example of the multiple ring buffers both from a study area scale, and a close-up scale can be seen in Figure 4. 5 m is most representative of the current level of protection given to many riparian zones in Sweden today, if any protection at all is granted. 30 m is sometimes considered the minimum width necessary to maintain many essential ecosystem services (Sweeney and Newbold, 2014).

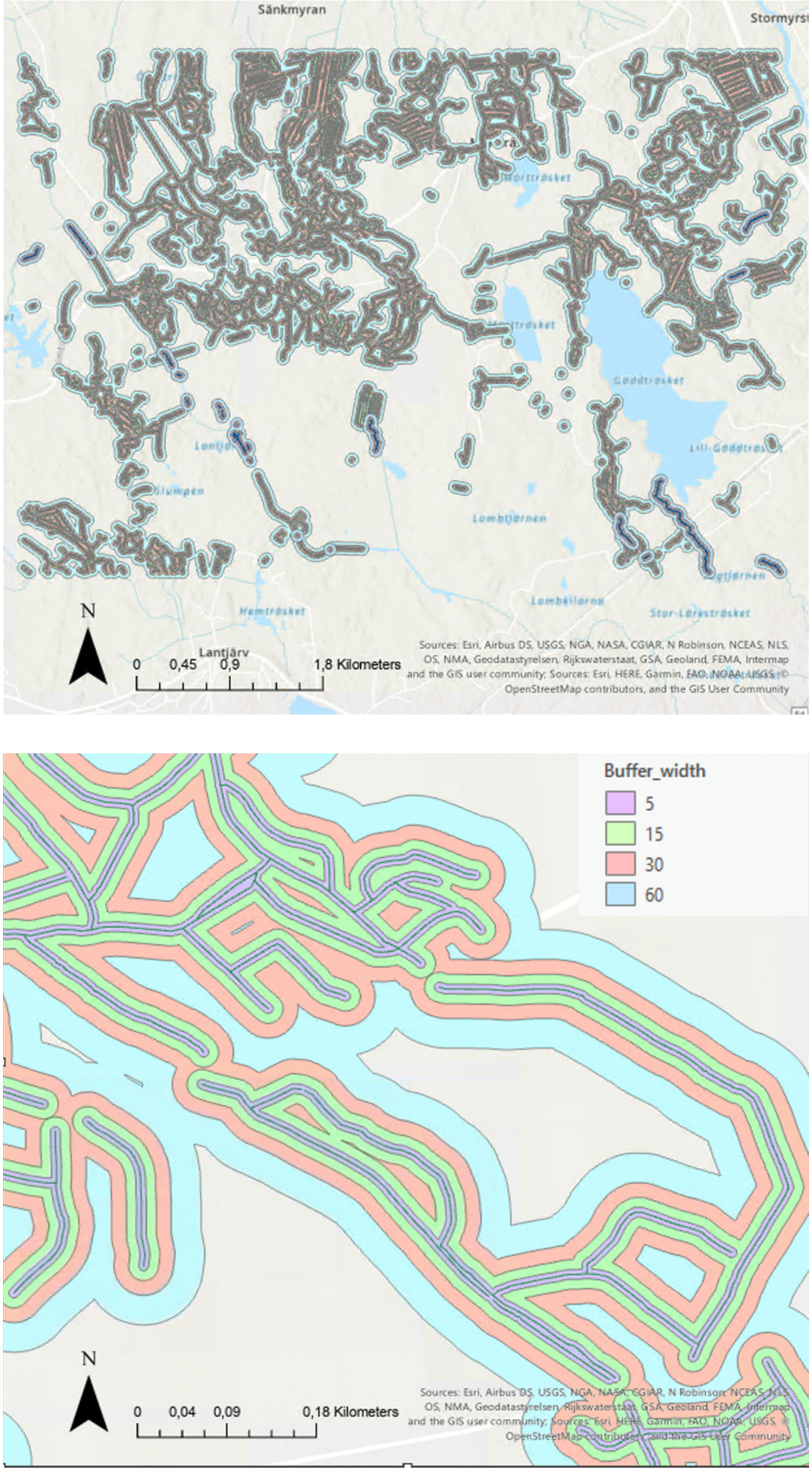


Figure 4. Maps showing the GIS multiple ring buffering process with both a view from all of Zone 1, and a close-up view of zone 1 showing the different buffer width distances.

This study used data from Paul et al., 2023 as the basis for the ditches and natural channels for examining riparian buffer alternatives. However, as I was interested in examining forested areas, I only utilized the forest ditches and natural channels. I used 'Select by Attributes' to select for ditch type: "forest" or "natural channel" and created a new layer from these. The layer with all four ditch types was then removed.

For each of the individual study areas, I then created a separate layer using 'Make Feature Layer' for each individual zone, where the parameters were set to include either only natural channels, or only forest ditches. This allowed me to individually analyse each study area based on the type of channel in the area.

Within each study area, I used summary statistics to determine the length in kilometres of both forest ditches and natural channels within each study area. I was then able to calculate the density of ditches and natural channels in km of waterway per km^2 of total area.

2.5.3 Productive forest land analysis

To determine the amount of productive, unproductive, and non-forest land within each buffer distance, I used the 'Zonal Statistics as a Table' tool. To use this tool on the NMD productivity layer, I first exported the productivity layer as a 32-bit float raster layer. I then used 'Extract by Attributes' to create a separate layer for productive forest, unproductive forest, and non-forest land.

I then used 'Zonal Statistics as Table' with the input layer set to each respective zone's multiple ring buffer layer. The overlay raster was set to the previously created NMD productive forest layer, unproductive forest layer, and finally non-forest land layer. This resulted in a separate table for each zone's multiple ring buffer with the amount of each type of land within the buffer zone. I was then able to combine all these results into a table using Microsoft Excel.

These data were then summarized into the total area of each sort of land contained within each buffer distance and compared to the distance in that size class itself. I also converted the land area to hectares and calculated the percentage of each sort of land cover in a given buffer distance comprised of the total study area.

2.5.4 Species composition analysis

To analyse tree volume measurements within the buffer zones, I utilized tree volume measurement layers from the SLU Skogskarta 2015 data. These data gather value estimates from a combination of national forest inventory field measurements, normalized surface models from Lantmäteriet stereo matched aerial photos and Sentinel 2 satellite data. The tree volume measured is the entire stem volume over normal stump height, including bark and treetop. However, branches, roots and stumps were not measured. SLU Skogskarta 2015 data has a raster size of 12.5 m x 12.5 m. (Produktbeskrivning: SLU Skogskarta, 2015).

As this data contains tree volume measurements from all land cover types, I first used the ‘Extract by Attribute’ tool within ArcGis Pro to extract the measurements for only forest land. I used ‘Extract by Attributes’ where the attribute was not equal to non-forest land within the National Land Cover Data layer. This gave an output file containing only productive and unproductive forest land, or all forest land. I was then able to use this layer in subsequent ‘Extract by Mask’ analysis with each of the individual tree volume layer types. This included total tree volume, pine volume, and spruce volume from the Skogskarta 2015 data. For deciduous tree volume, I ran the analysis with birch volume, beech volume, oak volume, and other deciduous tree volume, and then combined the layers using the ‘Raster Calculator’ within the ‘Image Analyst Toolset’.

This analysis provided the area included, as well as statistics such as the average tree volume per hectare, the maximum and minimum tree volume per hectare, and the median tree volume per hectare. I then calculated the total area, and total average of each different distance buffer zone.

2.6 Statistical analysis

I conducted all statistical analysis in the program SPSS Statistics (Version 29). I used SPSS “chart builder” to create the graphs. In order to assess tree volume variation in latitude (Figure 5), I utilized a linear regression model. In this model, the response variable was set to mean volume in m^3/ha/year for each of the species: spruce, pine, deciduous, and total volume. The explanatory variable or fixed factor in SPSS, was set to latitude. I assessed the model fit (R^2), and the significance level was $\alpha = 0.05$. I ran this analysis separately for ditches, natural channels, and the entire study area.

For analysis of the productivity status of the buffers (Figure 6), I split the file by productivity status, for each productive, unproductive, and non-forest land. I then ran a separate generalized linear model, where the dependent variable was set to percent cover, and the fixed factors were set to north/south, type of waterway (ditch or natural channel), and buffer width. I ran a sperate generalized linear model for proportion of forestland (Figure 7), where the dependent variable was changed to percent of forestland, and the fixed factors remained the same (north/south, type of waterway, and buffer width).

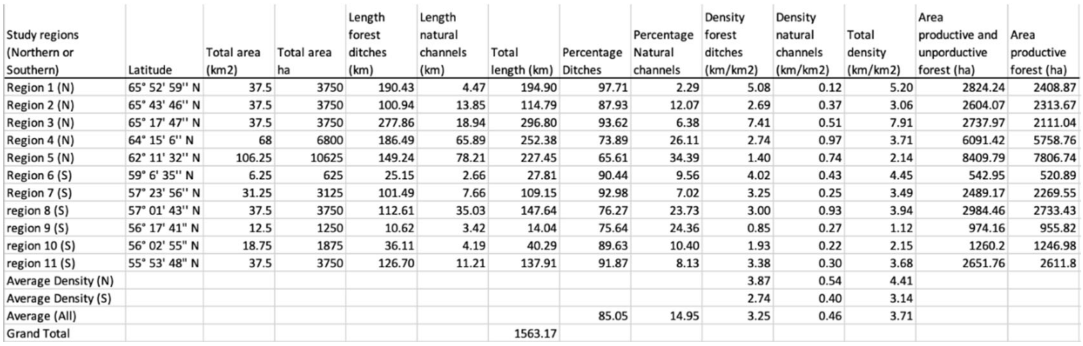
To analyze the proportion of land contained within the buffer zones as a proportion of the study area (Figure 8), I used a generalized linear model, where the dependent variable was the proportion of study area, and the fixed factors were north/south, and type of waterway (ditch or natural channel). I also ran this model for the proportion of productive forestland (Figure 9), where the dependent variable was changed to the amount of productive forestland as a proportion of the study area's productive forestland, and the fixed factors remained the same (north/south, and type of waterway).

