Universität Zürich^{UZH}

Geographisches Institut

Locating the Treeline:

Terminology, Modelling and Vagueness

Micha Franz
18-739-755

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Supervised by: Prof. Dr. Ross Purves, Dr. Peter Bebi
Faculty representative: Prof. Dr. Ross Purves

Abstract

The treeline is a widely used term that appears in various Swiss laws and regulations, often without further specification, implying a general understanding of the term. Scientific literature, however, paints a different picture: an analysis of over 30 publications revealed 72 distinct terms related to the treeline with varying definitions and inconsistencies across the different terms. Correspondence with Swiss authorities also indicated divergent understandings of the term in practice, varying by application context. This thesis investigates how the treeline can be defined, modelled using GIS methods and spatially visualised, with a particular focus on aspects of vagueness. The objectives are to clarify terminology, evaluate GIS-based modelling approaches, quantify and visualise uncertainty and vagueness in spatial delineation. A terminology review synthesised definitions from the literature into a framework distinguishing three hierarchical boundaries within the treeline ecotone: the forest line, treeline and shrubline. Four modelling approaches were reproduced and compared using qualitative and quantitative analysis, complemented by testing sensitivity to input data and forest definitions. The results demonstrate that methods produce differing treeline delineations regardless of whether original or harmonised input data is used. These differences stem from both methodological choices and conceptual ambiguities. Intrinsic vagueness emerges as the primary source of terminological inconsistency and modelling divergence, manifesting as conceptual vagueness and sorites vagueness. The thesis contributes a terminology framework for the treeline ecotone, a reproducible workflow enabling method comparison under harmonised conditions and a visualisation approach depicting zones of determinacy and indeterminacy across different treeline interpretations, representing vagueness. Rather than being eliminated, vagueness should be explicitly acknowledged. Visualisation techniques for spatial vagueness remain underdeveloped; the approach presented here offers an alternative to representing the treeline as a single crisp boundary. The thesis advocates for terminological transparency in both research and practice, alongside improved reproducibility in future studies.

Acknowledgments

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Chapter 1: Introduction

1.1 Motivation

The treeline is an important concept in geography and ecology, a significant boundary for both landscape and environmental conditions and the most studied of all distribution boundaries of trees (Körner, 1998; Szerencsits, 2012). It has an impact on land use, nature conservation and legal frameworks and has been researched for more than 200 years (Holtmeier and Broll, 2019).

Although it might not be the most well-known geographical term, many probably have an idea of what is meant when talking about the treeline as the term is for example used in several Swiss laws, without being further defined or explained. However, it is often far from straightforward to establish explicit definitions for geographic terms, as many of such terms are intrinsically vague (Bennett, 2001). Just as it is a challenge to define the extends and meaning of a mountain (Fisher et al., 2004) or a lake or river (Bennett and Third, 2008), Lund (2002) shows that the question of when an area is considered a forest is of rather complicated matter and is itself further dependent on the definition of the term tree. The answer to what constitutes a forest and a tree is thus inherently relevant for the term treeline (Holtmeier, 2003). Moreover, the definition of what constitutes as 'line' is similarly important (Körner and Hoch, 2023).

For Switzerland, the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) is a first possible point of reference. They define the treeline as a "transitional area where subalpine or boreal forests fade into tundra or alpine grasslands" (WSL, n.d). In another WSL publication (Hagedorn et al., 2006, p. 52) it is described as "the line that can be drawn along the upper edge of a closed forest". Already these two definitions stemming from the same source, raise questions as the first talks about an area and the second about a line. This ambiguity is further enhanced when looking into treeline literature. Körner (1998, p. 446) defines the treeline as "roughly marking the line connecting the highest forest sections within a slope or several slopes with similar exposure". Paulsen and Körner (2001, p. 820) go in a similar direction talking about "the upper connecting boundary line of the uppermost forest patches". Szerencsits (2012) argues it is not simply a line but rather a transition zone. He follows the logic of Armand (1992) stating the paradox that all natural boundaries are actually transition zones with two boundaries, which are themselves transition zones and so on. Also Holtmeier (2003) talks about a transition zone between closed forest and the most advanced individual tree. Holtmeier, however, uses the term timberline, which brings up another issue: different terms such as timberline, treeline or forest line are all associated with the upper elevational boundary of a forest, but there is no consensus on their definition. In Switzerland, where this thesis is focused on, the related German terms are *Waldgrenze* and *Baumgrenze*, but it first has to be evaluated how these two terms relate to the three aforementioned English terms[1].

Another related term is the climatic or potential treeline as for example mentioned in Paulsen and Körner (2014), where a model on the basis of temperature and other climate related data was developed to calculate the treeline on a global scale[2]. Könz et al. (2022) modelled the same for the extent of Switzerland, but referring to it as *obere Waldgrenze*, translated to 'upper treeline'. These terms describe the altitude up to which a forest could theoretically grow, which again differs substantially from the previous definitions. What complicates this debate is that trees are often absent at this climatic limit, since the growth of trees can also be limited by other elements than temperature, leading to yet more terms. The orographic treeline for example, refers to a growth limitation through rocky terrain, slope debris or reoccurring avalanches

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[1] Since Switzerland has four official languages, there are more translations, besides the German one but for for simplicity reasons, these are not considered here.

[2] The reason trees stop growing at certain altitudes is heat deficiency — the globally dominant constraint for high-altitude tree growth. While tree canopies are exposed to ambient air temperatures, smaller plants can decouple from the atmosphere and gain warmth from solar heating, allowing them to survive above the treeline (Körner, 2021a).

(Holtmeier, 2003). Trees can also be limited by frequent forest fires, as is the case along the slope of Mount Kilimandjaro, where the treeline varies across several thousand meters in elevation (Körner and Hoch, 2023). The term anthropogenic treeline is used for limits caused by human activity such as land use (Holtmeier, 2003). This limit is predominant in Switzerland through extensive agriculture in the last centuries. In fact, Paulsen and Körner (2001) state that undisturbed, natural limits are actually rare in the European Alps. Holtmeier (2003) mentions the term actual timberline and uses it to refer to the position up to where the uppermost forest grows. Szerencsits (2012) uses the term forest line for the same thing.

These examples show that treeline terminology is a complicated topic and requires a more in depth review. But why should we bother with the definition of that term with all its vagueness and subjectivity, why does it matter? As mentioned, the term treeline, more precisely, its German translation *Waldgrenze*, is used in various Swiss laws. Some examples are listed below:

- *Auf öffentlichem Grund ist das Campieren in Zelten, Wohnmobilen und dergleichen verboten. Ausgenommen von diesem Verbot ist das kurzfristige Aufstellen von einzelnen Zelten über der Waldgrenze im Rahmen von Hochgebirgstouren.*[3]
- *Grasschäden verursacht durch Gämsen, Hirsche, Steinböcke sowie Wildschweine in Sömmerungsgebieten oberhalb der Waldgrenze werden nicht ersetzt.*[4]
- *Die Leitung von Wanderungen mit Übernachtung im Biwak oberhalb der Waldgrenze, die im Bereich bis und mit T3 stattfinden, benötigen eine Zusatzausbildung.*[5]

In such a context, it seems relevant to know if that term refers to a line connecting forest patches, a transitional area or a hypothetical limit of forest growth based in physical parameters. Otherwise, how could one determine whether they are below or above that line? Beyond legal applications, this definitional complexity also affects scientific research, for example in studies analysing upward treeline shifts that have been widely documented in recent decades as response to climate change. To better understand these dynamics, Nguyen (2025) analysed the upward treeline shift rates in Switzerland over the last 80 years. She used an approach that differentiates forest growth near the climatic treeline and upward shifts occurring significantly further below. This distinction allows to assess what amount of forest upward shifts are actually responses to changing climate as opposed to the mere recovery of previously depressed treelines caused by agricultural land use.

My motivation to research GIS-based treeline models results from its relevant yet ambiguous role in both legal and scientific contexts. As illustrated with the Swiss regulation prohibiting wild camping below the treeline and others, a lack of clear and consistent definition may complicate its enforcement. Does the term in legal texts refer to a line connecting patches, a diffuse transition zone or a hypothetical, invisible line limiting forest growth? And if that issue was resolved, what definition of forest or tree is used? Each interpretation may lead to a different spatial delineation. In the case of laws this leads to different legal boundaries or in upward treeline shift analysis to different rates even with the same methodology. Through a comparison of different definitional approaches across treeline literature, coupled with uncertainty quantification and visualization techniques, I aim to catalogue the range of terminological variations and synthesize these into a comprehensible terminological framework of the treeline ecotone[6]. By mapping how different terms are used and defined across studies, this analysis tries to identify patterns of usage, highlight conceptual overlaps and distinctions. This can support the appropriate selection of definitions for specific applications and treeline-based research, while making aspects of vagueness explicit.

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[3] Art. 14: Polizeigesetz der Gemeinde Zuoz.

[4] Art. 3 Abs. 2 lit. G: Verordnung über die Verhütung und Entschädigung von Wildschäden. BSG 922.51, Kanton Bern

[5] Anhang 3[34] (Art. 20), Ziff. 2: Erforderliche Zusatzausbildungen, Verordnung des BASPO über «Jugend und Sport» SR 415.011.2.

[6] Ecotones are areas where two habitats meet (Cambridge Dictionary, 2025)

1.2 Research Questions

The issues outlined above lead to the following three research questions, which I will analyse in this thesis:

- RQ1: How is the term treeline defined and what issues arise with its definition?
- RQ2: What GIS-based methods are suitable for spatially modelling the treeline and what are their respective strengths and limitations?
- RQ3: What types of uncertainty and aspects of vagueness arise in the spatial delineation of the treeline and how can they be quantified and visualized?

1.3 Thesis Outline

The second chapter builds on this introduction by presenting the background, beginning with the terminology and the many definitions of the term treeline. In the third chapter, authorities behind relevant laws and regulations were contacted to explore how they define and apply the term treeline and whether they see a need for greater clarity. The chapter is concluded by looking into the field of uncertainty and vagueness to address the issue of precise delineation in contrast to the ecological reality of the treeline. Chapter 4 details selected treeline modelling approaches and how I replicated them. Chapter 5 aims to determine similarities and differences between the models. Chapter 6 synthesises these findings with insights from the literature review and requirement analysis to assess the suitability of these methods for different applications, while addressing terminological issues, aspects of vagueness, reproducibility and limitations of the thesis. Chapter 7 concludes the thesis.

Chapter 2: Background

2.1 Treeline Terminology

The transition between forest and treeless alpine tundra is a widely known phenomenon. When viewed from a distance, the boundary is often striking and can be pointed out by layman throughout the alps and other mountain ranges. Among all distributional forest boundaries, it is the most thoroughly studied (Körner, 2012). It is the only biogeographic unit on land that exists globally, which was already observed by Alexander von Humboldt more than 150 years ago in his illustration *Die Verbreitung der Pflanzen in senkrechter Richtung*, as shown in Figure 2.1.

Figure 2.1: Humboldt's early recognition of consistent altitudinal patterns, including sharp transitions between forested and non-forested mountainous areas that represent treeline boundaries across geographically distant ranges (Humboldt, 1860).

Despite this conspicuity and extensive research around the ecotone, the literature reveals widespread terminological inconsistencies, with researchers using a variety of overlapping terms and definitions such as treeline, timberline, forest line, tree limit, tree species limit and many more. Each of these terms carries specific nuances with it that describe particular parts of the ecotone. But if no consensus exists on which terms correspond to which parts of the ecotone and how those parts are defined, issues arise quickly. For example, if two papers were to examine how the treeline responds to rising temperatures due to climate change, it makes a difference if they are talking about "the line connecting the uppermost [...] patches of trees of at least 3 m height in undisturbed areas" (Paulsen and Körner, 2014, p. 1) or "the line connecting the highest patches of forest within a given slope [...]" (Körner, 1998, p. 446). Surely, the line connecting the highest patches of forest is not the same line as the line connecting the uppermost patches of trees. Otherwise, the terms tree and forest become synonyms. Further, in the first definition a minimum tree height is given and the area is specified ('undisturbed') and in the second the area is differently specified ('within a given slope'). Yet, the authors used these definitions for the same term, treeline. And even if they were talking about the same thing it is likely that they do not use the same exact definition. For example Wang et al. (2022, p. 890) define the treeline as "line that connects the uppermost, undisturbed group of trees of a certain height", which sounds similar the definition of Paulsen and Körner (2014). But is an 'undisturbed group of trees' the same as a 'patch of trees'? Also, group and patch are rather vague terms and the meaning of undisturbed can be understood in different ways. And is a 'certain height' the same as three meters? It might seem pedantic to take such a critical and close look at these definitions but the terminological confusion can lead to consequences. Meta-analyses become complicated if researchers have to navigate potential definitional mismatches between studies and combining results from inconsistent definitions can be misleading when subjective or individual definitions are used.

Such terminological issues also arise in a broader context than treeline research as Lund (2002) shows in his extensive analysis on tree and forest definition. I do not want to advocate a rigid field-wide standardization that may not always be suitable for the diverse contexts and scales of treeline research, but

there should always be definitional transparency since establishing terminological conventions is needed for effective scientific communication (Körner, 2007). This means stating an explicit explanation of which terminological decisions have been made and why, so that other researchers know which concept is being discussed and can make informed decisions about the comparability and interpretation of results across different studies.
It is important to note that much of this terminological variation stems from researchers focusing on the broader phenomenon of altitudinal forest and tree growth limitation due to physical factors rather than attempting to create precise distinctions between different boundary types. Many studies appropriately define their specific research target without necessarily intending to differentiate treeline from forest line or timberline — a distinction that may not be central to their research objectives. However, when the goal shifts to spatial representation and mapping of these boundaries, as in this thesis, such definitional precision becomes critical. The challenge lies not in the existence of varied definitions per se, but in the lack of explicit acknowledgment of which specific boundary type is being studied and mapped. Körner (2012, p. 18), one of the most influential treeline researchers of the last 25 years, puts it simply: "Terminology is not science, but without terminology there is confusion."

By going through 30 papers from 1923 to 2023, I have collected a wide variety of mentioned terms and definitions related to the treeline ecotone. The world cloud in Figure 2.2 provides a first impression and reveals the vast array of competing terms.