Finally, for analyzing species composition (Figure 10), I first split the file to run separate analysis for each species: spruce, pine, and deciduous tree volume. I ran a generalized linear model where the dependent variable was set to proportion of total tree volume, and the fixed factors were set to buffer width, north/south, and type of waterway (ditch or natural channel).

3. RESULTS

The 11 study areas ranged in latitude from northern to southern Sweden. The size of the study area also varied, ranging from 6.25 km^2 for the smallest study area, to 106.25 km^2 for the largest study area (Table 1). The average size of study area was 39.1 km^2. Throughout all study areas, there was a much higher density of forest ditches than of natural channels. The average density of forest ditches was 3.25 km/km^2 and the average density of natural channels was only 0.46 km/km^2 (Table 1). On average, ditches made up 85% of the total channel length, and natural channels made up 15% of the total channel length.

Table 1. Background information about the 11 study sites



Study regions (Northern or Southern)	Latitude	Total area (km2)	Total area ha	Length forest ditches (km)	Length natural channels (km)	Total length (km)	Percentage Ditches	Percentage Natural channels	Density forest ditches (km/km2)	Density natural channels (km/km2)	Total density (km/km2)	Area productive and unporductive forest (ha)	Area productive forest (ha)
Region 1 (N)	65° 52' 59'' N	37.5	3750	190.43	4.47	194.90	97.71	2.29	5.08	0.12	5.20	2824.24	2408.87
Region 2 (N)	65° 43' 46'' N	37.5	3750	100.94	13.85	114.79	87.93	12.07	2.69	0.37	3.06	2604.07	2313.67
Region 3 (N)	65° 17' 47'' N	37.5	3750	277.86	18.94	296.80	93.62	6.38	7.41	0.51	7.91	2737.97	2111.04
Region 4 (N)	64° 15' 6'' N	68	6800	186.49	65.89	252.38	73.89	26.11	2.74	0.97	3.71	6091.42	5758.76
Region 5 (N)	62° 11' 32'' N	106.25	10625	149.24	78.21	227.45	65.61	34.39	1.40	0.74	2.14	8409.79	7806.74
Region 6 (S)	59° 6' 35'' N	6.25	625	25.15	2.66	27.81	90.44	9.56	4.02	0.43	4.45	542.95	520.89
Region 7 (S)	57° 23' 56'' N	31.25	3125	101.49	7.66	109.15	92.98	7.02	3.25	0.25	3.49	2489.17	2269.55
region 8 (S)	57° 01' 43'' N	37.5	3750	112.61	35.03	147.64	76.27	23.73	3.00	0.93	3.94	2984.46	2733.43
region 9 (S)	56° 17' 41'' N	12.5	1250	10.62	3.42	14.04	75.64	24.36	0.85	0.27	1.12	974.16	955.82
region 10 (S)	56° 02' 55'' N	18.75	1875	36.11	4.19	40.29	89.63	10.40	1.93	0.22	2.15	1260.2	1246.98
region 11 (S)	55° 53' 48'' N	37.5	3750	126.70	11.21	137.91	91.87	8.13	3.38	0.30	3.68	2651.76	2611.8
Average Density (N)									3.87	0.54	4.41		
Average Density (S)									2.74	0.40	3.14		
Average (All)							85.05	14.95	3.25	0.46	3.71		
Grand Total						1563.17							

3.1 Latitudinal variation in both tree species composition and productive forest land

To answer if the productive forest land and tree species composition within the different buffer width scenarios vary between northern and southern Sweden, I analysed a latitudinal gradient in Sweden. The 11 study sites were divided into northern sites being those that were north of Limes Norrlandicus (approximately latitude 60 degrees N). This resulted in sites 1-5 categorized as northern sites and sites 6-11 categorized as southern sites.

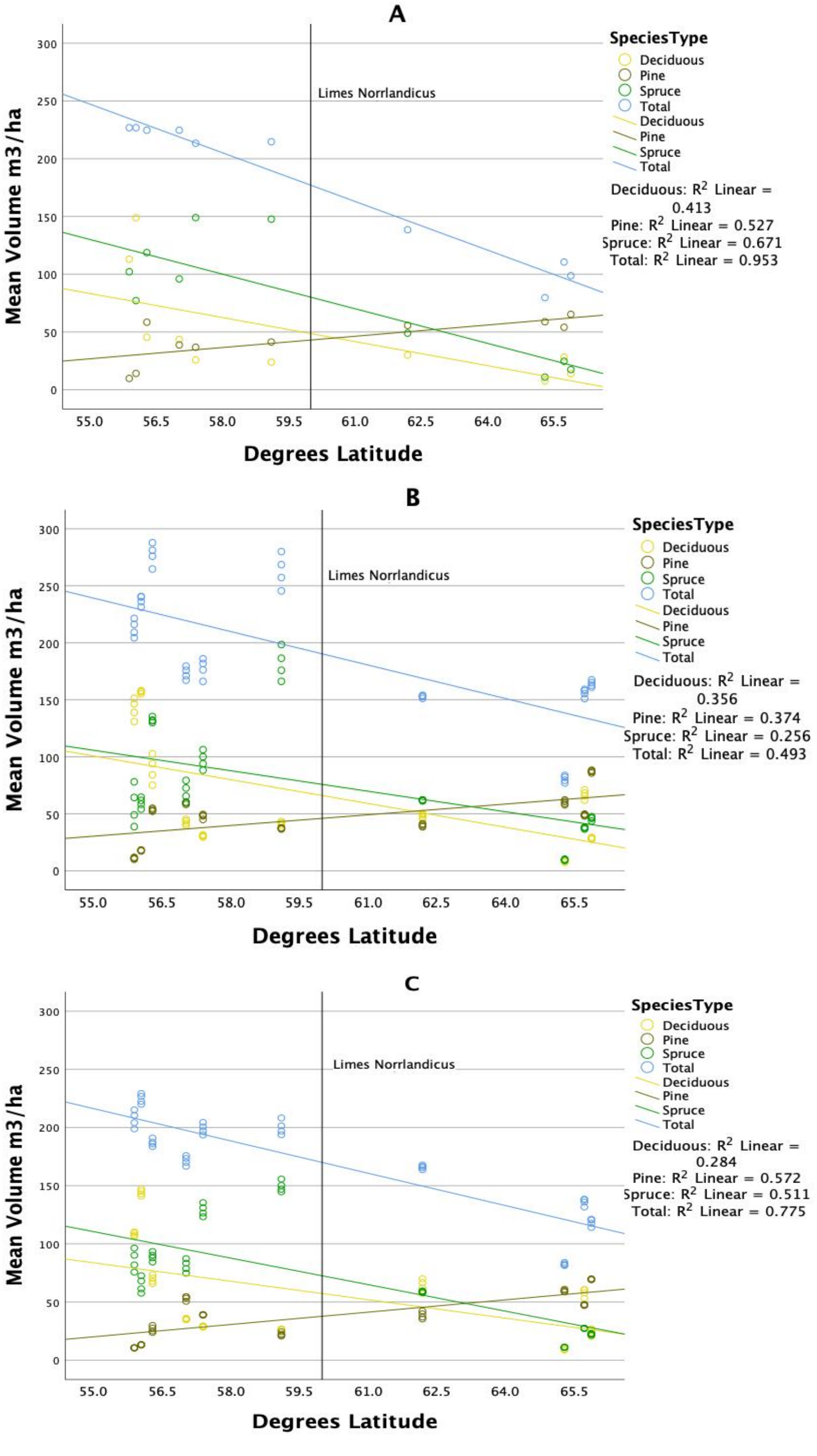


Figure 5. Latitudinal variation in species composition (measured by volume) of the entire study area (A), natural channels (B), and ditches (C). Areas in ditch and stream volume include points for each buffer width (0-5, 0-15, 0-30, 0-60 m), and often overlap. The study area volume is for the entire study area and only includes one point. The vertical black line shows the latitude of Limes Norrlandicus, the division between northern and southern Sweden.

Within the study area, total volume of all tree species combined significantly decreased with increasing latitude (Linear regression model, R2 = 0.953, Figure 5A). Both the volume of deciduous species (Linear regression model, R2 = 0.413) and spruce (Linear regression model, R2 = 0.671) significantly decreased with increasing latitude (Figure 5A). Pine, however, showed the opposite relationship, with increasing volume from south to north (Linear regression model, R2=0.527, Figure 5A). This was also seen in the riparian forests surrounding natural channels (Figure 5B) for total tree volume (Linear regression model, R2 = 0.493), deciduous volume (Linear regression model, R2 = 0.356), spruce (Linear regression model, R2 = 0.256), and pine (Linear regression model, R2 = 0.374). Ditches (Figure 5C) showed the same trend for total tree volume (Linear regression model, R2 = 0.775), deciduous volume (Linear regression model, R2 = 0.284), spruce volume (Linear regression model, R2 = 0.511) and pine (Linear regression model, R2 = 0.572). All these trends were significant to a significance level of $P < 0.05$.

There was no significant latitudinal trend for the area of productive forest land to be transitioned to alternative management (Linear regression model, $p = 0.879$). Furthermore, the proportion of productive forest land contained within the different buffer width scenarios was similar in both northern and southern study sites.

3.2 Percentage of productive forest land transitioned to alternative forest management within different riparian buffer scenarios

Using the Productivity layer from the national land cover data, I was able to determine how much productive forest, unproductive forest, and non-forest land would be transitioned to alternative forest management under 5, 15, 30, and 60 m buffer width scenarios around natural channels and ditches, for both northern and southern regions. The proportional results from each of the individual study areas can be seen in Appendix 1.

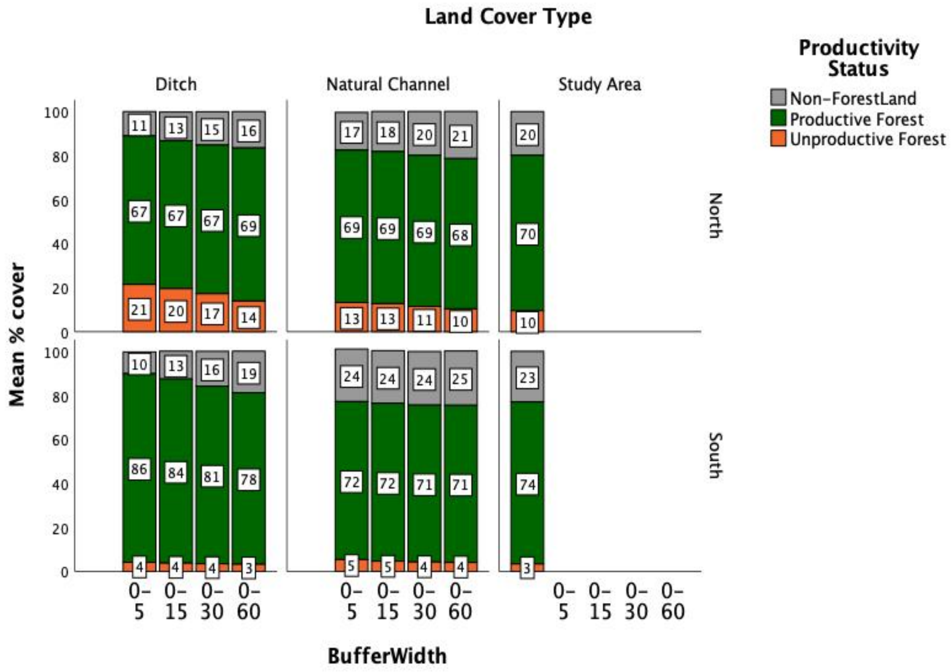


Figure 6. Productivity status of the total study area contained within the different buffer width scenarios. Ditches, natural channels, and the overall study area are separated into northern and southern study regions.

The percent cover of productive forest land was significantly higher in the southern region compared with the northern region (GLM, P < 0.005). However, the amount of non-forest land was not affected by latitude (GLM, P = 0.187).

For both northern and southern regions, productive forest area makes up approximately 70-74% of the forest land in the study area (Figure 6, far right panel). Southern regions also had significantly less unproductive forest than the northern regions did (GLM, P < 0.001, Figure 6). This pattern was seen for ditches, natural channels, and the study area as a whole.

The difference in productivity status between buffers around ditches and natural channels was also significant for the land cover type for unproductive forest, productive forest, with more productive forest in buffers surrounding natural channel, and more unproductive forest around ditches, although only to a significance level of P < 0.1.

For productive forest, unproductive forest, and non-forest land the buffer width did not significantly affect the proportion of cover type (GLM, P > 0.3, Figure 6).

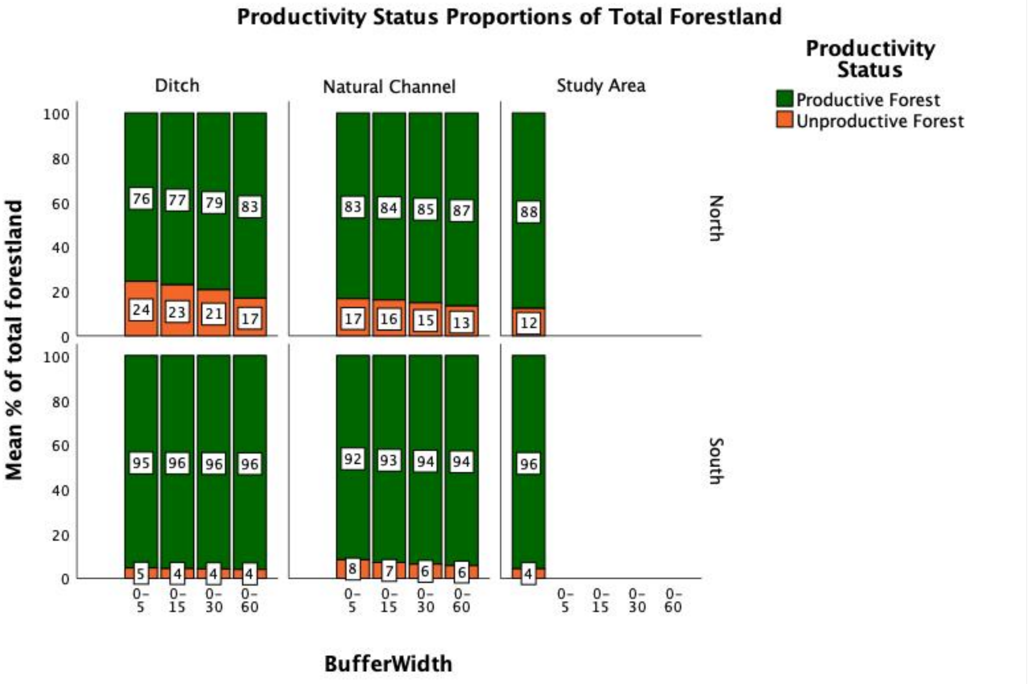


Figure 7. Percentages of forest land that the productive and unproductive forest land in the different scenarios contained.

The analysis in Figure 7 looks more closely at only the forest land as opposed to the entire study area. Here, I analysed the percentage of this total forest land that is productive or unproductive. This offers more perspective into the economic side of the switch to alternative management, as it only looks at forest land as opposed to also examining non-forest land. However, the patterns between latitude, and lack of pattern between buffer width match those seen in Figure 6.

In southern study sites, there was a much lower percentage of the forest land that was unproductive, with very low numbers for ditches, ranging from 5% in the 5 m buffers to 4% for the wider buffers (Figure 7). In natural channels, the number was slightly higher, ranging between 6% and 8% of the total forest land that was unproductive. The average for the study area in southern study sites was 4%. In the north, there was a much higher percentage of forest land that was unproductive. This was especially true for ditches, where 24% of the forest land in a 5 m buffer was unproductive, going down to 17% for a 60 m buffer. Natural channels had a lower proportion of unproductive forest, ranging from 17% for a 5 m buffer, down to only 13% for a 60 m buffer in northern study areas. All the buffers in the northern study region, however, had a higher proportion of unproductive forest land than did the study area, at only 12% (Figure 7).

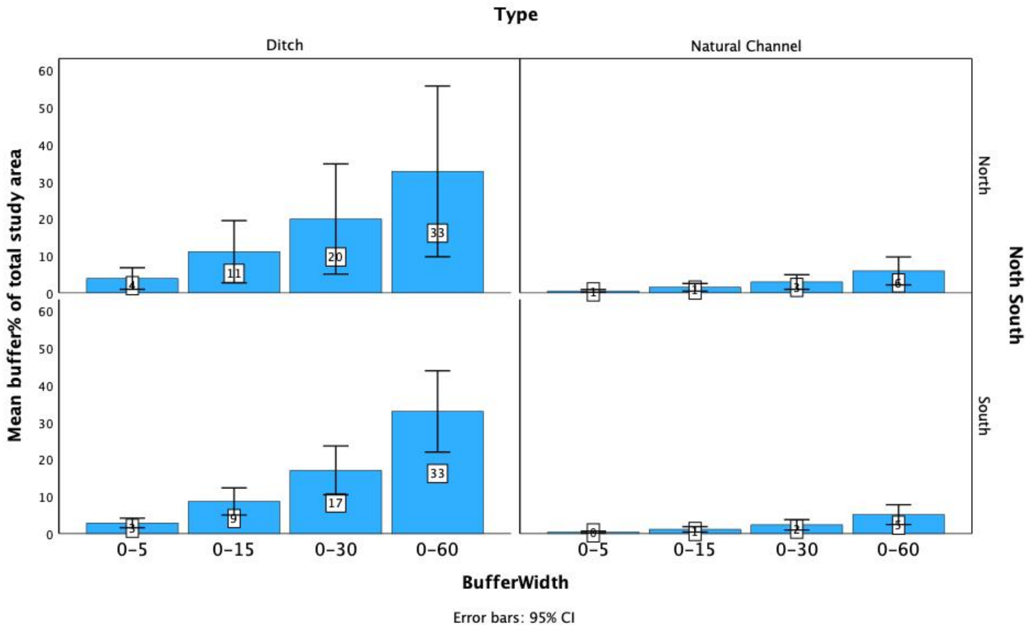


Figure 8. Percentage of the total study area that each buffer width constitutes for both ditches and natural channels, in northern and southern study regions. The exact percentage of the study area included in each buffer scenario are included in white boxes embedded in the bars. Error bars = 95% confidence intervals.