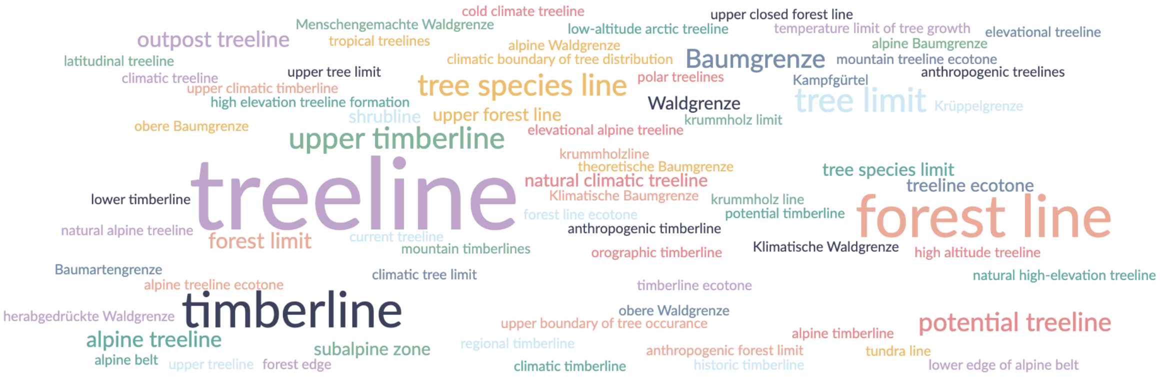

Figure 2.2: Word cloud showing frequently used terms in treeline literature. Larger font size indicates more frequent mentions, colours are random. Source: https://wordclouds.ethz.ch/

To make sense of this abundance of terms, I will try to categorize them in a meaningful way and establish a framework of the treeline ecotone. It has to be noted that the selection of papers was not done in a systematic approach, as this would have been out of the scope of this thesis. The papers were selected through snowball sampling by starting from key sources in the general literature review such as Körner (2021a) and following citation chains to identify additional relevant studies. Thus, this selection of terms and definitions is not complete, but it should be enough to demonstrate the issue that it poses for this thesis. I collected a total of 72 distinct terms, that were categorized into seven different groups, as shown in Figure 2.3.

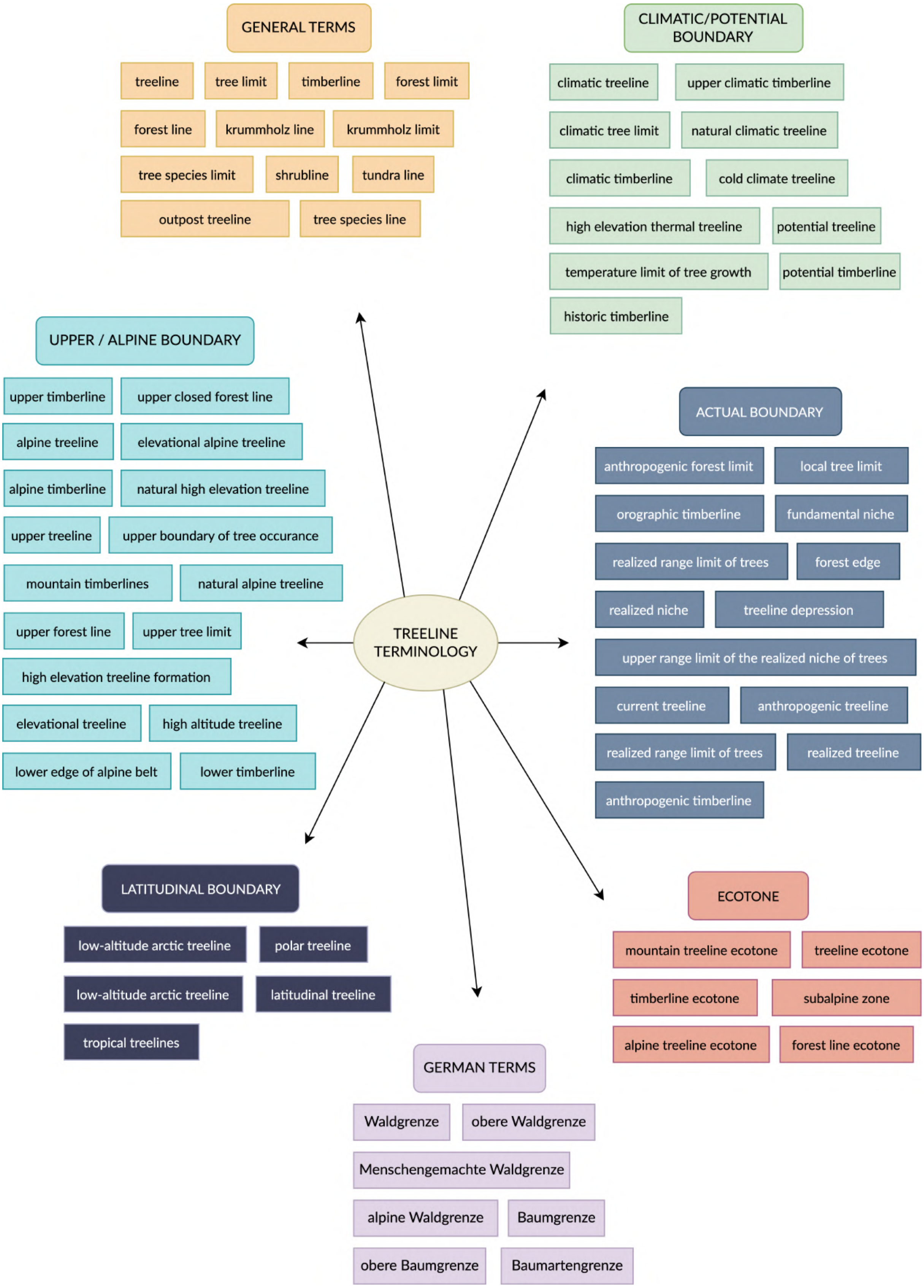

Figure 2.3: Mind map of all used terms within the 30 analysed papers, structured into seven categories. Source: Own Figure.

2.1.1 General Terms

General terms are the most commonly used for describing different components of the treeline ecotone. They frequently serve as general terms when authors discuss treeline phenomena repeatedly throughout their work. For example, authors may specify that they are examining the natural climatic treeline in their paper, but subsequently use the simplified term treeline for the rest of the paper for the sake of briefness. To better understand what these terms spatially represent, several illustrations of different papers sketching the treeline ecotone are looked at as a starting point.

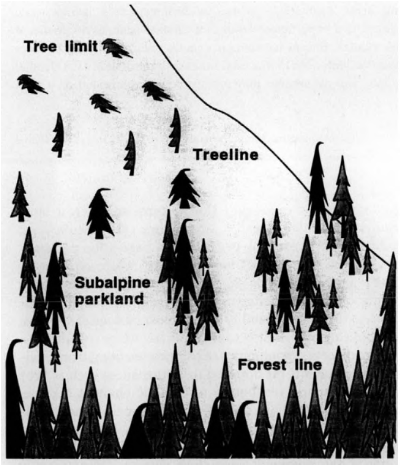

Figure 2.4: Treeline ecotone illustration by Rochefort et al. (1994).

As visible in Figure 2.4, Rochefort et al. (1994) clearly distinguish between an upper boundary of forest, called forest line and two upper boundaries of trees called treeline and tree limit. The definitions in their paper are the following (Rochefort et al., 1994, p. 90):

- **Forest line:** The upper limit of closed contiguous forest.
- **Treeline:** The highest elevation at which erect trees are found within the subalpine parkland.
- **Tree limit:** The highest elevation at which any trees are found, including prostrate or krummholz[1].

Figure 2.5 from Díaz-Varela et al. (2010) shows a slightly different sketch, with the forest line and the treeline corresponding to roughly the same thing as in Rochefort et al. (1994) but without the term tree limit and instead drawing what they call the tundra line. They are defining the following terms (Díaz-Varela et al., 2010, p. 622):

- **Forest line or timberline:** marks the transition from dense forest to an open formation of scattered or patched trees.
- **Treeline or tree limit:** sets the limit of the timberline with an open formation characterised by the absence of full-sized trees and the presence of krummholz.
- **Tree species limit or tree species line or krummholz limit:** separates the krummholz area from the treeless tundra.

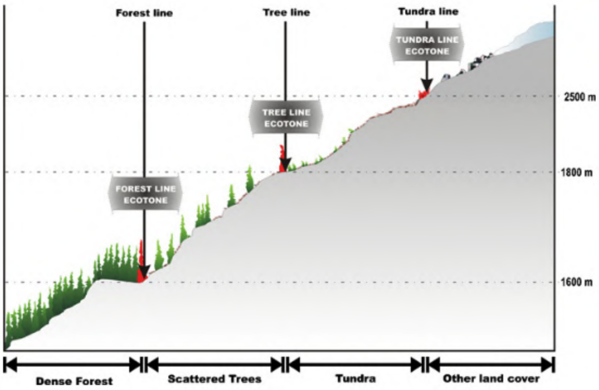

Figure 2.5: Illustration of alpine ecotones by Díaz-Varela et al. (2010).

Slightly confusing is the appearance of the term tundra line in the illustration, whereas the same line is called tree species in the definition. A problem that arises when comparing the definitions of these two papers is that they both use the term tree limit, but for Rochefort et al. (1994) this forms the uppermost line beyond where no trees grow any more, whereas for Díaz-Varela et al. (2010) it is the same as the treeline. In this instance, it seems just like different wording while roughly describing the same three lines. Of course, this must be taken into account if the papers were to be compared, but it is not that big of an issue. Díaz-Varela et al. (2010) also name the term timberline, which they use as a synonym for the forest line. Again, as

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[1] The German term Krummholz (EN = bent wood) refers to distorted, shrub-forming trees, usually above the uppermost normal trees growth. Prostrate refers to plants growing along the ground rather than upright (Körner, 2021a)

long as it is just about different wordings, the problem is neglectable. Whereas in many papers this entire zone is called treeline ecotone, they use three different names for the ecotones around the three defined boundaries, but it simply looks like a more specific terminology.

It starts getting more complicated when looking at another illustration, this time from Price (1981) in Figure 2.6. In this illustration, showing altitudinal zones across the world, the timberline and forest line are clearly two distinct things with the timberline positioned higher up than the forest line, which contradicts with the previous definition from Díaz-Varela et al. (2010), where the two terms were used for the same boundary.

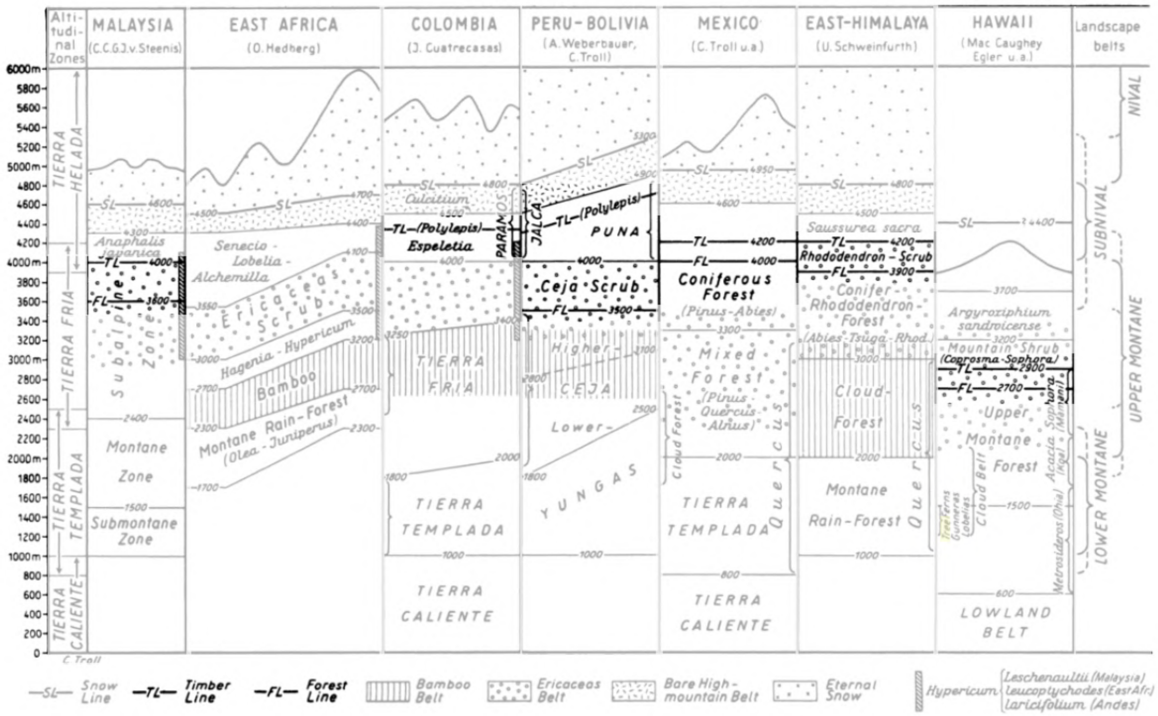

Figure 2.6: Vertical zones of vegetations, modified after Price (1981).

Unsurprisingly, Price (1981, p. 271) uses different definitions:

- **Timberline:** The entire transition from closed forest to open treeless tundra.
- **Forest line:** The upper limit of contiguous forest.
- **Treeline:** The upper limit of erect arborescent growth, usually represented by scattered clumps of trees or isolated individuals beyond the forest line.
- **Shrubline or krummholzline:** the upper limit of stunted scrub-like trees.

So Price (1981) uses the term timberline for the entire ecotone within which the forest line, treeline and the shrubline or krummholz line are located. According to that definition, the timberline in his sketch probably indicates the upper limit of the ecotone. Clearly, this leads to terminological problems if in one case the term stands for an ecotone that includes the forest line while in another instance the term is a synonym for the forest line. The definition of the other three terms are again similar to the previous ones from Díaz-Varela et al. (2010) and Rochefort et al. (1994).

A fourth illustration by Körner (2012) in Figure 2.7 draws yet another picture. In this illustration, Körner uses the term treeline ecotone to describe the area ranging from the timberline to the tree species line, with the treeline positioned in-between. He does not explicitly define the term timberline but states that

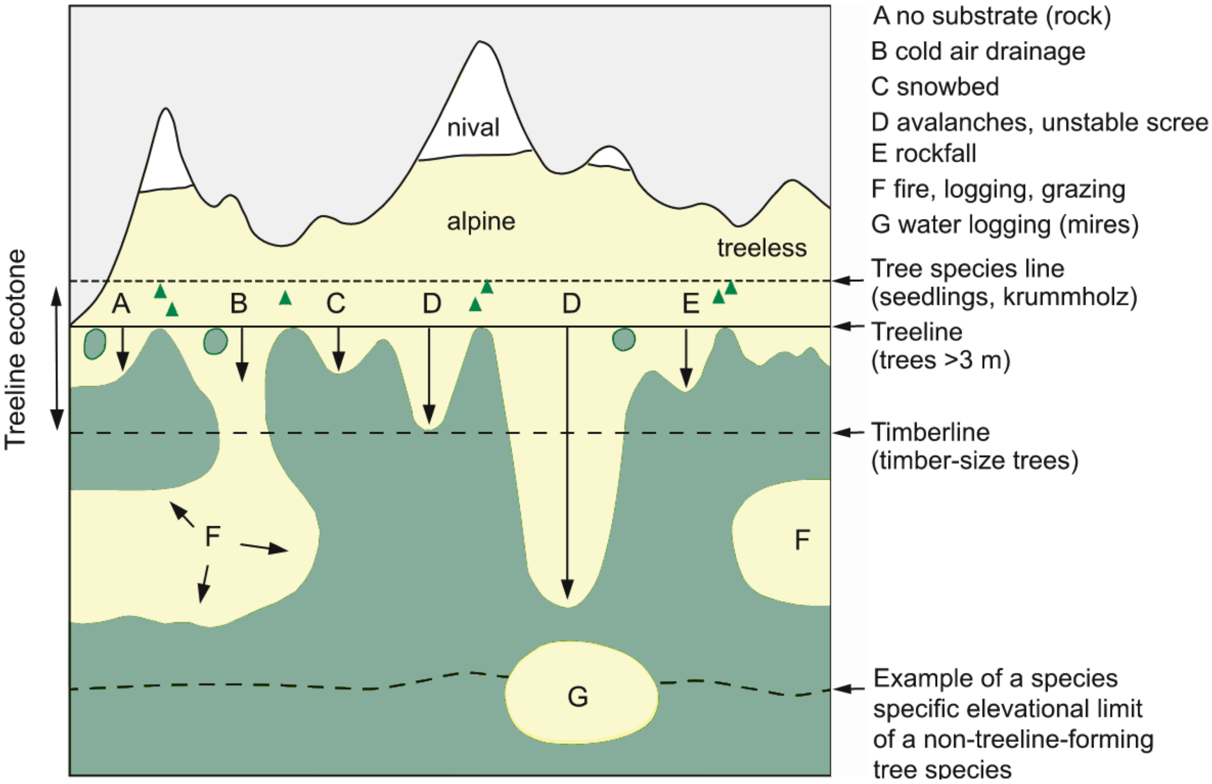

Figure 2.7: Treeline ecotone by Körner (2012).

this term has been used for the upper limit of closed forest. In his illustration, it is indicated that it marks the limit of the uppermost trees of timber size[2]. He argues that this term is unsuitable since a forest does not have to consist of only trees the size of timber to be a forest and in a later publication (Körner and Hoch, 2023) that timber does not represent a biological category within the life form concept[3]. Körner (2012, p. 18) defines the following terms:

- **Treeline or forest line:** roughly marks a line connecting the highest patches of forest — composed of trees of at least 3 m height — within a given slope or series of slopes of similar exposure.
- **Outpost tree line:** a line connecting the uppermost individual trees.
- **Tree species line:** the upper limit of the occurrence of tree species, i.e. the uppermost individuals irrespective of their small size.

Regardless of the terminology used by Körner (2012), the three boundaries are similar to those illustrated earlier. This indicates consistency, even when different terms are employed for identical concepts and vice versa. However, this work also demonstrates terminological confusion within a single author's perspective. Körner (2012) treats treeline and forest line as synonyms while acknowledging that forest line would be terminologically more appropriate than treeline. He retains the term treeline due to its established usage in the field. The confusion appears when comparing Figure 2.7, where treeline and timberline are clearly distinguished, with Körner and Hoch (2023), who argue that timberline should be replaced by forest line.This creates a contradiction: if treeline $\neq$ timberline, and forest line replaces timberline, yet treeline = forest line, the terms become logically inconsistent. Alternatively, Körner and Hoch could mean that not just the term timberline but the underlying concept should be replaced, referring to a different boundary within the treeline ecotone — though it remains unclear which interpretation was intended.

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[2] Timber is a tree that has grown such that it can be used for building (Oxford Dictionary, 2025).

[3] The life form concept classifies plants by their structural and physiological characteristics (e.g., trees, shrubs, herbs) (Adamson, 1939)

Bell (2012) uses the same terms as Körner (2012) in Figure 2.7, but in his illustration (Figure 2.8), the treeline is clearly within closed forest, which is different to what Körner shows. The three definitions from Bell (2012, p. 194-195) are, again, similar to previously mentioned boundaries.

- **Timberline:** upper limit of continuous canopy forest.
- **Treeline:** limit for individuals to grow erectly up to two metres tall and be recognizable as trees.
- **Tree species:** limit where trees will grow, although by this time they are stunted and deformed.

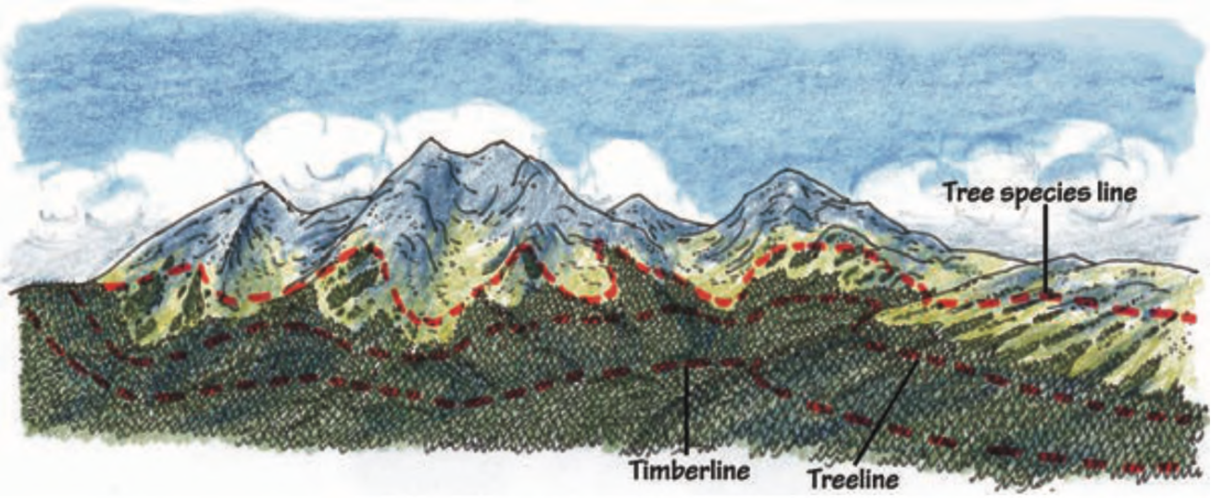

Figure 2.8: Conceptual treeline ecotone by Bell (2012).

A more recent illustration from Cansler et al. (2018) in Figure 2.9 shows again the same three lines limiting forest, trees and tree species as Díaz-Varela et al. (2010) and Rochefort et al. (1994). Cansler et al. does not define these terms further.

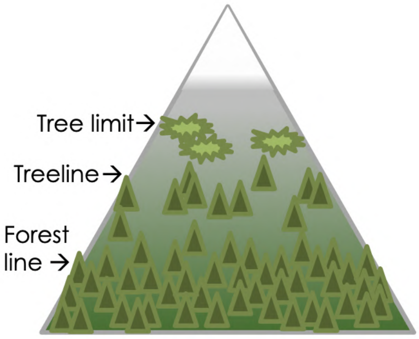

Figure 2.9: Conceptual treeline ecotone by Cansler et al. (2018).

Table 2.1 shows all collected definitions or descriptions of the three most prevalent terms timberline, forest line and treeline within the analysed literature. They are sometimes used conceptually and not as formal definitions. For example Körner and Paulsen (2004, p. 713) write: "the high altitude limit of forests, commonly referred to as treeline, timberline or forest line represents one of the most obvious vegetation boundaries." which shows that these terms are often used interchangeably, but the authors do not explicitly define the three terms as "high altitude limit of forests".

Such listed definitions are more descriptions of the broader phenomenon of forests becoming discontinuous due to climatic constraints, they are rather general and most often do not compete with the more specific definitions that were explicitly phrased by authors. Nevertheless they show how diversely descriptions of the same matter can be formulated.

Table 2.1: Definitions of treeline-related terms in the literature.

(a) Timberline

Price (1981)	Transition from closed forest to open treeless tundra.
Arno (1984)	Upper elevational limit of forest and tree growth on high mountains; transition zone between continuous forest and the treeless alpine tundra; area stretching from forest line to krummholzline.
Heikkinen (1984)	Ecotone between closed forest and treeless alpine tundra.
Paulsen et al. (2000)	Upper limit of closed forest.
Körner and Paulsen (2004)	High altitude limit of forests.
Körner (2007)	Line connecting the uppermost lobes of timber sized forest[4].
Holtmeier (2009)	Transition zone between closed forest and the most advanced individuals of the forest forming tree species.
Díaz-Varela et al. (2010)	Transition from dense forest to an open formation of scattered or patched trees.
Bell (2012)	The upper limit of continuous canopy forest.

(b) Forest line

Price (1981)	Upper limit of contiguous forest.
Arno (1984)	General upper limit of continuous forest.
Rochefort et al. (1994)	Upper limit of closed contiguous forest.
Körner and Paulsen (2004)	High altitude limit of forests.
Körner (2007)	Line connecting the uppermost lobes of closed forest.
Körner (2012)	Line roughly connecting the highest patches of forest within a given slope or series of slopes of similar exposure.
Bell (2012)	The limit for individuals to grow erectly up to two metres tall and be recognizable as trees.
Körner (2021a)	Upper limit of closed montane forest.

(c) Treeline

Price (1981)	The upper limit of erect arborescent growth.
Arno (1984)	General upper limit of erect though stunted trees.
Rochefort et al. (1994)	The highest elevation at which erect trees are found within the subalpine parkland.
Paulsen et al. (2000)	Line connecting the highest patches of forest within a given slope or series of slopes of similar exposure.
Körner and Paulsen (2004)	High altitude limit of forests.
Körner (2007)	Boundary for upright, emergent tree stature (irrespective of nature).
Holtmeier and Broll (2009)	Transition zone extending from the forest limit to the tree limit.
Díaz-Varela et al. (2010)	Sets the limit of the timberline with an open formation characterised by the absence of full-sized trees and the presence of krummholz.
Körner (2012)	Line roughly connecting the highest patches of forest within a given slope or series of slopes of similar exposure.
Bell (2012)	The limit where trees will grow, although by this time they are stunted and deformed.
Paulsen and Körner (2014)	Line connecting the uppermost or most northern patches of trees of at least 3 m height in undisturbed areas.
Körner (2020)	Natural high elevation limit of tree growth; defines the biogeographic boundary between montane and alpine belt.
Körner (2021a)	Natural limit set by low temperature at high elevation or high polar latitudes; line connecting the uppermost groups of trees.
Wang et al. (2022)	Line that connects the uppermost, undisturbed group of trees of a certain height; cold edge of the fundamental niche of trees.

Körner (2007) argues that the terminology is also an issue of scale. When viewed from a distance, a description such as "High altitude limit of forests" from Körner and Paulsen (2004, p. 713) makes perfectly sense. However, when zoomed in more closely on the same part of a slope, "Line that connects the uppermost, undisturbed group of trees of a certain height" (Wang et al., 2022, p. 890) might be more appropriate but also more difficult to make out, as Figure 2.10 shows.

Figure 2.10: Treeline ecotone in Bever, Switzerland. While the forest-grassland boundary appears clearly delineated from a distance, finer-scale observations reveal a more complex mixture of trees and shrubs, demonstrating the need for specific terminological distinctions.

Although there is variation in wording and criteria and the terms are sometimes mutually used for the entire ecotone and specific boundaries within the ecotone, most definitions converge on describing boundaries that mark the transition from continuous forest to patches of trees to scattered tree occurrences at high elevations. It suggests that the treeline ecotone contains multiple identifiable boundaries that can be legitimately described using different terms, depending on the specific ecological or spatial criteria being emphasized. Three distinct boundaries can be concluded:

- The first marks the upper edge of continuous or closed forest
- The second delineates the limit of patches of trees or individual trees
- The third represents the uppermost occurrence of tree species in any growth form except trees, such as prostrate or krummholz

While terminology and demarcation criteria vary, the underlying structure of three hierarchical boundaries can be recognized. This suggests that it is not mainly disagreement about what spatial patterns exist within the ecotone, but rather the lack of standardized terminology when referring to these patterns. For spatially explicit research and mapping efforts, recognizing these three distinct boundaries and explicitly defining which boundary is being studied is essential for methodological clarity.

The remaining terms from this category in Figure 2.3 describe the uppermost boundaries within the treeline ecotone. They seem less relevant and are thus less frequently mentioned. Tree species limit (or line) is the uppermost limit of occurrence of tree species, meaning any individuals from that species, irrespective of their size (Körner, 2012). Shrubline is the upper limit of stunted shrub-like trees or krummholz, krummholz line is treated as synonym (Díaz-Varela et al., 2010). Thus, all three terms describe roughly the same boundary. Körner (2012, 2021a) and Paulsen et al. (2000) are the only ones using the term outpost treeline in the analysed papers. They define it as line connecting the uppermost individual trees. This conflicts with several definitions of the treeline for example the one from (Rochefort et al., 1994, p. 90) "The highest elevation at which erect trees are found within the sub-alpine parkland". However, it may result from Körner (2007) using the term treeline synonymously with forest line and wanting to make a distinction between uppermost patches of forest or trees and uppermost individual trees.

German Terms

German terms mentioned in the literature are included because this thesis focuses on Switzerland, where understanding the correspondence between English scientific terminology and German legislative language is important for accurately interpreting policy documents and their intended ecological targets. Since most literature is in English, not many occurrences of these terms were found. Even fewer are translations between the two, which are only found when abstracts are available in the two languages. The most straightforward and literal translation would pair treeline with *Baumgrenze* and forest line with *Waldgrenze*. Körner (2007) translates treeline to both German terms interchangeably, but this aligns with his previously discussed synonymous treatment of treeline and forest line in English. However, also Holtmeier and Broll (2009) translate treeline to *Waldgrenze*. Consulting well-known English-German dictionaries to clarify the translation of these terms does not fully resolve the issue, as illustrated in Table 2.2. The only consistency across all dictionaries is the translation of treeline to *Baumgrenze* and forest line to *Waldgrenze*. But the other way around *Waldgrenze* is often translated to treeline or in one case even used for all three English terms and the translation of timberline is also not consistent.

Table 2.2: Translations of treeline terminology across dictionaries.

Source	English → German		German → English	
Langenscheidt	treeline	Baumgrenze	Waldgrenze	treeline
	forest line	–	Baumgrenze	timberline, treeline
	timberline	Baumgrenze		
dict.cc	treeline	Baumgrenze	Baumgrenze	treeline, timberline
	forest line	Waldgrenze	Waldgrenze	timberline, forest line, tree line
	timberline	Waldgrenze		
leo.org	treeline	Baumgrenze	Baumgrenze	timberline, treeline
	forest line	Waldgrenze	Waldgrenze	forest line, timberline
	timberline	Baumgrenze		
DeepL	treeline	Baumgrenze	Baumgrenze	treeline
	forest line	Waldgrenze	Waldgrenze	treeline
	timberline	Baumgrenze, Waldgrenze		
PONS	treeline	Baumgrenze	Baumgrenze	treeline
	forest line	Waldgrenze	Waldgrenze	treeline
	timberline	Baumgrenze		
Cambridge Dict.	treeline	Baumgrenze	Baumgrenze	treeline
	forest line	Waldgrenze	Waldgrenze	treeline
	timberline	Baumgrenze		

Ecotone

The entire transition zone from forested areas to the treeless tundra is most often called treeline ecotone or in a more specified way such as alpine treeline ecotone. The only ambiguity in this category arises when terms like treeline or timberline are used when actually talking about the ecotone.

2.1.2 Specifying Terms

The above described general terms form the core vocabulary for the treeline ecotone, but the terminology extends further. Additional categories include geographic specifications that distinguish alpine from polar or tropical treelines and critically, the distinction between climatic and actual treeline positions.

Alpine/Upper & Latitudinal Boundary

The growth of forests and trees is naturally limited by temperature in various environments across the planet. In alpine regions like the Alps, this limitation occurs at specific elevations, but similar temperature-driven boundaries exist also in other geographic contexts, requiring specifications. When this limit occurs in high mountains, terms like upper, alpine or high elevation are added. The polar or arctic treeline occurs at the boundary between boreal forests and the arctic tundra and is mainly driven by latitude rather than elevation, with conditions getting more extreme towards north. Tropical treelines occur for example in the Andes in South America. In less prominent instances lower treelines, limited at low elevation boundaries of forests, can exist in semi arid mountains, due to a general lack of moisture or summer droughts (Bell, 2012).