One of the main aims of the study was to examine the total proportion of an overall area, and of an area's productive forest land that would be transitioned to alternative forest management under different buffer width scenarios. In terms of the total area that the different buffers contain within the study area, there was a significant difference between ditches and natural channels (GLM, $P < 0.001$, Figure 8). There was not, however, any significant difference between northern and southern study areas (GLM, $P = 0.469$, Figure 8). As is to be expected, the buffer width did significantly affect the proportion of the study area impacted (GLM, $P < 0.001$), as there was much more area contained within a larger buffer size.

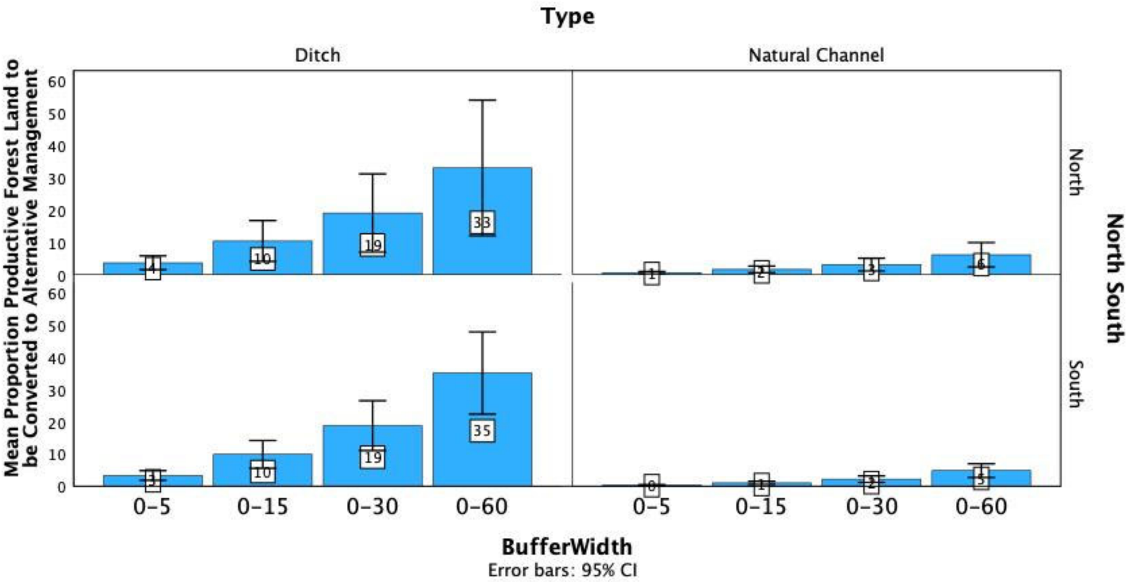


Figure 9. Percentage of productive forest land within the study area that is contained within the different buffer widths, i.e., the amount of forest land that would be converted to alternative management. Error bars = 95% confidence intervals.

An understanding of how much area the buffers take up in regard to total study area is important, as is knowing how the amount of productive forest land within the buffers compares to the total amount of productive forest land in the study area, i.e., the percentage of productive forest land that would be converted to alternative forest management (Figure 9). These patterns mimic the ones seen in Figure 8. Again, there was no significant variation between northern and southern study sites (GLM, $P = 0.879$, Figure 9). The buffer width did significantly affect the proportion of the study areas' productive forest land (GLM, $P < 0.001$, Figure 9). The type of waterway also significantly affected the proportion (GLM, $P< 0.001$, Figure 9), with ditches having a much higher proportion, as there are a greater number of ditches in the landscape. Together, for both ditches and natural channels combined, the average productive forest land within a 5 m buffer was 3.89% of the total productive forest land; 11.36% for a 15 m buffer; 21.48% for a 30 m buffer; and 39.55% for a 60 m buffer.

3.3 Variation in the species composition within the buffer scenarios

Examining the species composition within buffer zones will help answer the question of the potential and feasibility of transitioning different buffer zones to alternative forest management. Volumes of deciduous species, pine, and spruce were all different when comparing northern study regions to southern (GLM, P <

0.05, Figure 10), but within northern and southern study regions, volumes did not significantly differ between ditches and natural channels or among any of the buffer width scenarios (GLM, P > 0.05, Figure 10).

Within northern sites, spruce volume was constant throughout all buffer widths, with an average percentage of 22% of total tree volume for the ditches and 26% of total tree volume for both the study area, and the natural channels. This was in stark contrast to the southern sites, where spruce volumes were much higher, around 40-50% of the total tree volume. Deciduous volumes were also significantly higher in southern study regions (GLM, P < 0.05, Figure 10), with 32-40% of the total tree volume in buffers being deciduous. In the north, deciduous species only composed 25-30% of the total tree volume. Pine volumes, however, were much higher in the northern study regions (GLM, P < 0.05, Figure 10), with values of about 47% in northern regions, compared with only 14-18% in the southern study regions.

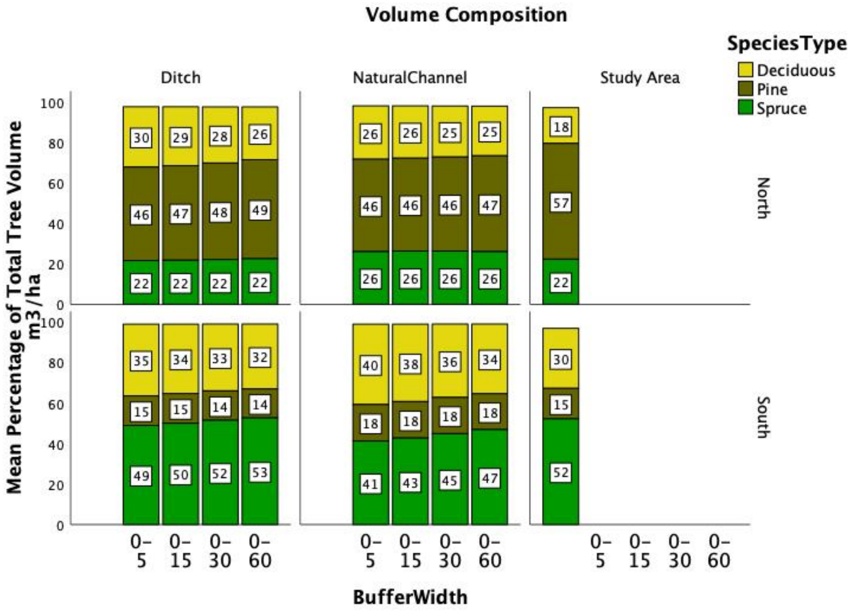


Figure 10. Species composition within the different buffer scenarios as a percentage of the total volume. This is further divided by northern and southern study regions, and ditches, natural channels, and the study area as a whole.

A total view of the mean volume levels found in the different buffer widths for each of the individual zones can be seen in Appendix 2, and for the study area as a whole in Appendix 3. These tables give a detailed view of how mean tree volume levels for each species varied both between study regions, between species, and in comparison, with the study region.

4. DISCUSSION

4.1 Analysis of the buffer land cover types and amount of productive forest land to transition to alternative management

One of the major aims of this study was to determine the proportion of forest land that could be converted to alternative management under different buffer width scenarios.

4.1.1 Forest productivity status in the buffer zones

Looking specifically at forest land on a country-wide perspective, Sweden consists of 68% forest land. Of this, 84% of the forest land is productive and 16% is unproductive forest land (SCB, 2023). Both the northern and southern study regions as a whole lie above this average for percentage of productive forest (Figure 7). This is especially true for the southern study regions, with 96% of the forest land being productive. When study sites were chosen, one of the selection criteria was that the study sites were predominantly forest land. Because both the northern and southern study sites contain more forest land (Figure 6), and a higher proportion of productive forest land (Figure 7), they may not be totally representative of Sweden as a whole. Our study could thus overestimate the amount of productive forest land affected by alternative management in buffers on a national scale. However, I expect this to be a small problem, as most future stand management decisions would also be conducted on a stand-by-stand basis on primarily forest land. Northern study regions, in turn, had a higher proportion of unproductive forest land (Figure 7). Unproductive forest land, however, would not be converted to alternative management. Unproductive forest is forest land with growth less than 1 m^3/ha/year and includes mires, rock outcrops, mountains etc., and under Sweden's Skogsvårdslag, any unproductive forest areas over 0.1 ha are to be left undisturbed (Skogsstyrelsen, 2023). However, the proportion of productive forest land closely followed that of the study area itself, suggesting that the northern study areas simply were not as productive overall, not that the buffer area itself had any great impact on the proportion of productive forest land to unproductive forest land, although the growth rates may still be affected.

4.1.2 Proportion of productive forest land to be transitioned

When discussing changing land management methods, it is this overall proportion of productive forest land to the study area's productive forest land that is most important. Landowners and managers would be interested in this proportion, as this is the percentage of their productive forest land that they would be converting to alternative forest management, or continuous cover forestry. There was no significant variation between northern and southern study regions, suggesting that in terms of how much area would be converted, both northern and southern regions may be equally suited for conversion to continuous cover forestry (Figure 6).

Particularly interesting is the large variation between natural channels and ditches. While for ditches the proportion of productive forest land ranges between 3% for a 5 m buffer up to 35% for a 60 m buffer, for natural channels, the percentage ranges from only 1% to 6% for a 60 m buffer (Figure 9). This is largely due to how few natural channels are left in the landscape, and the miniscule overall proportion that natural channels compose of the waterway network in the study areas. Natural channels composed on average only 15% of the waterway length (Table 1). In addition, it may be a remnant of past land management, as ditches were dug to increase forest growth and to allow for growth and regeneration on wetlands (Miettinen et al., 2020).