Climatic/Potential Boundary

What has only been briefly discussed in the introduction, but is of utmost importance, especially in the context of this thesis, is that there can be large differences between the elevation up to where a tree or forest could grow according to climatic conditions and the elevation where they actually grow up to. The former case is called natural, climatic or potential treeline and is generally similarly defined: Brockmann-Jerosch (1925) defines the *theoretische Baumgrenze* (EN = theoretical treeline) as the height to which trees could grow for climatic reasons. Nguyen (2025) calls the potential treeline boundary that connects the uppermost forest patches in undisturbed areas, representing the maximum elevation at which forests can establish and persist, determined solely by climatic factors. In more recent papers, such as Körner (2021b) and Körner and Hiltbrunner (2024) the term fundamental niche is used, essentially meaning the same thing as it is defined as climatic limit of the life form tree. The distinction of the two categories — where trees actually grow up to and where they could theoretically — is crucial in treeline research in order to enable theory based, mechanism-orientated understanding, yet it is often confused or not clearly stated (Körner, 2007).

One reason is that identifying factors that globally determine treeline elevation becomes impossible if local variations with different causes are included in such estimations. For example, if in one study region treelines are constantly lowered through anthropogenic factors, the temperature at that elevation cannot be used to estimate treeline elevations in other regions since it is not the limiting factor. The work from Gehrig-Fasel et al. (2007) is another reason why the distinction is crucial. The authors researched how much of forest upward growth is attributed to rising temperatures caused by climate change in comparison to forest growing back to its natural limitation elevation when land is not agriculturally used any more. They concluded that the majority of upward shifts is not attributed to climate change, a finding that is crucial for estimating how much further up forest may grow in the future, with rising temperatures. The following three definitions hint at the last category of this terminology. Körner and Paulsen (2004) describe the natural climatic treeline, as the treeline without any anthropogenic, mechanical, or meteorological influences that regionally prevent growth. Holtmeier (2009, p. 28) define the potential treeline as "altitudinal position forest could achieve at the present climate without being disturbed by human impact". Rather simply, Körner (2020) calls the potential treeline the line where trees could grow if they were ’allowed’ to.

Actual Boundary

The position of the actual treeline can be called differently, depending what the cause is. General terms describing the actual compared to the potential position are treeline depression, current treeline, realized niche or simply actual treeline. Reasons for trees and forests being absent from their physical limit are multifaceted. The most prominent cause is of anthropogenic nature, leading to the term anthropogenic treeline (Bonanomi et al., 2025). Throughout the last 300 years, the actual treeline in the alps has been lowered extensively. In fact, cases where the potential treeline matches the actual treeline are rare in the alps (Paulsen and Körner, 2001) and treelines in Europe are approximately 150-300 m below their climatic limitation (Cansler et al., 2018). While land use is the most dominant cause to override the temperature limit of growth, there are plenty of natural causes as well, often tied to local circumstances (Däniker, 1923). Avalanches, rockfall, scree slopes and mudflows frequently prevent tree establishment at potential treeline positions (Furrer, 1923; Körner, 2012; Malanson et al., 2011). Fire, whether natural or anthropogenic, can devastate forests and depress treelines, as documented for Mount Kilimanjaro (Körner, 2009; Cansler et al., 2018). Extreme exposure, particularly strong winds on summits can create unsuitable conditions for tree survival (Körner, 2012). Additionally, storms and severe climate events, along with pests and insects, can cause widespread tree mortality at treeline ecotones (Körner, 2009; Cansler et al., 2018). One factor that does not effectively lead to depression of the treeline but simply hinders the growth of vegetation is the lack of substrate on rocky terrain or steep topography leading to the terms orographic or edaphic timberline. However, besides Holtmeier (2009) no other of the reviewed literature has used these specifications. The remaining terms from that category in Figure 2.3 are more or less synonymously used. Lastly, in a completely undisturbed region, the actual treeline may be identical to the potential treeline.

2.1.3 Terminology Framework

The terminology review reveals the extent of confusion in term usage, varying definitions, inconsistent translations between languages and conflation of boundary types within ecotone zones. Despite the terminological complexity, a consistent spatial pattern can be recognized across the analysed literature. Three hierarchical boundaries are repeatedly pointed out:

- the upper edge of closed, continuous, or dense forest
- the upper limit of open forest formations, groups of trees, or individual upright trees
- the uppermost occurrence of any tree species individuals, regardless of growth form

While different authors apply varying terms to these boundaries and define them with different specific criteria, their conceptual persistence suggests they represent real, distinguishable ecological boundaries. Equally critical, but often insufficiently addressed, is the distinction between potential (climatic) and actual positions of these boundaries. Failure to explicitly separate these two concepts complicates comparative research and can lead to erroneous interpretations of climate-treeline relationships.
For clarity in the subsequent chapters of this thesis, I establish the following terminology:

Terminology Framework

- **Forest line** refers to the upper edge of closed forest
- **Treeline** denotes the upper limit of tree-form individuals, whether in groups or isolated
- **Shrubline** marks the uppermost occurrence of tree species or shrubs in any growth form

The latter, while less central to this research, serves as the upper boundary of the **treeline ecotone** — the term I use for the entire transition zone. Figure 2.11 shows a sketch of this framework.

I distinguish between the climatic treeline and the actual treeline for all three boundaries. Whenever I am talking about such boundaries in a general manner, I will use the most established term: treeline.

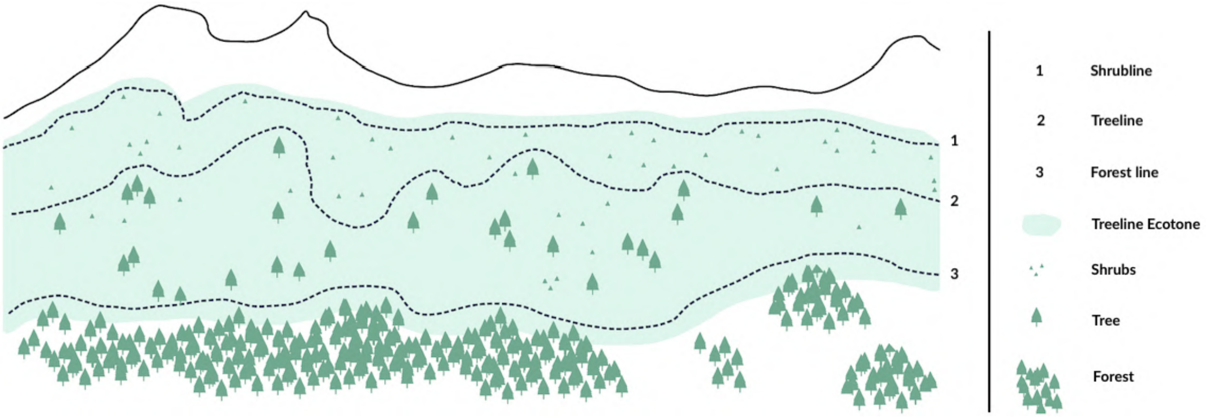

Figure 2.11: Sketch of the established treeline terminology. Source: Own Figure.

This terminological distinction is essential for the spatial delineation in the following chapters, enabling clear communication which specific boundary is spatially represented and whether it represents a climatic limit or an actual, potentially depressed position.

Chapter 3: Requirement Analysis

The previous chapter has given an insight of the state of treeline terminology in the literature, showing inconsistencies but still some underlying coherence between different works. This chapter now examines how the German translation *Waldgrenze* is used in practice, in the context of legal regulations in Switzerland.

3.1 Legal Usage of the term Waldgrenze

The term *Waldgrenze* is used in various Swiss legal articles, these are listed below.

- **Bund**[1]: *Die Leitung von Wanderungen mit Übernachtung im Biwak oberhalb der Waldgrenze, die im Bereich bis und mit T3 stattfinden, benötigen eine Zusatzausbildung.*
- **Bund**[2]: *Höchstbesatz für Schafweiden werden in Kategorien unterhalb und oberhalb der Waldgrenze angegeben.*
- **Bund**[3]: *Mindestens 25 km² der Kernzone [eines Nationalparkes] befinden sich unterhalb der Waldgrenze.*
- **Kanton Bern**[4]: *Grasschäden [...] in Sömmerungsgebieten oberhalb der Waldgrenze werden nicht ersetzt.*
- **Kanton Bern**[5]: *Jagdhunde, die während der Rehjagd vorwiegend Gämsen oberhalb der Waldgrenze jagen sind ungeeignet und nicht zugelassen.*
- **Kanton Freiburg**[6]: *[...] Oberhalb der Waldgrenze genügt es, die Eingeweide [von erlegtem Jagdwild] mit Steinen zu bedecken.*
- **Kanton Graubünden**[7]: *Ski- und Snowboardtouren [...] unterhalb der Waldgrenze gelten als nicht bewilligungspflichtige Aktivitäten.*
- **Gemeinde Zuoz**[8]: *Auf öffentlichem Grund ist das Campieren [...] verboten. Ausgenommen von diesem Verbot ist das kurzfristige Aufstellen von einzelnen Zelten über der Waldgrenze [...]*

In these articles, the term is used as spatial demarcation for various applications without further specifying what the term refers to. As shown in the previous chapter, it is far from unambiguous what this exactly means — at least from a scientific point of view — which leaves room for interpretation. In order to find out why this term was used as spatial demarcation and if it is clear what it refers to from an administrative perspective, various authorities were contacted. The approach was not carried out systematically but rather step by step by contacting authorities behind these articles. Additionally, other relevant organisations such as the Swiss Alpine Club (SAC), Mountain Wilderness or the Forest Division from the Federal Office for the Environment (FOEN) were asked similar questions. In some cases, I received direct responses, in others, my inquiry was forwarded to a staff member considered more appropriate to answer. All responses were provided by administrative staff representing their respective offices or departments but I cannot determine to what extent personal interpretation influenced individual responses, however, the purpose was exploratory rather than definitive. I wanted to assess whether the term is further specified in practice,

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[1] Verordnung des BASPO über «Jugend und Sport», Anhang 3. https://www.fedlex.admin.ch/eli/cc/2012/463/de

[2] Verordnung über die Direktzahlungen an die Landwirtschaft, Anhang 2. https://www.fedlex.admin.ch/eli/cc/2013/765/de

[3] Verordnung über die Pärke von nationaler Bedeutung, Art. 16. https://www.lexfind.ch/fe/de/tol/29312/versions/247511/de

[4] Verordnung über die Verhütung und Entschädigung von Wildschäden, Art. 3. https://www.lexfind.ch/fe/de/tol/19565/versions/253659/de

[5] Direktionsverordnung über die Jagd, Art. 6. https://www.lexfind.ch/fe/de/tol/19590/versions/253749/de

[6] Jagdverordnung, Art. 71. https://www.lexfind.ch/fe/de/tol/5615/versions/255693/de

[7] Ausführungsbestimmungen zum Gesetz über das Berg- und Schneesportwesen, Art. 2. https://www.gr-lex.gr.ch/app/de/change_documents/928

[8] Polizeigesetz, Art. 14. https://www.zuoz.ch/fileadmin/user_upload/Zuoz_Dokumente/Dienstleistungen/Polizei/Polizeigesetz_03.pdf

whether concerns about its usage exist and what reasons underlie its application. Responses from twelve authorities across different contexts should provide reasonable indications of whether clarity or ambiguity prevails, regardless of potential variation in individual interpretations. Only the German term *Waldgrenze* is used in all legislative texts as well as in the answers that I received. As mentioned in Chapter 2, I will still use the term treeline as translation.

3.2 Authority Perspectives

3.2.1 Reasons for using the term Waldgrenze

The term *Waldgrenze* is generally used in a pragmatic and practical sense. For example, the Swiss Alpine Club (SAC)[9] uses it as a simple guide: below it, the forest is considered a sensitive area that requires special protection, while the areas above tend to be less sensitive and setting up a tent should not be a problem. From the SAC's point of view, the term is therefore a practical distinction that helps to ensure the protection of the forest. Similarly, the Office for Forestry and Natural Hazards from the Canton of Graubünden[10] describes the use as pragmatically motivated, with the aim of preventing overnight stays in the forest, as these could disturb nature. Alternatives such as a fixed elevation would either cover too many or too few areas and a boundary based solely on forest area would not take into account agricultural zones which are often more sensitive in lower elevations, but less so higher up.

The Federal Office of Sport (BASPO)[11] sees it as a pragmatic point of reference for a legally manageable demarcation. It serves as an indicator of changing environmental conditions with increasing elevation, which requires additional qualification. What exactly these environmental conditions refer to was not specified. Further, a pure elevation specification would be unsuitable for such purposes, as ecological and climatic conditions do not increase linearly with elevation and the treeline seems to serve as a better proxy. Contrary to earlier statements by the SAC, the emphasis here is not on forest protection but on establishing a practical boundary that separates less demanding activities below the treeline from more challenging ones above it. The Office for Forestry and Natural Hazards Graubünden rightly state, that the usage of the term strongly depends on its application. From the perspective of the municipality of Celerina (GR)[12], it follows a simple rule: anyone in a closed forest is too low to camp. Some authorities, such as the Hunting Inspectorate of the Canton of Bern [13], were unable to give a clear reason for choosing the term as demarcation and supposed that it was once agreed upon for practical reasons. The FOEN[14] points out that it is an ecological or phenological feature and not a legal or administrative term. They did not comment on the fact that it is nevertheless used in legal texts.

Organisations such as Mountain Wilderness[15] recommend the term as a guideline for avoiding disturbances in ecologically sensitive areas and preventing forest fires, similarly to the SAC. In the commune of Bever (GR)[16], the assumption is that dense forest indicates proximity to settlements, eliminating the need for camping. This reasoning differs from other camping regulations, as the term here serves more as a boundary between civilization and wilderness. Lastly, the Federal Office for National Economic Supply (FONES)[17] also emphasises the practical application of the term, that allows for a case by case estimation on site.

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[9] Schweizer Alpen Club (SAC), Ressort Hütten und Umwelt

[10] Amt für Wald und Naturgefahren, Regionalzentrum Zuoz

[11] Bundesamt für Sport, Helpline Jugend + Sport & Erwachsenensport

[12] Gemeinde Celerina, Revierforstamt

[13] Kanton Bern, Amt für Landwirtschaft und Natur, Jagdinspektorat

[14] Bundesamt für Umwelt, Abteilung Wald, Sektion Walderhaltung und Waldpolitik

[15] Mountain Wilderness, Geschäftsleitung

[16] Gemeindeverwaltung Bever

[17] Bundesamt für Landwirtschaft BLW, Fachbereich Direktzahlungsgrundlagen

3.2.2 Definition of the term Waldgrenze

There does not seem to be a uniform or legally binding definition of the term treeline. The Office for Forestry and Natural Hazards Graubünden again points out that the term is interpreted differently in different contexts, such as spatial planning or nature conservation and is not further defined. In response to how areas around the elevation of the treeline with missing trees or forest are treated, they said it can probably be assumed that the demarcation continues on the same elevation in such instances, to protect the previously mentioned sensitive agricultural zones. The Hunting Inspectorate of the Canton of Bern refers to a 'general understanding' without defining this in more detail. The FOEN defines the treeline as the point where there is no longer a continuous stand of tall trees. Neither a specific definition nor a cartographic representation exists, as this has never caused any problems to date.

According to the commune of Bever, the area above the closed forest is considered to be above the treeline — a view that fits with the statement of the Office for Forestry and Natural Hazards Graubünden about the sensitive agricultural zones below the treeline. They also stated 'above' simply means outside the forest and not under branches. The commune of Celerina on the other hand argues that one is not necessarily above the treeline if one is above closed forest and further, that the term 'above' (referring to their ban of camping below the treeline) is not precisely defined, but that this lack of clarity does not cause any problems. Mountain Wilderness understands their recommendation of camping above the treeline as areas as much above the last trees as possible. While the Office for Forestry and Natural Hazards Graubünden said shrub forest legally belongs to forest according to the national forestry law, the commune of Bever said it hardly makes sense to include shrubs, open forest or individual trees when talking about the treeline as there exist many patches of trees and individual trees above the treeline. While the SAC said a cartographic representation of the treeline would be interesting, Mountain Wilderness said there is no need, unless there were more such laws (referring to the camping bans below treelines from communes like Zuoz, Bever or Celerina). The Office for Forestry and Natural Hazards from the Canton of Glarus said a definition and a cartographic representation of the treeline is explicitly not desired, due to the dynamic concept of forest[18].

These responses indicate a fundamental characteristic: the term *Waldgrenze* lacks a clear definition in legal and regulative contexts and is according to some sources even deliberately kept vague. Authorities rely on a general understanding of the term, case by case assessments an pragmatism rather than a precise delineation. While it seemed that the vagueness of the term was not always recognized — as some stated its definition was rather obvious — a certain flexibility was not considered disadvantageous. This raises the conceptual question, whether or not the observed definitional ambiguity is merely a matter of insufficient precision, or if it reflects an inherent characteristic of the term itself. The next section explores this question by examining the nature of such vagueness through the concept of Bona Fide and Fiat boundaries.

3.3 Vagueness

Geographical phenomena including the treeline are often difficult to precisely define due to their complexity and lack of crisp boundaries, which leads to inherent vagueness (Galton and Hood, 2005). One way of testing this vagueness is by applying the sorites[19] paradox (Fisher, 2000): Suppose a person stands in

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[18] With the dynamic forest concept, the forest boundary adapts to the actual vegetation and is only recorded selectively when necessary, whereas with the static forest concept, the forest boundary is mapped in a fixed manner and legal changes require a formal procedure. There are cantons using entirely static and some using static and dynamic boundaries.

[19] Sorites is Greek for heap. A short version of the classic formulation of the paradox is this: 'If a heap is reduced by a single grain repeatedly, at what point is it no longer considered a heap'?

the middle of a mountain forest. Clearly, this person is below the treeline. If the person takes a small step upward, they remain within the forest and thus below the treeline. Each subsequent small step yields the same result. Yet eventually, the person reaches a point where there are no trees in sight and they are certainly out of the forest and hence above the treeline. This paradox can be logically formalized as follows: Let $P(x)$ denote "The person at position x of a slope stands below the treeline." Assume:

1. $P(0)$ (at $x = 0$, the person stands below the treeline.)
2. $\forall x \in \mathbb{N},\ P(x) \rightarrow P(x+1)$ (If the person is below the treeline, they will remain below the treeline after one small step upwards.)
3. $\exists N \in \mathbb{N}$ such that $\neg P(N)$ (There exists a position N where the person is no longer below the treeline.)

This leads to the paradox: how can there exist N such that $\neg P(N)$ if $\forall x,\ P(x)$ holds true?

The paradox highlights the fundamental problem of aligning the apparent continuity of small changes (e.g. one step upwards) with the existence of a boundary (e.g. above or below the treeline). Solutions to the sorites paradox suggest that either the premise or the process of reasoning is wrong or the Law of Excluded Middle [20] does not hold. However, as Fisher (2000) points out, these three assumptions still fail to resolve the paradox in such a situation. The underlying problem is the insufficient definition of these phenomena such as the treeline as a boundary. Vagueness thus, does not arise because knowledge is lacking or imprecise, but rather due to a lack of clear criteria for a certain linguistic term (Bennett et al., 2010).

To better understand issues with boundaries, we can consider Barry Smith's ontological concept of bona fide and fiat boundaries (Smith, 1995). Bona fide boundaries describe real, physical boundaries that exist independently of human cognition, they are intrinsic features of the world such as the shell of an egg, a coastline or a mountain range. Fiat boundaries describe boundaries solely created through human cognition and perception, without any visible properties (Smith and Varzi, 2000). Examples of fiat boundaries are national borders, time zones or property borders. They rely on convention, agreement or perception and lack natural definitions. More intuitive names for these categories are simply natural and artificial boundaries (Varzi, 2011)[21]. The treeline can be interpreted in different ways:

- **Bona fide boundary:** As stated in 2.1.2 the climatic treeline represents a physical limit at which the growth of forests and trees is no longer possible due to environmental factors such as temperature and soil conditions. This limitation exists objectively and independently of human cognition. Even if the boundary itself is not directly visible and only approximated when trees are present, it still exists as a real, physical limit.
- **Fiat boundary:** Looking at one of the definitions used by the WSL or Körner (2012), defining the treeline as the line connecting the uppermost patches of forest, the term deviates from its natural and physical limitation of growth and becomes a fiat boundary. The uppermost forest patches do not necessarily represent the climatic limitation due to the factors mentioned in 2.1.2. Hence, defining this boundary as the treeline is a matter of convention and therefore fiat. The physical boundary between forest and alpine grassland exists somewhere as bona fide, but drawing lines connecting scattered patches and designating this as for example the actual treeline involves convention. Which patches qualify as uppermost? How should connecting lines be drawn? These decisions are fiat.

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[20] The Law of Excluded Middle states that a condition is either true or its negation is true (Britannica, 2025). In our case a person stands either below or above the treeline.

[21] Bona fide translates in Latin to 'in good faith, sincerely'. In ontology it can be understood as "naturally". Fiat translates in Latin to 'let it happen', meaning in ontology that something is brought into existence by (human) decision, therefore artificial (Dictionary, 2025).

> Furthermore, once the treeline is legally articulated, it inherently becomes a fiat boundary (Bennett et al., 2010). The question of which physical boundary it refers to — closed forest, open forest, scattered trees, shrub forest — is entirely convention-dependent and varies by interpretation and application.

This dual nature explains the contradictions in authority responses documented earlier. The commune of Bever excludes scattered trees and shrubs from the *Waldgrenze* definition, while the commune of Celerina includes them. Bever interprets 'above the *Waldgrenze*' as above closed forest, whereas Celerina argues one is not necessarily above the *Waldgrenze* even when above closed forest. Mountain Wilderness understands above as 'above the most upward trees' while for the commune of Bever it simply means outside of forest. The fiat characteristics introduce aspects of subjectivity and variability, making its use as legal boundary tricky. Mark et al. (1999) too note that boundary placement is a matter of fiat when dealing with geographic objects as it largely involves perception, which may differ substantially along different groups of population and the task to decide where to place such boundaries is by no means simple. But this does not necessarily mean that such ambiguity is a bad thing. Bennett et al. (2010) researched the use of natural boundaries for land and marine administration in Australia and note that effective boundaries may actually require both bona fide and fiat characteristics: a physical existence that is cognitively recognized and agreed upon. The treeline could in theory have these characteristics, if it was mostly undisturbed and formed an easy to follow line between closed forest and alpine grassland. But as already discussed, this is rarely the case within the alps.

The terminology review in Chapter 2 revealed extensive scientific efforts to define and distinguish treeline-related terms. Researchers differentiate between forest line, treeline and shrubline; between climatic and actual positions; and have proposed dozens of competing definitions. This scientific context stands in contrast to the applied context examined in this chapter. In legal and administrative usage, a single term — *Waldgrenze* — is employed without specification. There is no distinction between climatic and actual positions, no clarification of which boundary is meant (forest line, treeline, or shrubline) and no reference to the scientific literature's definitional debates. Instead, authorities rely on what the Hunting Inspectorate of Canton Bern called 'allgemeines Verständnis' (EN = general understanding) or what the FOEN described as rather obvious — the point where there is no longer continuous forest with tall trees. This raises a fundamental question: which of the many scientific boundaries does the legal term *Waldgrenze* actually refer to? When the SAC recommends camping above the *Waldgrenze*, or when communes like Zuoz legally prohibit camping below it, which specific boundary are they referencing? The climatic limit where trees physiologically cannot grow, or the actual uppermost forest edge shaped by centuries of human land use? The line of closed forest canopy, or the elevation of the highest scattered individual trees?

The responses from authorities suggest these distinctions are largely unrecognized in practice. When asked about areas with missing trees or forest at treeline elevation, the Office for Forestry and Natural Hazards Graubünden stated the demarcation probably continues at the same elevation — a pragmatic spatial interpolation that could be similar to definitions connecting upper forest patches, yet leaves plenty of room for interpretation. When asked whether shrub forest should be considered as forest, responses contradicted each other: legally it belongs to forest (Office for Forestry and Natural Hazards Graubünden), yet it 'hardly makes sense' to include it (commune of Bever). However, such ambiguities remain largely unproblematic in current practice, according to several statements. The Office for Forestry and Natural Hazards from Canton Glarus even explicitly stated the importance of a dynamic, rather than a fixed definition of the treeline. This deliberate embrace of vagueness provides practical flexibility, but raises the question of whether such a boundary can or should be spatially modelled at all.

3.3.1 Implications for Spatial Modelling

The earlier discussion highlights a core conflict: Chapter 2 illustrated the scientific diversity with numerous competing terms and definitions, while this chapter points out that practical scenarios accept ambiguity as a viable solution or at least see no problem with it. This poses a challenge for spatial modelling efforts: how can we cartographically represent something that lacks both scientific consensus and legal definition? An uncertain, context-sensitive boundary may simply be too ambiguous to accurately model.

However, spatial models of the treeline do exist. Paulsen and Körner (2001), Gehrig-Fasel et al. (2007), Szerencsits (2012) and Nguyen (2025) have conducted modelling the treeline in Switzerland. Analysing what concept the researchers refer to as well as the spatial outcomes of their methods, could be insightful, even if such models aim at scientific contributions rather than practical usage for authorities. Each modelling approach must decide which physical boundary to use, the forest line, treeline or something else and what data best represents their definition of forest and trees. They must decide how to handle scattered trees, how to interpolate across gaps where no trees exist and how to distinguish between climatic absence and human-caused absence of trees. These choices have spatial consequences: a model using the highest closed forest patches is likely to produce different results than one using the highest individual tree. Methods requiring restrictive forest density thresholds likely place the boundary differently than those accepting open forests. And of course, many methodological decisions can impact the results just as much.

By reproducing and comparing existing modelling approaches for Switzerland, the following chapter examines how different definitional choices produce different spatial outcomes. The analysis in the following chapter aims to research what methods are used, whether representation of this inherently vague boundary are spatially consistent and how they relate to both the scientific definitions reviewed in Chapter 2 and the practical interpretations documented in this chapter.

Chapter 4: Treeline Modelling Methods

Cartographic representations of treelines were created for more than 100 years, long before modern mapping techniques were available. Figure 4.1 shows an early attempt of a treeline model for Switzerland by Brockmann-Jerosch (1925). It shows the climatic treeline, that is usually derived using physical parameters such as temperature or precipitation to determine treeline elevation.

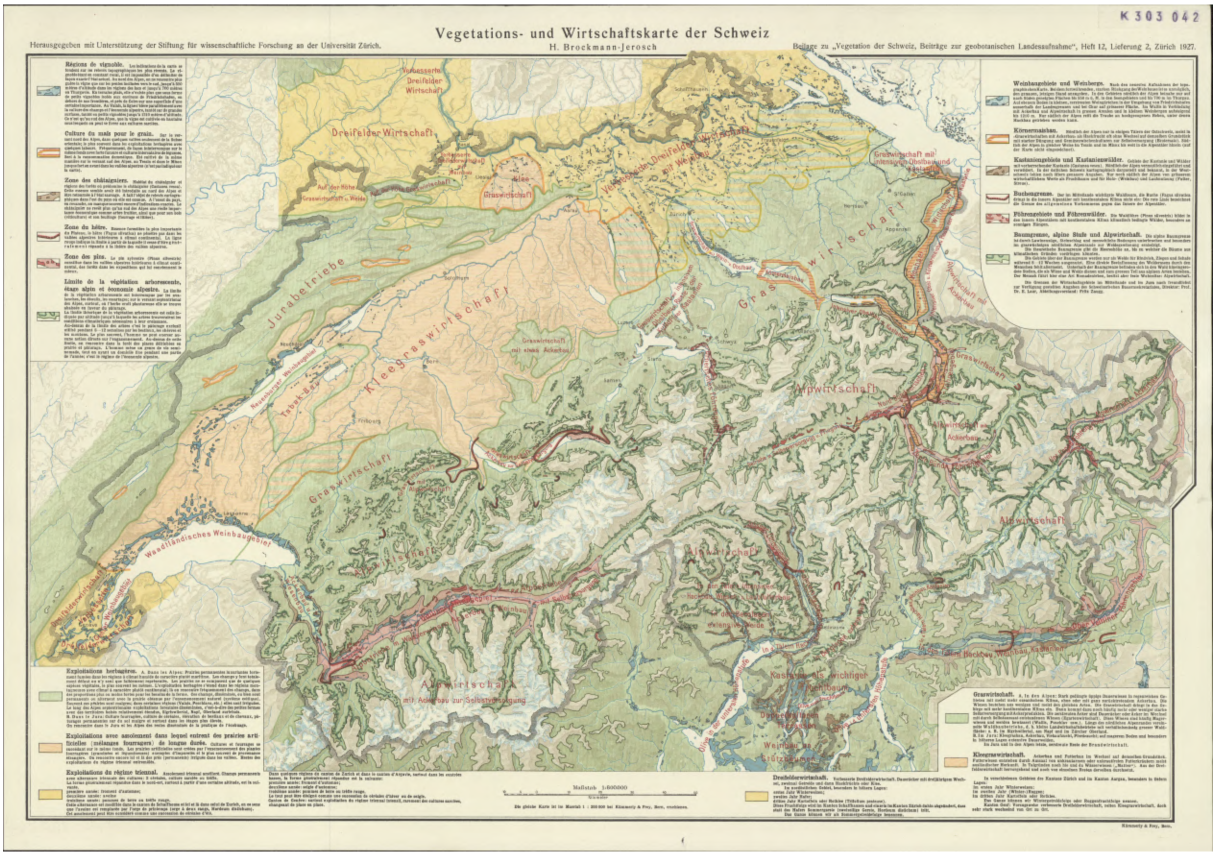

Figure 4.1: Vegetation and Economy Map of Switzerland by Brockmann-Jerosch (1925).