Implementing large buffers around natural channels would require a relatively insignificant allotment of productive forest land. Even at the largest buffer width scenarios, protecting natural channels with a 60 m buffer would only require converting 5 – 6% of the total productive forest land (Figure 9), a relatively small amount of land. If ditches were to be protected, the amount of productive forest land converted could significantly increase. However, at 35%, plus the 5 - 6% for natural channels, this would still not be significantly more than the 30% called for in the latest EU forest strategy. Looking at a 30 m buffer, the amount required would still be only around 20 %.

Protecting the riparian zones surrounding natural channels and ditches, and converting them to alternative forest management, could be a good way of meeting the goals set forth in the EU proposal, matching the 30% goal very closely. Management decisions will still likely have to be made on a case by case and forest tract by tract basis.

4.2 Variation in the species composition within the buffer scenarios

The species composition within buffer zones can have a large effect both on the ecological benefits of the buffer zone, and the feasibility of converting that zone to alternative forest management.

4.2.1 Ecological benefit of converting to alternative forest management

Riparian zones provide numerous ecological benefits to waterways. These include protecting important ground chemical processes, prevention of sediment transport, providing shade, provision of deadwood to provide subsidies to aquatic organisms, and protecting biological diversity (Skoggstyrelsen, 2014). However, the level at which riparian zones can provide these functions can vary depending on the species composition within the riparian zone. Throughout the study areas, at all buffer width scenarios, the buffers were primarily conifer dominated (Figure 10). This domination of conifers can negatively affect the functioning of the riparian zones. In terms of providing subsidies to aquatic organisms, conifer needles are more difficult for microbial processes to break down, and result in lower quality leaf litter than broadleaved species (Duan et al., 2014). The promotion of conifers for timber production has also possibly led to the brownification, or the increase of dissolved organic carbon in Swedish waterways (Kritzberg et al., 2020). Furthermore, broadleaved trees and stands can be incredibly important for biodiversity, as broadleaved forests are some of the most species rich forest types in Scandinavia, and support large numbers of red-listed species (Berg et al., 1994). This could mean that the southern study areas, which currently have a higher proportion of deciduous species, could offer more ecological benefit. Converting riparian zones to be more multi-species, with higher proportions of broadleaves, could also further increase the ecological benefit by providing higher quality subsidies to the streams, reducing brownification of the waterways, and positively contributing to biodiversity.

4.2.2 Feasibility of converting to alternative forest management

Species composition varied between northern and southern regions. Notably, there was a much higher proportion of pine in northern study regions, and deciduous species in southern Sweden (Figure 10). The high proportion of pine volume that I found in Northern Sweden, is contrary to what many previous studies have found showing that northern riparian zones are spruce dominated. Hasselquist et al., 2021 found in their literature review, that northern riparian buffers were composed of 68% spruce, and only 13% Scots pine. Lundqvist 2022, found in a study of northern riparian forests in Sweden, that the dominant tree species in his study areas was

79% Norway spruce. I am not sure why my results showed such higher proportions of Scots pine, compared with other studies. Lundqvist 2022, used stem count as opposed to volume when analysing the proportion of spruce composition, and this could lead to some variation; however, the papers used in Hasselquist et al., 2023 literature review relied on basal area or volume, and so I do not expect this to be the only explaining factor. It is possible that some variation could be due to the individual study sites utilized in this study, as site 3 has very large proportions of pine volume at around 70%, which could affect the overall average. However, all three study areas used in the northern study zones still showed higher proportions of pine than either Hasselquist et al., 2023, or Lundqvist, 2022 (Appendix 2). Finally, the difference could be a result of the raster cell resolution of 12.5 m x 12.5 m used in this study. While the data used in this study, is the best available species-specific volume data on a nationwide scale, the 12.5 m x 12.5 m may lead to uncertainty, especially in the small buffers of 5 m and 15 m right next to the watershed. If surrounding areas are more pine dominated, as can be seen for the study areas as a whole in northern study zones (Figure 10), then the large resolution size could lead to an overweighting of the surrounding area, on such small buffers right next to the stream. To better understand the difference in results from previous studies, future work and field trials would need to be done to better understand the species composition in zones immediately surrounding the waterways.

Nonetheless, current species composition is significant when considering the feasibility of converting riparian buffer forests to CCF or other alternative forest management methods. There was an increasing proportion of spruce, deciduous, and total volume going from northern to southern Sweden (Figure 10). Pine, however, increased within buffer zones at higher latitudes. This could possibly affect the feasibility of CCF, as pine requires larger disturbances and more sunlight to regenerate and is thus harder to utilize for CCF (Lundqvist, 2019). It could also, however, merely affect the form that CCF takes, with higher levels of pine necessitating larger disturbances to regenerate. This disturbance could possibly take the form of strip cutting or large patch cutting as opposed to single tree selection systems. In addition, if one of the goals of alternative forest management in buffer zones is to benefit multi-species stands, and specifically deciduous species, then sites in southern Sweden with higher levels of deciduous species in the buffer zones could lead to shorter conversion times to multi-species multi-storied stands.

Looking specifically at deciduous species, in southern study areas, natural channels had the highest proportion of deciduous species, with 40% seen in the 5 m buffer, and nearly 35% in the 60 m buffer, although this was not significantly different (Figure 10). This larger percentage seen in natural channels, as opposed to ditches, could suggest even more possibilities in converting natural channels to multi-species multi-storied stands.

These volume measurements do not differentiate between species of deciduous trees. Different species of deciduous trees have different regeneration methods depending whether they rely on seeding or can regenerate through root shoots. This may affect the feasibility and the methods for converting the stand to CCF, as certain species may be easier to convert depending on their regeneration strategy.

An important consideration when examining these tree volume measurements, is the possible effects that management could have on the current species composition, as opposed to direct effects from the riparian zone. The current species compositions closely match those of the surrounding landscape, especially in southern study regions. This suggests that the current tree species makeup of the buffer zones is largely the result of surrounding management, as opposed to effects of the ditch or natural channel.

While the composition trends seen closely matched that of the surroundings, overall volume levels were lower in the buffer zones than in the overall study area (Figure 5). This could mean that the buffer zones were less productive than the surrounding area thus lowering any negative economic impact of transitioning these areas to alternative forest management will likely be less.

This could also however, be a result of current management. It is possible, that management techniques such as fertilization or site preparation could have boost productivity in the surrounding area, whereas these methods may not have been conducted close to the stream, out of concern to the riparian zone. Most likely however, this is an error due to the pixel resolution of the raster files used for volume measurements. 12.5 m x 12.5 m pixels were used to measure volume, and these would have picked up water cover as well, where volume levels would be zero, thus lowering the total volume levels in pixels surrounding the stream.

Future studies looking more deeply into the productivity of different buffer width scenarios could help determine the economic impacts.

4.3 Limitations of species composition

This study examined the current volume contained within potential riparian buffer zones for pine, spruce, deciduous trees, as well as the total tree volume, providing a good overview of what currently exists within potential buffer zones. This knowledge will be of great importance when considering the transition of these areas to both multi-storied, but also multi-species stands. However, these volume estimates do little to explain the current stand structure present. They do not show nor explain whether the stand is single or multi-storied, or yet the age distribution of the trees in the stand. Gathering this information would be important before transitioning to multi-species multi-storied CCF managed stands.

While this study provides a good basis for both the area of land included under different buffer scenarios, as well as current volume in these buffer zones, estimates of growth rates, productivity rates or stand index for different buffer scenarios cannot be calculated due to current limitations in existing maps and data. However, it would be interesting and beneficial to conduct fieldwork or small-scale studies at a few of the study sites to calculate stand index and productivity rates of the different buffers, giving land managers and researchers an understanding of how different buffer widths could affect the level of productive land placed under alternative forest management.

Furthermore, volume measurement data was taken from SLU Skogskarta 2015 data. This data has a raster cell size of 12.5 m x 12.5 m. While this is a significant improvement over previous Skogskarta data with a resolution of 25 m x 25 m, this is still a larger than ideal resolution size for examining smaller buffer zones of 5 m. This is also the case for the national land cover data gathered from the Swedish environmental protection agency, which has a resolution of 10 m x 10 m. When dealing with small 5 m buffers, and small increments between buffer size, having a large 12.5 m x 12.5 m resolution could minimize any variation seen at such a small scale, as average values may be used for each similar buffer width.

The 12.5 m x 12.5 m resolution is also likely why such minimal change was seen in species composition between different buffer widths. With large pixels, many of the pixels used to estimate volume for a 5 m buffer for example, may have been the same pixels used for a 15 m buffer. This highlights the need for gathering additional detailed field measurements on a stand-by-stand basis.

4.4 Multiple ring buffers

When creating buffers, I utilized the multiple ring buffer tool. This tool allows for creation of multiple desired size buffers as one analysis, and subsequent analysis to be conducted on the singular created layer. However, the multiple ring buffer tool does not allow for the creation of square end buffers ending flush with the end of the waterway in the same way that the normal buffer tool does. As a result, all buffer ends created had extended-rounded ends. While in some ecological situations it may be beneficial to have rounded end buffers, and thus protect more area as well as the source of the stream, it does lead to more overall area being included within the buffer, as opposed with square end buffers that only extend on the sides of the waterway. A visualization of the difference in buffers can be seen in Appendix 4.

Furthermore, due to separate evaluation of natural channel buffers and ditch network buffers, there is slight overlap in some instances between the natural channel buffers and ditch network buffers. This could lead to a slight overestimation of certain statistics such as total area, as some small areas are being counted twice. In the future, a separate evaluation of the total buffers combined as a single layer should be conducted to avoid double counting.