Of course, back then such data was barely available, but the map is still impressively similar to more recent models as visible in Figure 4.2. The resulting position of these treelines is not related to forest or tree cover at all and rely entirely on physical parameters. They do not account for local or regional disruptions of the treeline such as anthropogenic activity, reoccurring avalanches or unsuitable topography as discussed in Chapter 2. More recent examples can be found in Paulsen and Körner (2014), Byrne et al. (2022), Irl et al. (2016), Karger et al. (2019) or Könz et al. (2022) with a regional focus on Switzerland. The latter sampled 3000 locations where the climatic treeline and the actual treeline were estimated to match.

To these locations the parameters maximum air temperature and average precipitation in July, mean snow free period, exposition, slope and rock substrate were assigned and used to estimate the climatic treeline for the entire extend of Switzerland. Since actual forest or tree cover is not part of such a model they may place the treeline in locations entirely absence of forest or trees. This can be observed in Figure 4.3 and will be discussed later on.

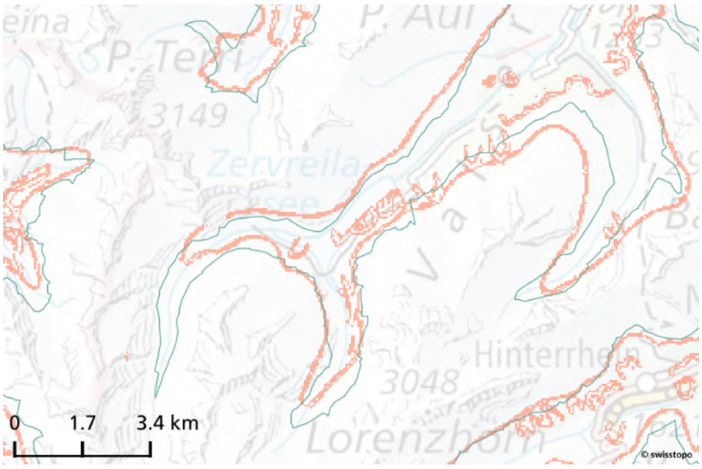

Figure 4.2: Comparison of the georeferenced treeline from Brockmann-Jerosch (1925) with the treeline from Szerencsits (2012).

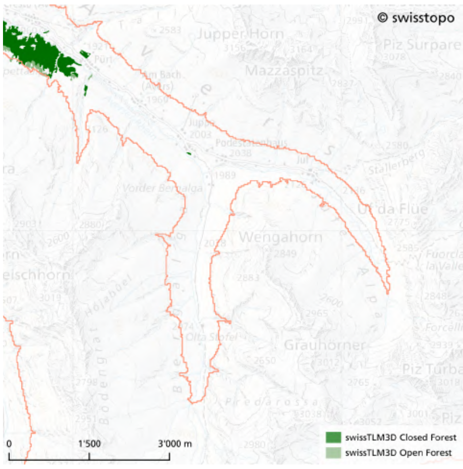

Figure 4.3: The treeline model of Könz et al. (2022) shown at the back of a valley entirely absent of forest and only few individual trees.

Another way to model treelines is to consider where uppermost forest and trees exist, take the elevation of those locations and extrapolate this elevation within a suitable spatial region. The logic behind this is to claim that if forest can grow up to a certain height in one location, it is likely to be able to grow up to that elevation in that entire region, since climatic conditions are expected to be similar. Nguyen (2025) calls this method observation-based as opposed to the first way, model-based.

In this chapter I reproduce four papers that modelled the treeline observation-based in Switzerland: Paulsen and Körner (2001), Gehrig-Fasel et al. (2007), Szerencsits (2012) and Nguyen (2025). These were selected because they represent, to my knowledge, all existing observation-based approaches to treeline modelling in Switzerland. The reproduction involved first comprehending each method's workflow and documenting it as a flowchart, then translating each step into code. Selected intermediate steps are shown visually to illustrate the processing chain. As some of these methods require larger amounts of processing power and input data is not fully available, they will not be carried out for all of Switzerland, but instead, restricted to a manually selected, representative region. The region consists of several catchment areas (Federal Office for the Environment (FOEN), 2025), as they separate valleys and slopes appropriately for treeline analysis (Szerencsits, 2012). The code to reproduce the methods was written in the R programming language, version 4.4.1 using RStudio IDE and is available under https://github.com/mifranz/msc_thesis.

4.1 Paulsen and Körner, 2001

The earliest GIS-based treeline model for Switzerland was, to my knowledge, developed by Paulsen and Körner. The aim of their work was to find out, whether or not the exposition of slopes impacts the elevation of the treeline. It had been previously observed that exposition has an impact on tree growth at a micro scale in the treeline ecotones, but large scale analysis was not yet conducted. To examine such possible effects, they created a model of the treeline using geospatial techniques. The base data for their analysis was the Arealstatistik product from GEOSTAT[1] of the years 1992/97. The dataset is a 100 m grid of fixed sample points with assigned land use and land cover from overlaid digital aerial images from 1992–1997. The categories used by Paulsen and Körner are shown in Table 4.1.

Table 4.1: Selected forest categories from GEOSTAT.

Code	Category (DE)	Category (EN)
50	Normalwald	Normal forest
51	Schmaler Wald	Narrow forest
55	Aufgelöster Wald auf Landwirtschaftsflächen	Open forest on agricultural land
56	Aufgelöster Wald auf unproduktiven Flächen	Open forest on unproductive land

First, the elevation from the DHM25[2] was assigned to each point of the forest categories. Then, they created an 10x10 km grid over the entire study area and for each grid cell they extracted the highest elevation of a forest cover point. This value is then taken as treeline elevation for the respective cell. Only cells with a maximum elevation of at least 1750 m are kept, which is the minimum treeline elevation in Switzerland according to the authors. Further, the highest point with forest cover must be at least 150 m lower than the highest land point elevation within that 10x10 km cell. This ensures that mountains where trees grow up to the top are disregarded as well as low elevation, treeless mountain tops caused by strong winds or other factors. To derive the treeline, the maximum forest elevation is subtracted from the original DEM. Any point lower than this value is below the treeline, any point higher is above. Subtracting the forest elevation from the maximum forest elevation and creating a binary mask at 0 categorizes the raster into areas below and above the treeline. In a last step, vectorizing this binary raster, the treeline can be extracted as a line. These last steps to extract the treeline are not explicitly mentioned and may not be carried out by the authors since the goal of the paper is not the treeline itself, but exposure effects.

The crucial step of this implementation is the maximum forest elevation inside a certain spatial unit, in this case the 100 km² grid cell. This method implicitly adopts the fundamental niche concept for treeline estimation, assuming the local maximum elevation of forest presence reflects the upper physiological boundary of tree growth, meaning that if forest can grow at a certain location, more can too (Körner and Hoch, 2023). As discussed in 2.1.2 the realized niche may also be understood as actual treeline. This treeline may be depressed due to disturbances like grazing, logging, or fire and hence does not necessarily represent the potential limit. But the authors argue that 100 km² is enough to disregard such local disturbances.

I document my reproduced workflow as a flowchart in Figure 4.4 and visualised the main intermediate steps in Figure 4.5 and 4.6. While they use the term treeline, what they are modelling is most likely what I defined as forest line earlier in section 2.1.3, since categories with only sparse forest or individual trees are not considered.

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[1] GEOSTAT is the centre of competence for geoinformation and digital image processing within the Swiss Federal Statistical Office (FSO)

[2] DHM25 is a digital elevation model from swisstopo with 25 m grid resolution, derived from the Swiss National Map 1:25000.

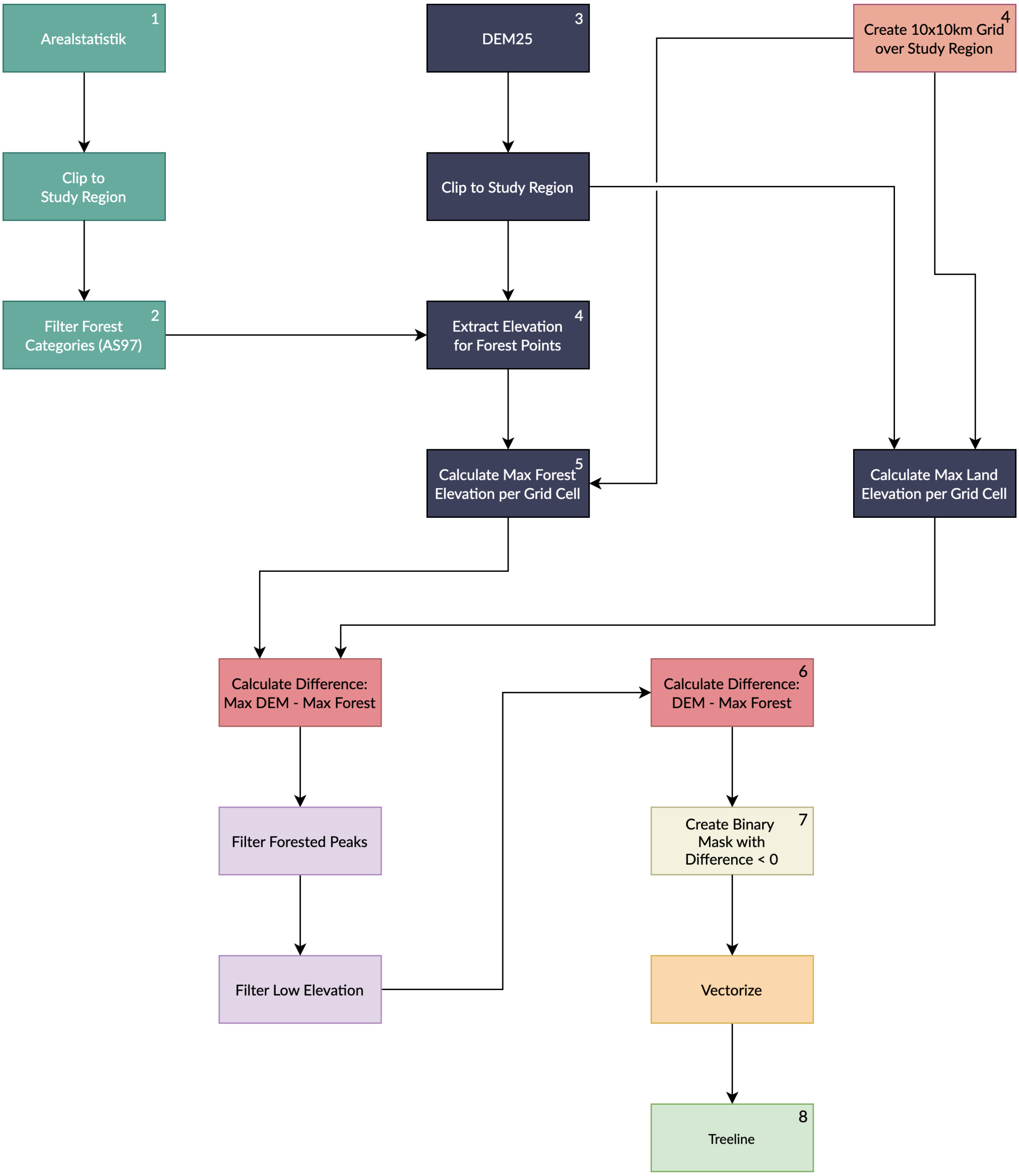


Figure 4.4: Workflow of the method from Paulsen and Körner. The numbers correspond to the steps on the following page. Source: Own Figure.

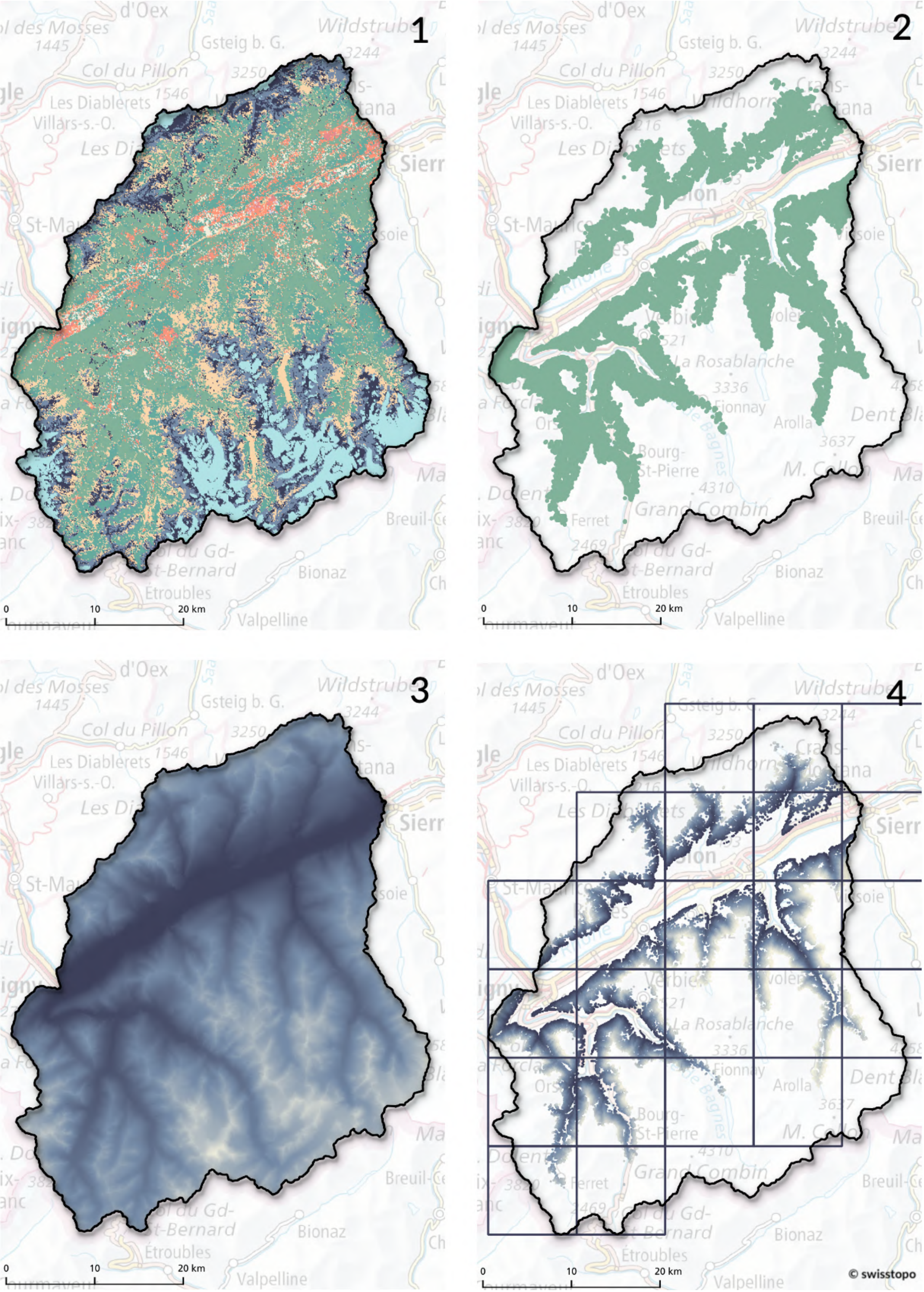


Figure 4.5: Selected individual steps of the workflow from Paulsen and Körner.