4.5 Going from theoretical work to practical CCF trials

This study offers the groundwork for planning buffer zone management for continuous cover forestry. However, little research has been conducted on the actual implementation of alternative forest management methods within riparian buffer zones in a boreal ecosystem. Hasselquist et al., 2021 examines possible theoretical methods for how best to transition to multi-layered and mixed species forests within riparian buffers. They examine what stage of management is most optimal for transition, as well as how best to incorporate it with normal forest management events such as pre-commercial thinning, thinning, and final felling. However, this is strictly a theoretical approach, and before these methods are adopted on a large scale, trials should be conducted to determine best practices. This is one of the major areas for future study of CCF in riparian buffer zones.

In addition, more work would be needed to discuss the potential results of CCF as a replacement for Ditch Network Maintenance (DNM). In Sweden DNM typically occurs after clear-cut to lower the water table and allow for successful establishment of seedlings. Mid-rotation DNM occurs occasionally, and for that to occur, trees must normally be removed to allow for machine driving (Kuglerová et al., 2017). However, with CCF in place surrounding the ditches, the water level would be kept low enough (due to continuous tree cover taking up water) that the ditches would no longer be needed to drain the landscape (Leppä et al., 2020). This would also help to avoid the negative water quality effects of DNM such as increased sediment and nutrient export (Nieminen et al., 2018).

This study focuses on assessing the area implications of conducting alternative forest management within riparian zones. I examined both the area of different sized riparian zones, as well as the area of production forest and the species composition within these zones. However, I did not study the practicalities of conducting continuous cover forestry or alternative forest management within riparian zones. In order for alternative management within these zones to be successful, field trials and additional studies should be conducted to determine the best management practices. Whether this management is seen as single tree selection, strip felling, gap cutting, or a different method altogether, future studies need to examine the impacts and implications of utilizing these different methods, and which method could be the most effective at both preserving biodiversity and the functioning of the riparian zones, while still allowing for forestry within the buffer zones.

4.6 European Union directive

The European Union's EU Forest Strategy for 2030 calls for several changes to be made within the forestry sector throughout the member countries. One of the proposals set forth in the Forest Strategy was an overall target of protecting at least 30% of the EU land under a current forest management regime (European Commission, 2021). This proposal goes on to discuss the possibilities of alternative forest management practices such as continuous cover forestry which can ensure the long-term environmental and socio-economic viability of forests. In Sweden, one method of achieving the EU goal would be to utilize riparian buffer zones as an area of protection or alternative forest management such as continuous cover forestry.

Utilizing riparian buffers would be a good way to meet the EU Forest Strategy for 2030 of having 30% of managed forest land under alternative management methods (Figure 9), while at the same time protecting areas that are of great importance for ecological functioning and biodiversity. I found that if both ditches and natural channels were managed with 30 m wide CCF managed buffers, approximately 20% of the productive forest land would be transitioned to CCF. If buffers were expanded to 60 m, this percentage would increase to about 40% of productive forest being transitioned to alternative forest management. Thus, these zones could, in fact, be utilized to meet the EU Forest Strategy goals, highlighting the importance of this study. However, there may be a trade off in converting areas surrounding streams to alternative forest management, and the need to protect other areas of important conservation status. Not all conservation areas can be allocated to riparian areas, and while riparian zones are an important area to protect, so too are other areas of high conservation importance such as areas affected by wildfire, or woodland key habitat areas. This highlights again the fact that while burned areas or woodland key habitats may be set aside for strictly conservation purposes, these riparian zones would rather be converted to alternative management. Harvest could still be allowed, and they could still be used for commercial forest management. To my knowledge a comprehensive study of the productivity status of riparian buffer zones, and tree volume compositions in different buffer zone management alternatives on a national scale has not previously been completed.

4.7 Scaling up to a landscape level and other future steps

More work is needed to scale this study to a landscape perspective. This study focused on 11 study sites ranging from southern Sweden to northern Sweden with a total area encompassing 43 050 hectares. While this offers a good basis for understanding ditch and natural channels throughout Sweden in these areas, a study scaling up this work to a country-wide perspective would be beneficial in determining the best riparian management methods.

In addition to scaling to the landscape level, additional buffer forms could be examined. One of the most promising of these is hydrologically adapted buffers. Hydrologically adapted buffers work by optimizing placement of riparian buffers around hydrologically important or sensitive areas. Because riparian function, biodiversity, biogeochemistry, and hydrology are not uniform, and vary at small spatial scales along streams, (Kuglerová et al., 2016; Leach et al., 2017), hydrologically adapted buffers can maximize the benefit by taking advantage of this fact. These hydrologically adapted buffers are created using soil wetness maps and can offer additional protection to groundwater discharge hotspots, which have higher ecological importance for many riparian functions (Kuglerová, et al., 2014).

This study looked at the entire network of both ditches and natural channels within the study areas, for a comprehensive view of riparian zone protection. However, all implementation of riparian buffer zones, alternative forest management, and setting aside forest from traditional management should be carefully considered when comparing the ecological and social benefits versus the potential economic costs. As all ditches and natural channels within the area were included, there was no differentiation between channel size, or ecological function of the waterways. Implementing alternative management in buffer zones will need to be done on a site-specific case-by-case basis, with careful consideration given to both ecological and social values, and economic value.

5. CONCLUSION

With increasing demand for alternative forest management methods alongside a relatively poor state of riparian buffers in Sweden, (Kuglerová et al., 2020) there is an opportunity to manage riparian zones in a way that maintains productivity, while also protecting the functioning and biodiversity of the riparian zone and stream. This study analysed the potential effects of a changed management regime on the area of productive forest, species composition of trees, and volume of trees within different riparian zone management scenarios.

I found a significant latitudinal trend between riparian buffer zone tree species composition between northern and southern study sites, with increasing spruce, deciduous, and total tree volume in the south of Sweden, and decreasing pine volume in the south. Buffer zones had overall lower tree volume than the surrounding area, suggesting that there would be less economic impact of converting these areas to alternative forest management. The current domination by conifer species in the buffer areas also shows how much riparian zones could benefit from increased tree species diversity in riparian zones.

This difference in species composition also affects the feasibility and form in which alternative forest management could occur within the riparian buffer zone, with potentially greater possibilities in the south, where there is already a higher species diversity, higher amount of broadleaved species, and less pine.

There was very little difference seen between northern and southern study sites in terms of the proportion of productive forest land that would be converted to alternative forest management. To get an accurate representation for each forest stand, the amount of productive forest land would need to be examined on a stand by stand basis, which this study and the methods used, showcase the tools and feasibility of doing so. However, it relies on access to accurate and fully digitized channel data, which is lacking for most of the country.

General conclusions can be drawn, however, about the difference in area that would be included in buffers around ditches versus natural channels. Protecting all riparian zones around natural channels, even with large 60 m buffers, would require a relatively small percentage (5 - 6%, Figure 9) of productive forest land being taken out of typical rotation forest management. To buffer ditches would require a much more extensive percentage (40%, Figure 9) of productive forest land. But, even with a 30 m buffer around both natural channels and ditches, it would be about 20% of productive forest land converted to alternative management. In a spatial and theoretical perspective, it is feasible to protect riparian zones by converting them to alternative forest management in a way that would allow for economic harvest within the zones while also meeting current demands from the public and the EU for conversion of currently managed forest to alternative forest management.

Future study is needed to examine how to practically implement alternative forest management within riparian buffers. An economic analysis of the costs and benefits of alternative forest management within riparian buffers would also help landowners and managers decide how best to manage their buffers for the protection of ecological function, while allowing for feasible economic forestry practices.

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Popular Science Summary

Within Sweden, pressure for forest management methods other than clear cut forestry has been increasing from both the general public, private forest owners, and even from outside pressure from the European Union. Riparian zones are one area where it has been proposed that alternative management methods could take place.

Riparian zones, or the area surrounding a waterway, provide several functions for the ecosystem, such as shading the stream and controlling water temperature, buffering the stream from an increase in sediment and nutrients when the surrounding area is harvested, and providing deadwood and nutrient subsidies to the stream, among other functions. However, the condition of riparian buffer zones following harvest in Sweden is often too poor to provide all these necessary functions. By conducting alternative forest management within riparian buffer zones, it is possible that the condition of the buffers could be improved, while also increasing the amount of land under alternative forest management. Therefore, this thesis aims to conduct a spatial analysis of how much land would be converted to alternative forest management under four different buffer width scenarios.

I conducted this study using previously collected geographical data of forest ditches and natural channel networks in 11 study areas throughout Sweden. I then looked at how the area of buffers within these study areas would vary between northern and southern Sweden, the proportion of productive to unproductive forestland contained within buffer zones, and how much of the overall productive forestland would be converted to alternative forest management. I also looked at the species composition within these buffer zones to determine the feasibility of converting these areas to alternative management, as well as to consider the forms that this alternative management may take.

I found that on a spatial basis, riparian buffer zones may offer a great opportunity for conducting alternative forest management. If all natural channels were to have very large 60 m buffer zones placed around them, it would require converting only 5% - 6% of current productive forestland to alternative forest management. If a 30 m buffer were to be placed around both natural channels and forest ditches, it would require converting about 20 % of currently managed forestland to alternative forest management. In terms of species composition, there was significant variation between northern and southern Sweden, with southern zones having more deciduous, spruce, and total tree volume, and northern zones having more pine tree volume. This could affect the methods that alternative forest management takes, with southern zones being more primed for single tree selection, and northern zones more primed for larger scale disturbance methods such as strip cutting or gap cutting.

This thesis, however, is strictly a theoretical approach looking at a spatial scale, and future study will need to be done on the practical implementation and possibilities of alternative forest management within riparian zones, as well as the possible economic consequences.