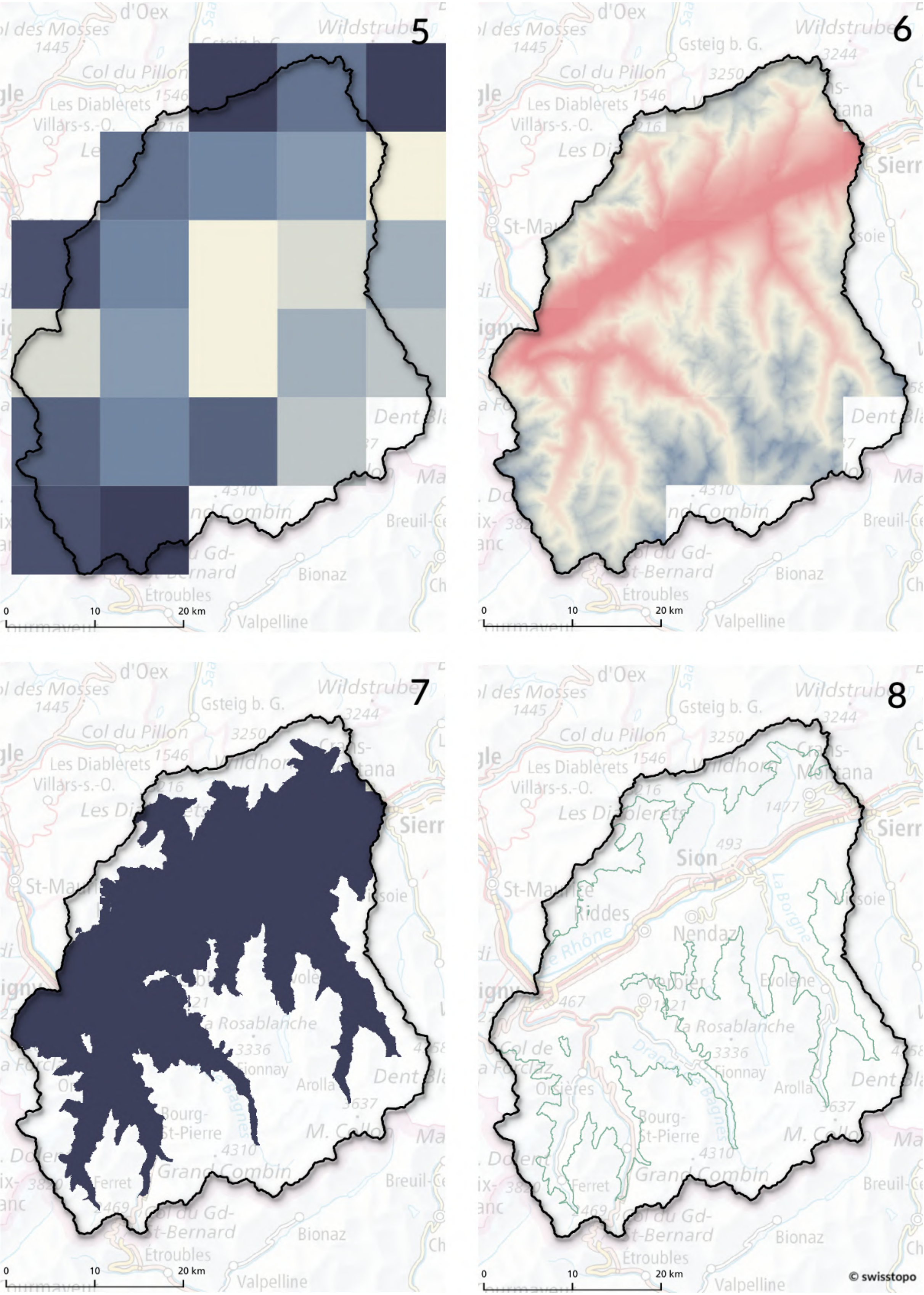


Figure 4.6: Selected individual steps of the workflow from Paulsen and Körner.

4.2 Gehrig-Fasel et al., 2007

This paper built on the basics of Paulsen and Körner (2001) by using similar data and methods. Their goal was to find out if forest was growing further up due to changing climate and what amount of that can be contributed to rising potential treelines in contrast to so called ingrowth. Ingrowth describes the expansion of forest into abandoned grasslands, that were cultivated in earlier times or in other words, forest growing back to its physical limitation, the potential treeline.

Gehrig-Fasel et al. used the same dataset as input, but with different categories, as shown in Table 4.2. They first conducted a local moving window operation of size 900 m on the forest elevation raster to get the maximum forest elevation within a search window. This maximum is then subtracted from the DEM as in Paulsen and Körner to get a local treeline. By calculating the local treeline for two different years (1985 & 1997), the differences can be quantified. This local treeline can be understood as the actual treeline. Since their goal was to distinguish between ingrowth and true upward shifts, they had to compare the actual treeline to the potential treeline in a second step. They chose a similar spatial unit as Paulsen and Körner by running a moving window of size 100 km^2 to get a regional treeline. Similar to Paulsen and Körner they also filtered out forest covered mountain tops effect, but did not state explicitly what distance was used. Since they cited Paulsen and Körner I assumed they also used 150 m. The calculated maximum elevation per search window was then interpolated using regression splines to smooth the elevations. From the method description it was not entirely clear what exactly served as input to the interpolation, as they stated using the extracted highest forested pixels. Since the authors did not respond to a request of mine, I assumed they refer to the individual forest pixels that have the same elevation as the maximum forest elevation within a search window. The interpolated raster was then subtracted from the DEM to derive the regional (=potential) treeline. The study does not explicitly state the DEM resolution used. The highest resolution elevation model available from that time was the DEM from swisstopo. Given that the input data has a 100 m resolution, the DEM could have been resampled to 100 m to align with that. Testing the workflow with both 100 m and 25 m did not lead to significantly different results, which is why I chose 100 m for computational reasons.

Table 4.2: Forest categories from the Arealstatistik used by Gehrig-Fasel et al.

Code	Category (DE)	Category (EN)
50	Normalwald	Normal forest
51	Schmaler Wald	Narrow forest
54	Waldschäden	Forest damage
55	Aufgelöster Wald auf Landwirtschaftsflächen	Open forest on agricultural land
56	Aufgelöster Wald auf unproduktiven Flächen	Open forest on unproductive land
57	Gebüschwald	Shrub forest
58	Feldgehölze, Hecken	Field groves, hedges
59	Baumgruppen auf Landwirtschaftsflächen	Tree groups on agricultural land
60	Baumgruppen auf unproduktiven Flächen	Tree groups on unproductive land

Figure 4.7 shows the workflow and 4.8 and 4.9 intermediate steps of the method. As in Paulsen and Körner, the final product visible in Figure 4.9 was not part of the paper because it was not necessary for the calculation of upward shifts. Since the authors did not include any individual trees in their analysis I call this product forest line — equally to the final product of Paulsen and Körner.

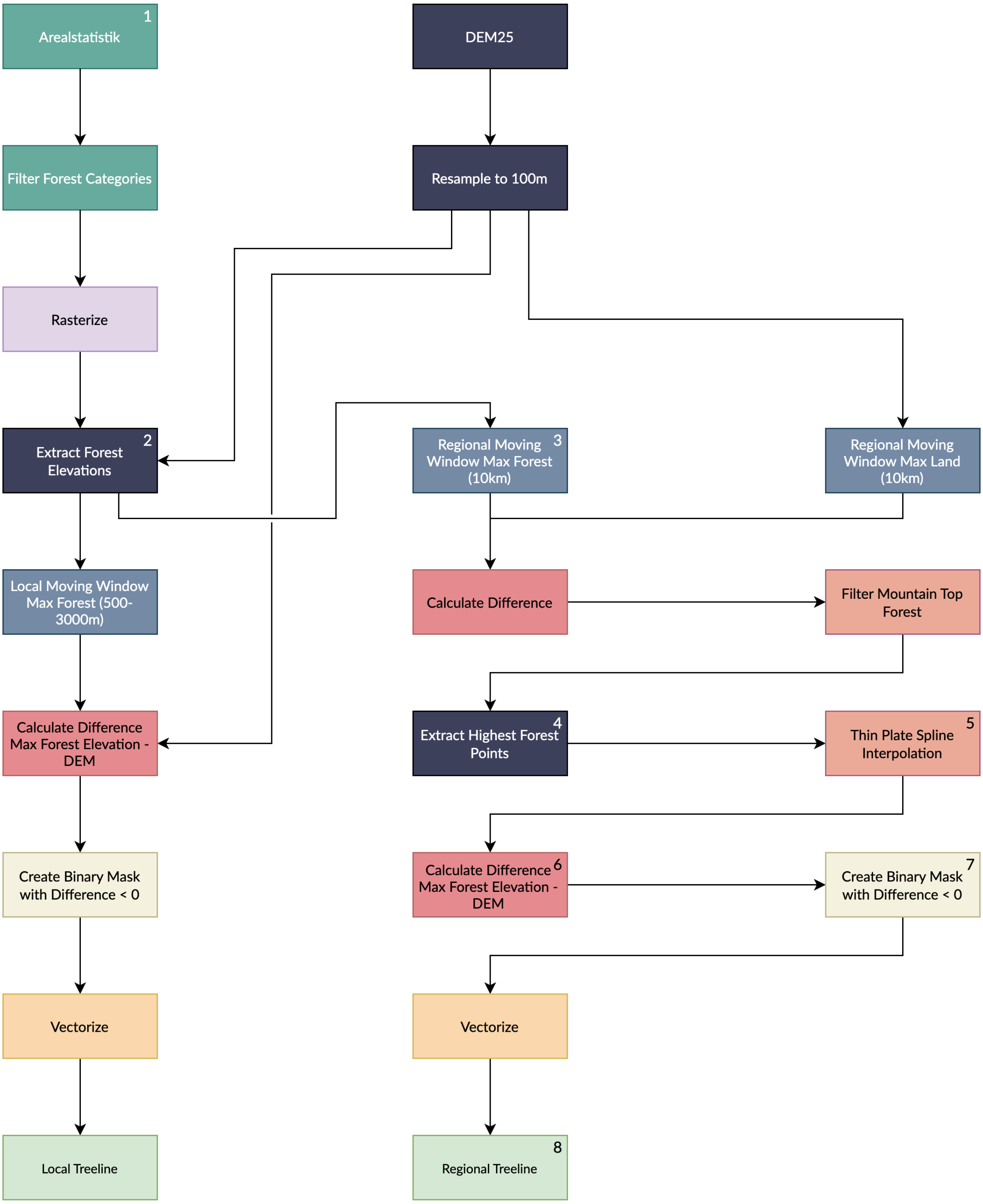


Figure 4.7: Workflow of the method from Gehrig-Fasel et al. Source: Own figure.

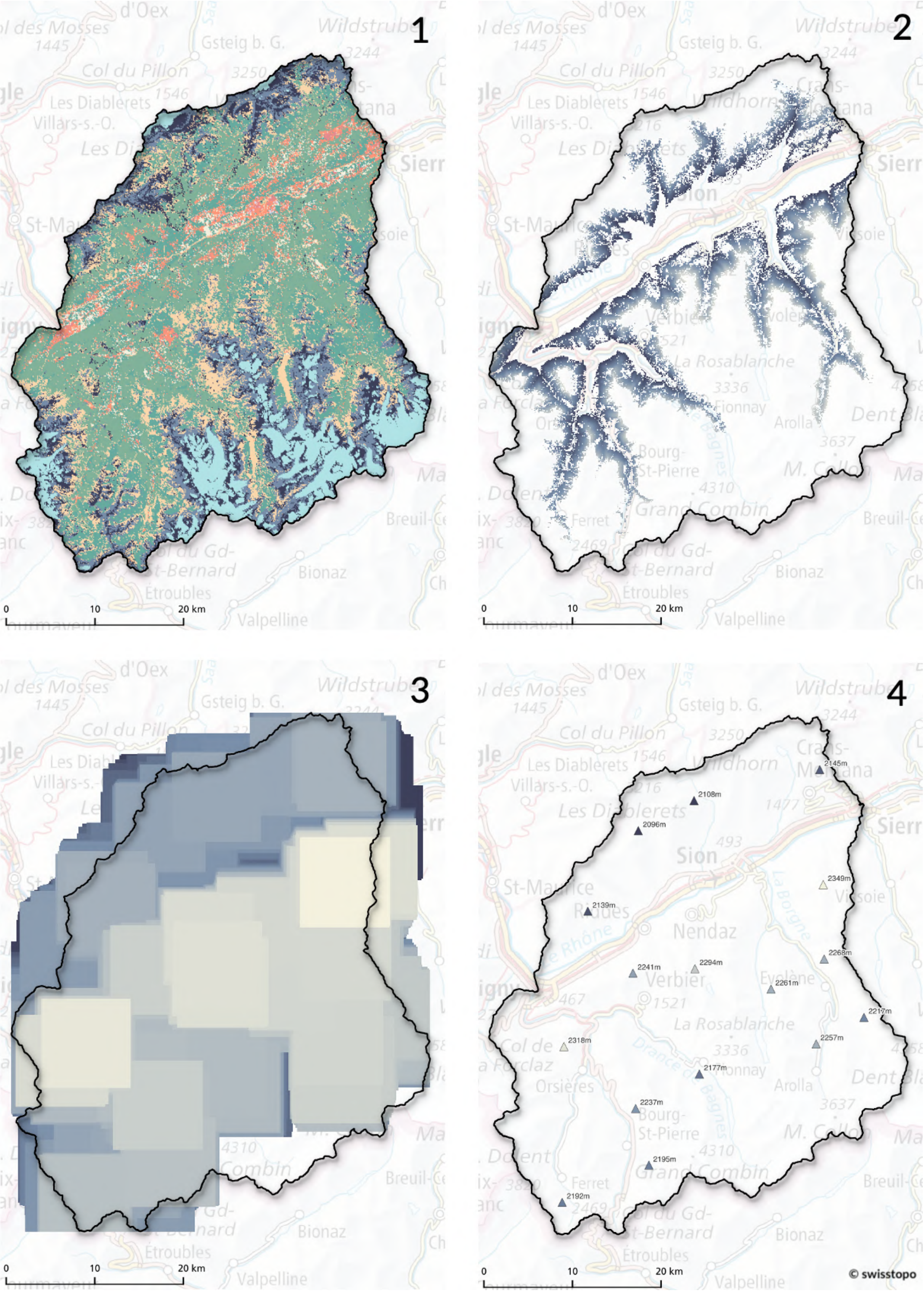


Figure 4.8: Selected individual steps of the workflow from Gehrig-Fasel et al. Only the steps from the regional treeline are shown.