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Appendix 1

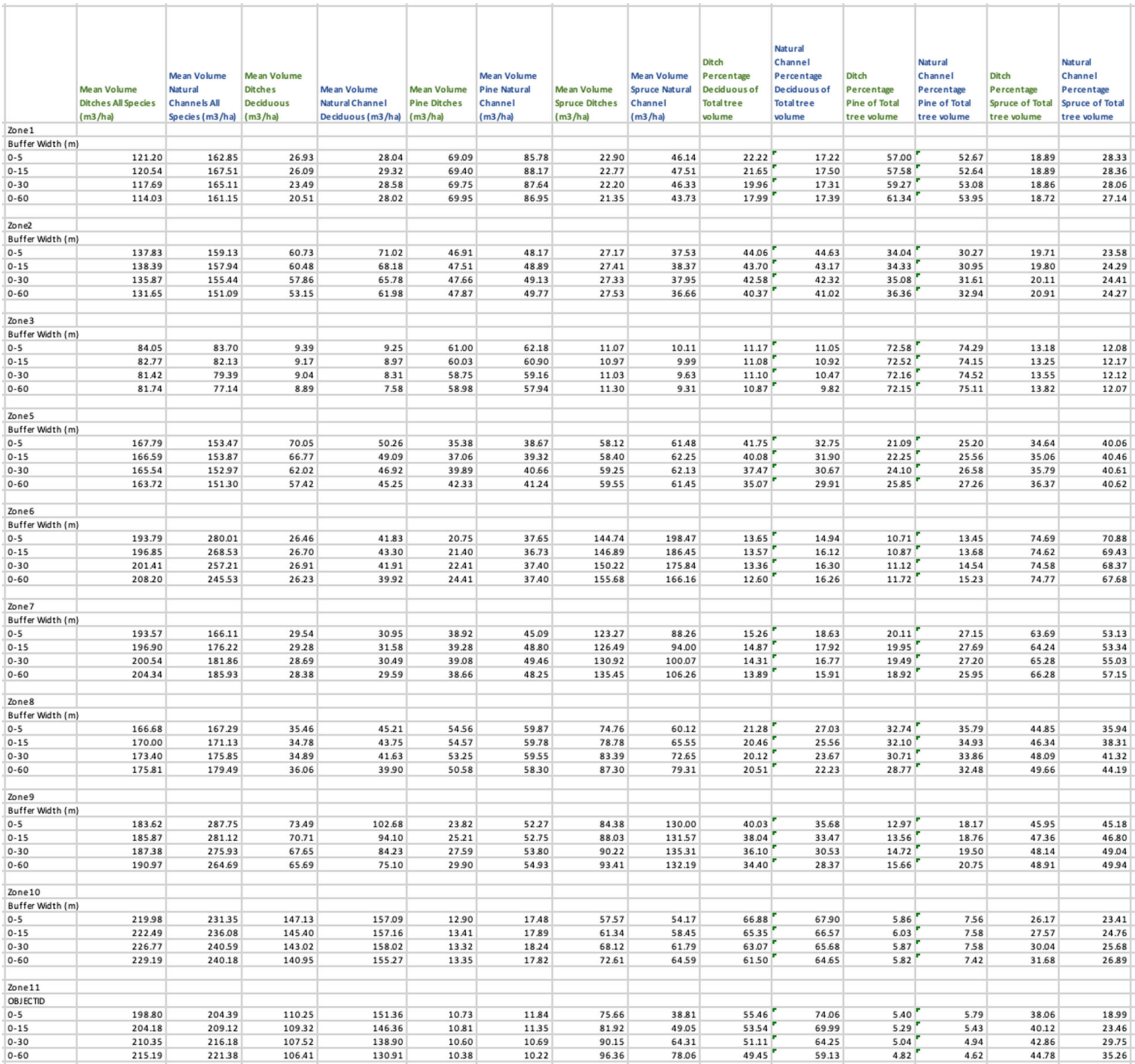
Appendix 1 shows the proportional area of each productivity status in the different buffer width scenarios. This is divided for natural channels and ditches.

	Natural Channel											
Zone	5m buffer productive forest Percentage of Study area	15m buffer productive forest Percentage of Study area	30m buffer productive forest Percentage of Study area	60m buffer productive forest Percentage of Study area	5m buffer Unproductive forest Percentage of study area	15m buffer Unproductive forest Percentage of study area	30m buffer Unproductive forest Percentage of study area	60m buffer Unproductive forest Percentage of study area	5m buffer Non-Forest land Percentage of study area	15m buffer Non-Forest land Percentage of study area	30m buffer Non-Forest land Percentage of study area	60m buffer Non-Forest land Percentage of study area
1	0.05	0.16	0.35	0.86	0.02	0.05	0.10	0.17	0.05	0.15	0.33	0.74
2	0.28	0.84	1.71	3.53	0.05	0.17	0.34	0.72	0.02	0.07	0.15	0.38
3	0.32	0.92	1.75	3.34	0.11	0.30	0.51	0.89	0.04	0.16	0.49	1.23
4	0.70	2.01	3.98	7.86	0.05	0.13	0.26	0.48	0.13	0.33	0.60	1.18
5	0.55	1.55	3.01	5.94	0.04	0.12	0.23	0.43	0.11	0.36	0.80	1.77
6	0.36	1.13	2.44	5.32	0.00	0.00	0.00	0.07	0.06	0.20	0.46	1.12
7	0.11	0.36	0.84	2.10	0.03	0.08	0.16	0.34	0.10	0.28	0.55	1.15
8	0.43	1.31	2.74	5.92	0.09	0.27	0.51	0.93	0.35	0.91	1.61	2.85
9	0.23	0.71	1.48	3.40	0.01	0.02	0.03	0.06	0.03	0.14	0.33	0.82
10	0.18	0.52	1.00	2.10	0.01	0.01	0.03	0.05	0.03	0.12	0.36	1.06
11	0.23	0.66	1.34	2.82	0.01	0.02	0.03	0.04	0.05	0.14	0.29	0.60
Average	**0.31**	**0.92**	**1.88**	**3.93**	**0.04**	**0.11**	**0.20**	**0.38**	**0.09**	**0.26**	**0.54**	**1.17**

	Ditches											
Zone	5m buffer productive forest Percentage of Study area	15m buffer productive forest Percentage of Study area	30m buffer productive forest Percentage of Study area	60m buffer productive forest Percentage of Study area	5m buffer Unproductive forest Percentage of study area	15m buffer Unproductive forest Percentage of study area	30m buffer Unproductive forest Percentage of study area	60m buffer Unproductive forest Percentage of study area	5m buffer Non-Forest land Percentage of study area	15m buffer Non-Forest land Percentage of study area	30m buffer Non-Forest land Percentage of study area	60m buffer Non-Forest land Percentage of study area
1	3.07	8.89	15.95	26.67	1.37	3.62	5.57	7.13	0.61	1.95	3.78	6.43
2	1.94	5.67	10.31	17.11	0.60	1.68	2.87	3.71	0.14	0.47	0.98	1.76
3	3.31	9.58	18.20	32.22	2.76	6.89	10.31	13.13	1.24	4.35	9.10	15.39
4	2.23	6.40	11.95	21.67	0.37	1.02	1.74	2.49	0.17	0.61	1.32	2.56
5	1.13	3.06	5.27	9.45	0.09	0.24	0.38	0.64	0.21	0.70	1.48	3.16
6	4.22	12.56	23.07	40.37	0.01	0.03	0.05	0.21	0.11	0.33	0.98	2.63
7	2.70	8.16	16.26	31.66	0.24	0.71	1.38	2.65	0.42	1.43	3.38	7.04
8	2.37	6.76	12.64	23.34	0.40	1.04	1.84	3.04	0.34	1.29	3.07	6.51
9	0.81	2.59	5.30	11.41	0.01	0.04	0.09	0.17	0.09	0.40	1.08	3.01
10	1.68	5.04	9.96	19.96	0.03	0.09	0.15	0.31	0.30	1.27	3.37	8.43
11	3.08	8.79	16.29	29.01	0.05	0.13	0.26	0.45	0.31	1.28	3.17	7.51
Average	**2.41**	**7.05**	**13.20**	**23.90**	**0.54**	**1.41**	**2.24**	**3.08**	**0.36**	**1.28**	**2.88**	**5.86**

Appendix 2

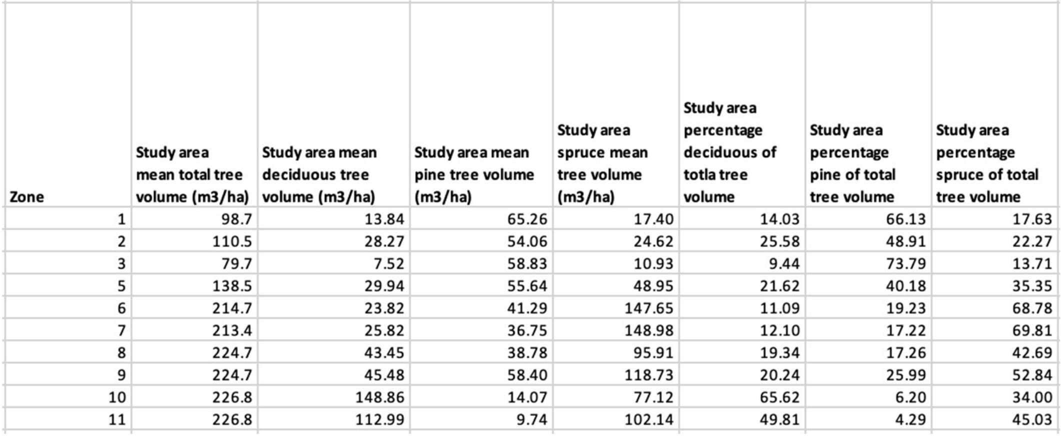
Appendix 2 shows the mean volume of the different tree species comprising different buffer widths. It also presents this as a percentage of the total tree volume in each buffer zone.



	Mean Volume Ditches All Species (m3/ha)	Mean Volume Natural Channels All Species (m3/ha)	Mean Volume Ditches Deciduous (m3/ha)	Mean Volume Natural Channel Deciduous (m3/ha)	Mean Volume Pine Ditches (m3/ha)	Mean Volume Pine Natural Channel (m3/ha)	Mean Volume Spruce Ditches (m3/ha)	Mean Volume Spruce Natural Channel (m3/ha)	Ditch Percentage Deciduous of Total tree volume	Natural Channel Percentage Deciduous of Total tree volume	Ditch Percentage Pine of Total tree volume	Natural Channel Percentage Pine of Total tree volume	Ditch Percentage Spruce of Total tree volume	Natural Channel Percentage Spruce of Total tree volume
Zone1														
Buffer Width (m)														
0-5	121.20	162.85	26.93	28.04	69.09	85.78	22.90	46.14	22.22	17.22	57.00	52.67	18.89	28.33
0-15	120.54	167.51	26.09	29.32	69.40	88.17	22.77	47.51	21.65	17.50	57.58	52.64	18.89	28.36
0-30	117.69	165.11	23.49	28.58	69.75	87.64	22.20	46.33	19.96	17.31	59.27	53.08	18.86	28.06
0-60	114.03	161.15	20.51	28.02	69.95	86.95	21.35	43.73	17.99	17.39	61.34	53.95	18.72	27.14
Zone2														
Buffer Width (m)														
0-5	137.83	159.13	60.73	71.02	46.91	48.17	27.17	37.53	44.06	44.63	34.04	30.27	19.71	23.58
0-15	138.39	157.94	60.48	68.18	47.51	48.89	27.41	38.37	43.70	43.17	34.33	30.95	19.80	24.29
0-30	135.87	155.44	57.86	65.78	47.66	49.13	27.33	37.95	42.58	42.32	35.08	31.61	20.11	24.41
0-60	131.65	151.09	53.15	61.98	47.87	49.77	27.53	36.66	40.37	41.02	36.36	32.94	20.91	24.27
Zone3														
Buffer Width (m)														
0-5	84.05	83.70	9.39	9.25	61.00	62.18	11.07	10.11	11.17	11.05	72.58	74.29	13.18	12.08
0-15	82.77	82.13	9.17	8.97	60.03	60.90	10.97	9.99	11.08	10.92	72.52	74.15	13.25	12.17
0-30	81.42	79.39	9.04	8.31	58.75	59.16	11.03	9.63	11.10	10.47	72.16	74.52	13.55	12.12
0-60	81.74	77.14	8.89	7.58	58.98	57.94	11.30	9.31	10.87	9.82	72.15	75.11	13.82	12.07
Zone5														
Buffer Width (m)														
0-5	167.79	153.47	70.05	50.26	35.38	38.67	58.12	61.48	41.75	32.75	21.09	25.20	34.64	40.06
0-15	166.59	153.87	66.77	49.09	37.06	39.32	58.40	62.25	40.08	31.90	22.25	25.56	35.06	40.46
0-30	165.54	152.97	62.02	46.92	39.89	40.66	59.25	62.13	37.47	30.67	24.10	26.58	35.79	40.61
0-60	163.72	151.30	57.42	45.25	42.33	41.24	59.55	61.45	35.07	29.91	25.85	27.26	36.37	40.62
Zone6														
Buffer Width (m)														
0-5	193.79	280.01	26.46	41.83	20.75	37.65	144.74	198.47	13.65	14.94	10.71	13.45	74.69	70.88
0-15	196.85	268.53	26.70	43.30	21.40	36.73	146.89	186.45	13.57	16.12	10.87	13.68	74.62	69.43
0-30	201.41	257.21	26.91	41.91	22.41	37.40	150.22	175.84	13.36	16.30	11.12	14.54	74.58	68.37
0-60	208.20	245.53	26.23	39.92	24.41	37.40	155.68	166.16	12.60	16.26	11.72	15.23	74.77	67.68
Zone7														
Buffer Width (m)														
0-5	193.57	166.11	29.54	30.95	38.92	45.09	123.27	88.26	15.26	18.63	20.11	27.15	63.69	53.13
0-15	196.90	176.22	29.28	31.58	39.28	48.80	126.49	94.00	14.87	17.92	19.95	27.69	64.24	53.34
0-30	200.54	181.86	28.69	30.49	39.08	49.46	130.92	100.07	14.31	16.77	19.49	27.20	65.28	55.03
0-60	204.34	185.93	28.38	29.59	38.66	48.25	135.45	106.26	13.89	15.91	18.92	25.95	66.28	57.15
Zone8														
Buffer Width (m)														
0-5	166.68	167.29	35.46	45.21	54.56	59.87	74.76	60.12	21.28	27.03	32.74	35.79	44.85	35.94
0-15	170.00	171.13	34.78	43.75	54.57	59.78	78.78	65.55	20.46	25.56	32.10	34.93	46.34	38.31
0-30	173.40	175.85	34.89	41.63	53.25	59.55	83.39	72.65	20.12	23.67	30.71	33.86	48.09	41.32
0-60	175.81	179.49	36.06	39.90	50.58	58.30	87.30	79.31	20.51	22.23	28.77	32.48	49.66	44.19
Zone9														
Buffer Width (m)														
0-5	183.62	287.75	73.49	102.68	23.82	52.27	84.38	130.00	40.03	35.68	12.97	18.17	45.95	45.18
0-15	185.87	281.12	70.71	94.10	25.21	52.75	88.03	131.57	38.04	33.47	13.56	18.76	47.36	46.80
0-30	187.38	275.93	67.65	84.23	27.59	53.80	90.22	135.31	36.10	30.53	14.72	19.50	48.14	49.04
0-60	190.97	264.69	65.69	75.10	29.90	54.93	93.41	132.19	34.40	28.37	15.66	20.75	48.91	49.94
Zone10														
Buffer Width (m)														
0-5	219.98	231.35	147.13	157.09	12.90	17.48	57.57	54.17	66.88	67.90	5.86	7.56	26.17	23.41
0-15	222.49	236.08	145.40	157.16	13.41	17.89	61.34	58.45	65.35	66.57	6.03	7.58	27.57	24.76
0-30	226.77	240.59	143.02	158.02	13.32	18.24	68.12	61.79	63.07	65.68	5.87	7.58	30.04	25.68
0-60	229.19	240.18	140.95	155.27	13.35	17.82	72.61	64.59	61.50	64.65	5.82	7.42	31.68	26.89
Zone11														
OBJECTID														
0-5	198.80	204.39	110.25	151.36	10.73	11.84	75.66	38.81	55.46	74.06	5.40	5.79	38.06	18.99
0-15	204.18	209.12	109.32	146.36	10.81	11.35	81.92	49.05	53.54	69.99	5.29	5.43	40.12	23.46
0-30	210.35	216.18	107.52	138.90	10.60	10.69	90.15	64.31	51.11	64.25	5.04	4.94	42.86	29.75
0-60	215.19	221.38	106.41	130.91	10.38	10.22	96.36	78.06	49.45	59.13	4.82	4.62	44.78	35.26

Appendix 3

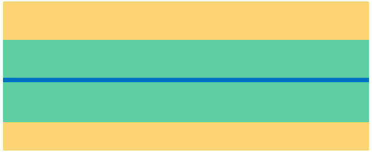
Appendix 3 shows the average volume in m^3/ha for the different tree species in the overall study area. It also presents this as a percentage of the total tree volume.

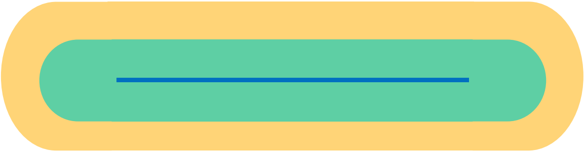


Zone	Study area mean total tree volume (m3/ha)	Study area mean deciduous tree volume (m3/ha)	Study area mean pine tree volume (m3/ha)	Study area spruce mean tree volume (m3/ha)	Study area percentage deciduous of totla tree volume	Study area percentage pine of total tree volume	Study area percentage spruce of total tree volume
1	98.7	13.84	65.26	17.40	14.03	66.13	17.63
2	110.5	28.27	54.06	24.62	25.58	48.91	22.27
3	79.7	7.52	58.83	10.93	9.44	73.79	13.71
5	138.5	29.94	55.64	48.95	21.62	40.18	35.35
6	214.7	23.82	41.29	147.65	11.09	19.23	68.78
7	213.4	25.82	36.75	148.98	12.10	17.22	69.81
8	224.7	43.45	38.78	95.91	19.34	17.26	42.69
9	224.7	45.48	58.40	118.73	20.24	25.99	52.84
10	226.8	148.86	14.07	77.12	65.62	6.20	34.00
11	226.8	112.99	9.74	102.14	49.81	4.29	45.03

Appendix 4

Appendix 4 shows a representation of the difference between square end buffers, and the rounded end buffers used in this study. In both visualizations, the blue line represents a waterway, with the green representing a small width buffer, and the orange a second wider buffer. On the left, is the square end buffer, with the buffer ending flush with the end of the stream, whereas a rounded end buffer also buffers upstream and downstream of the end of the waterway.





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