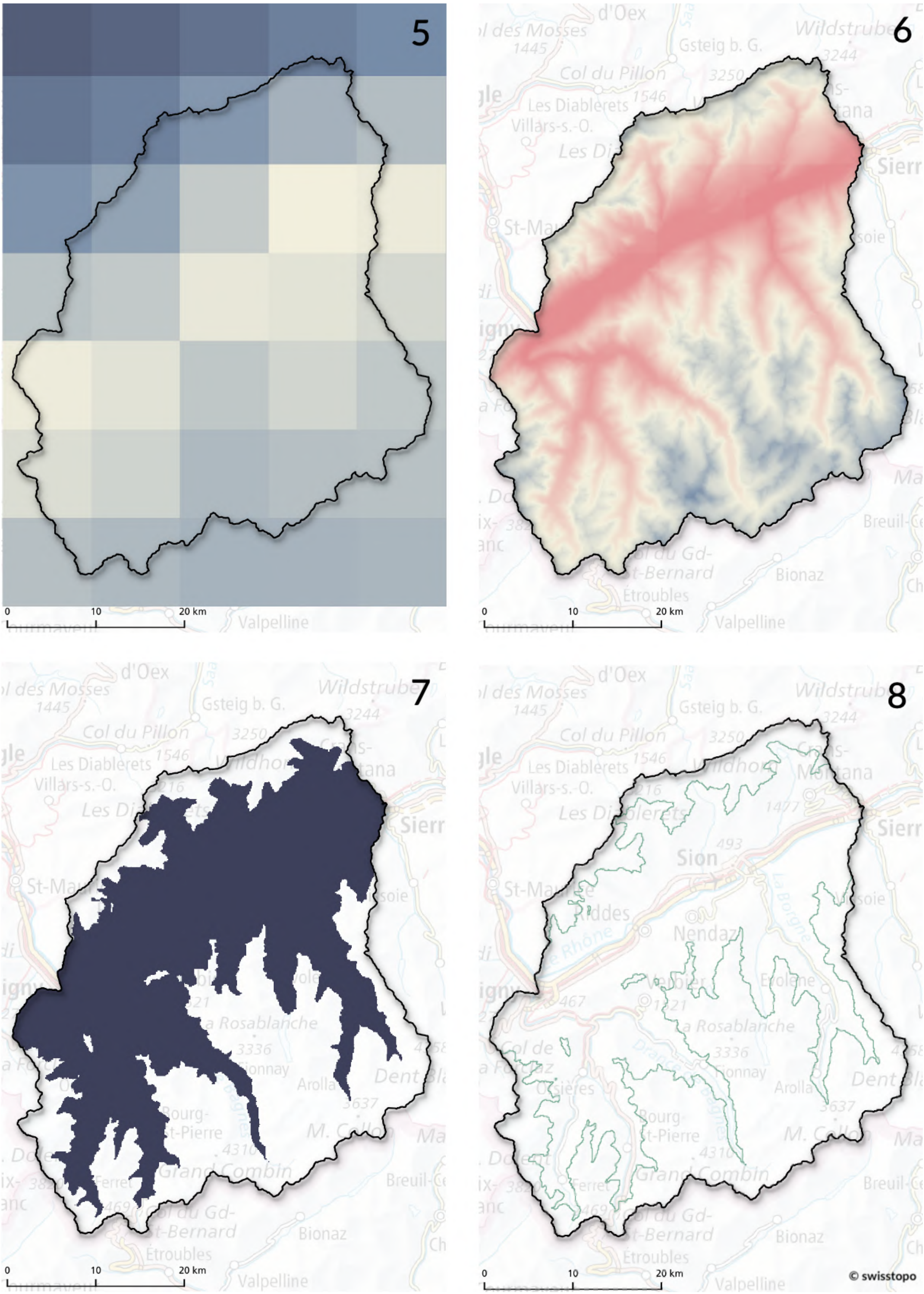


Figure 4.9: Selected individual steps of the workflow from Gehrig-Fasel et al. Only the steps from the regional treeline are shown.

4.3 Szerencsits, 2012

This paper is slightly different than the first two, because the treeline model is not only means to an end but the main purpose. Szerencsits also builds upon the previous two works, but introduces a more sophisticated and detailed process. This starts with the input data by combining two datasets, namely the Arealstatistik from 1997 (AS97) and Swiss Map Vector 25 product from swisstopo (SMV25). The author distinguishes between forest and tree categories, since both the forest line and the treeline are modelled. Table 4.3 gives an overview of all input data.

Table 4.3: Categories used for forest and tree cover by Szerencsits.

Source	Code	Category (DE)	Category (EN)
AS97	50	Normalwald	Normal forest
AS97	52	Aufforstungen	Afforestation
SMV25	-	Wald offen	Open forest

(a) Forest categories

Source	Code	Category (DE)	Category (EN)
AS97	37	Obstanlagen	Orchards
AS97	38	Feldobst	Field fruit trees
AS97	50	Normalwald	Normal forest
AS97	51	Schmaler Wald	Narrow forest
AS97	52	Aufforstungen	Afforestation
AS97	54	Waldschäden	Forest damage
AS97	55	Aufgelöster Wald auf landwirt. Flächen	Open forest on agricult. land
AS97	56	Aufgelöster Wald auf unprod. Flächen	Open forest on unprod. land
AS97	57	Gebüschwald	Shrub forest
AS97	58	Feldgehölze, Hecken	Field groves, hedges
AS97	59	Baumgruppen auf landwirt. Flächen	Tree groups on agricult. land
AS97	60	Baumgruppen auf unprod. Flächen	Tree groups on unprod. land
SMV25	-	Einzelbaum	Individual tree

(b) Tree categories

To derive the treeline he used both forest and tree categories. While the AS97 dataset is still available, the SMV25 has been replaced by the topographic landscape model swissTLM3D and some of the categories have been changed and not all can be replicated, as swisstopo told me upon request. For example *Baumreihe* (EN = row of trees) and *Gebüschreihe* (EN = row of bushes) have been merged to *Gehölzfläche* (EN = wooded area). The problem is that Szerencsits only used *Baumreihe*, but not *Gebüschreihe*. Swisstopo also told me that there are significantly more individual trees within swissTLM3D compared to SMV25, likely due to different data collection methods. This has lead me to disregard the category *Gehölzfläche* in order not to overestimate the amount of individual trees even more. The author also mentioned manually removing 72 individual trees and two sample points from the Arealstatistik as they were erroneous points, but this was not looked into further due to lack of additional information.

Preprocessing the forest and tree cover involves rasterizing vector data. This can be done in different ways, for example a cell can be set as forest only if the centre of the cell or if any part of the cell intersects with a forest polygon, where the latter will generally lead to a larger number of forest pixels. Since this was not specified, I stuck to the default option of the algorithm I used, using the cell centre.

The method of this paper is twofold, consisting of a slope zone analysis and a moving window analysis. The former is similar to the 100 km^2 grid method from Paulsen and Körner, except that a different spatial unit — slope zones — were used. Szerencsits derived the slope zones by calculating the aspect from a DEM, smoothing it with a 3x3 majority filter and a stepwise integration of small polygons (<4 km²) into neighbouring polygons. There are several ways to conduct this integration, because many polygons have more than one neighbour, and a rule is therefore required to decide which neighbouring polygon the selected polygon is merged into. Since Szerencsits did not describe this process in detail, I decided to merge them according to the longest shared boundary. Another method would be to merge with the largest neighbouring polygon. The difference between the two approaches will be discussed in Chapter 5.

In a next step, for each slope zone the maximum elevation of forest (or tree) cover was extracted, set as treeline elevation for the entire zone and then subtracted from the DEM, resulting in the slope zone based treeline. The second part of the analysis consists of a moving window operation, as in Gehrig-Fasel et al. but with a size of only 10 km² compared to 100 km² to derive the maximum forest elevation per window. This elevation was then again subtracted from the DEM, resulting in the moving window based treeline. The two binary rasters showing cells above (0) and below (1) the treeline were then added and all cells > 1 were set as below the treeline. Thus, it was sufficient that either method classified a pixel as below the treeline, to be below in the final result. The resulting raster was vectorised and all areas < 0.5 km² were removed. All steps were conducted for forest cover to derive the forest line and forest and tree cover to derive the treeline. Figure 4.10 shows the workflow and 4.11, 4.12 and 4.13 intermediate steps of the method.

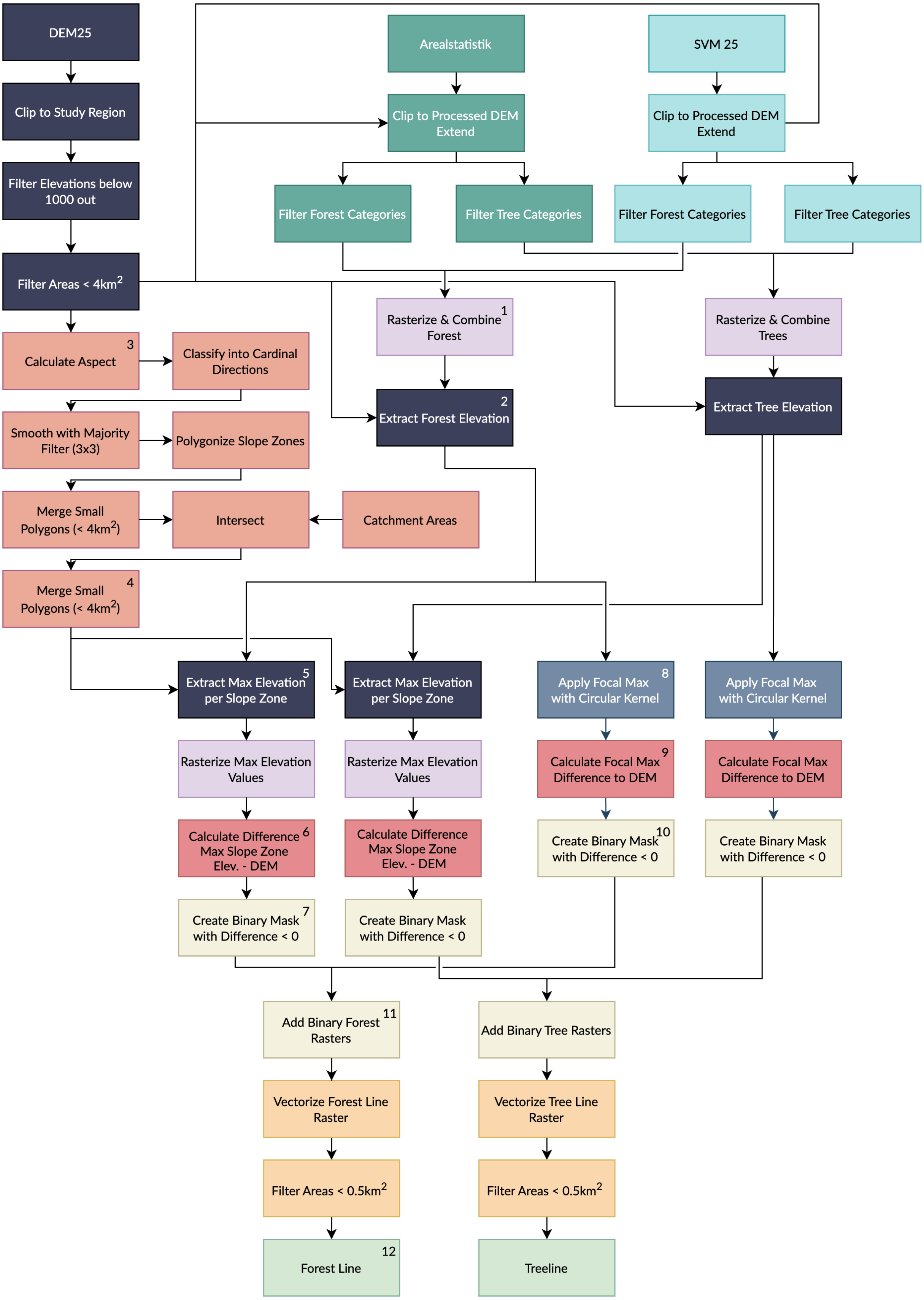


Figure 4.10: Workflow of the method from Szerencsits. Source: Own figure.

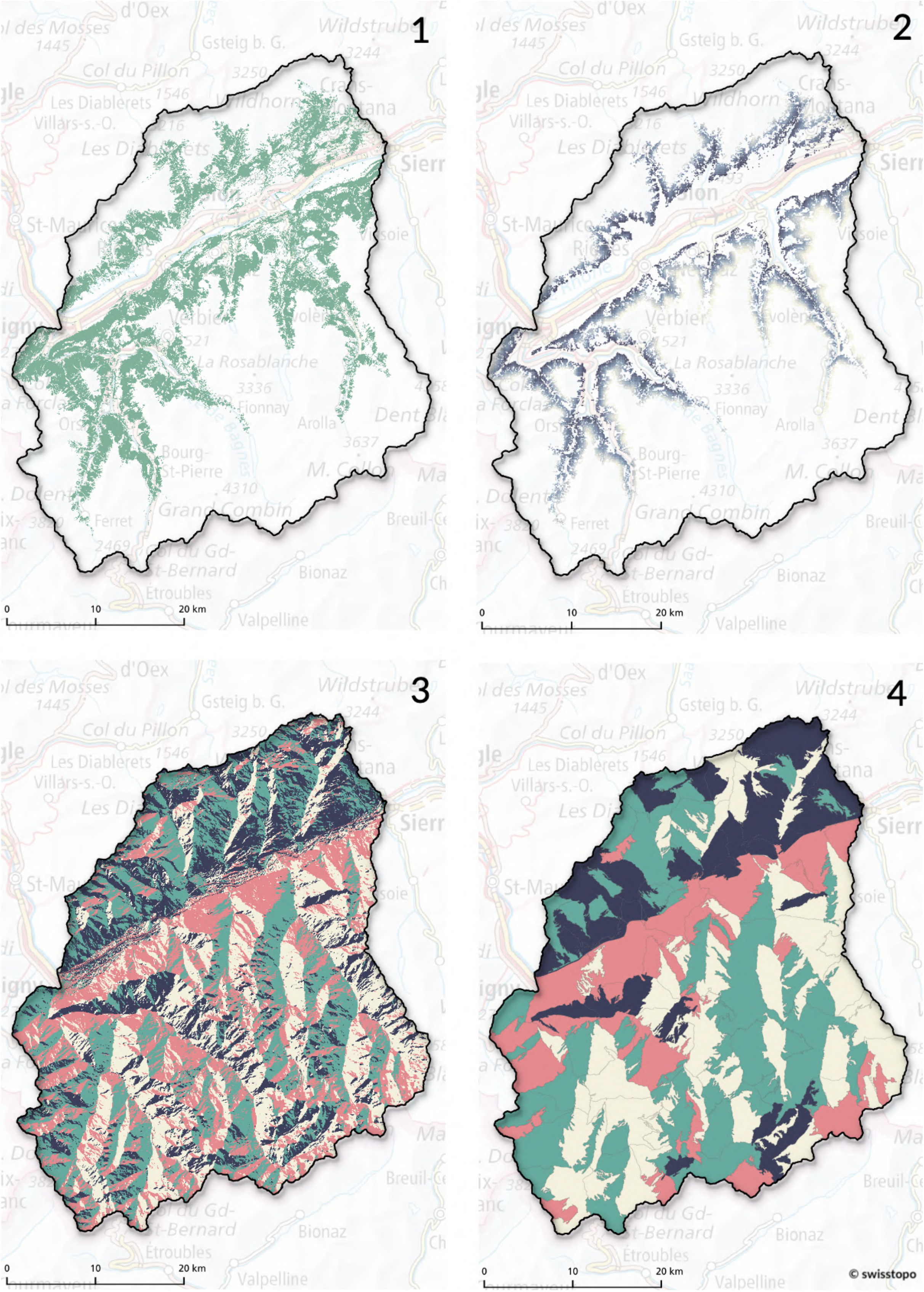


Figure 4.11: Selected individual steps of the workflow from Szerencsits.

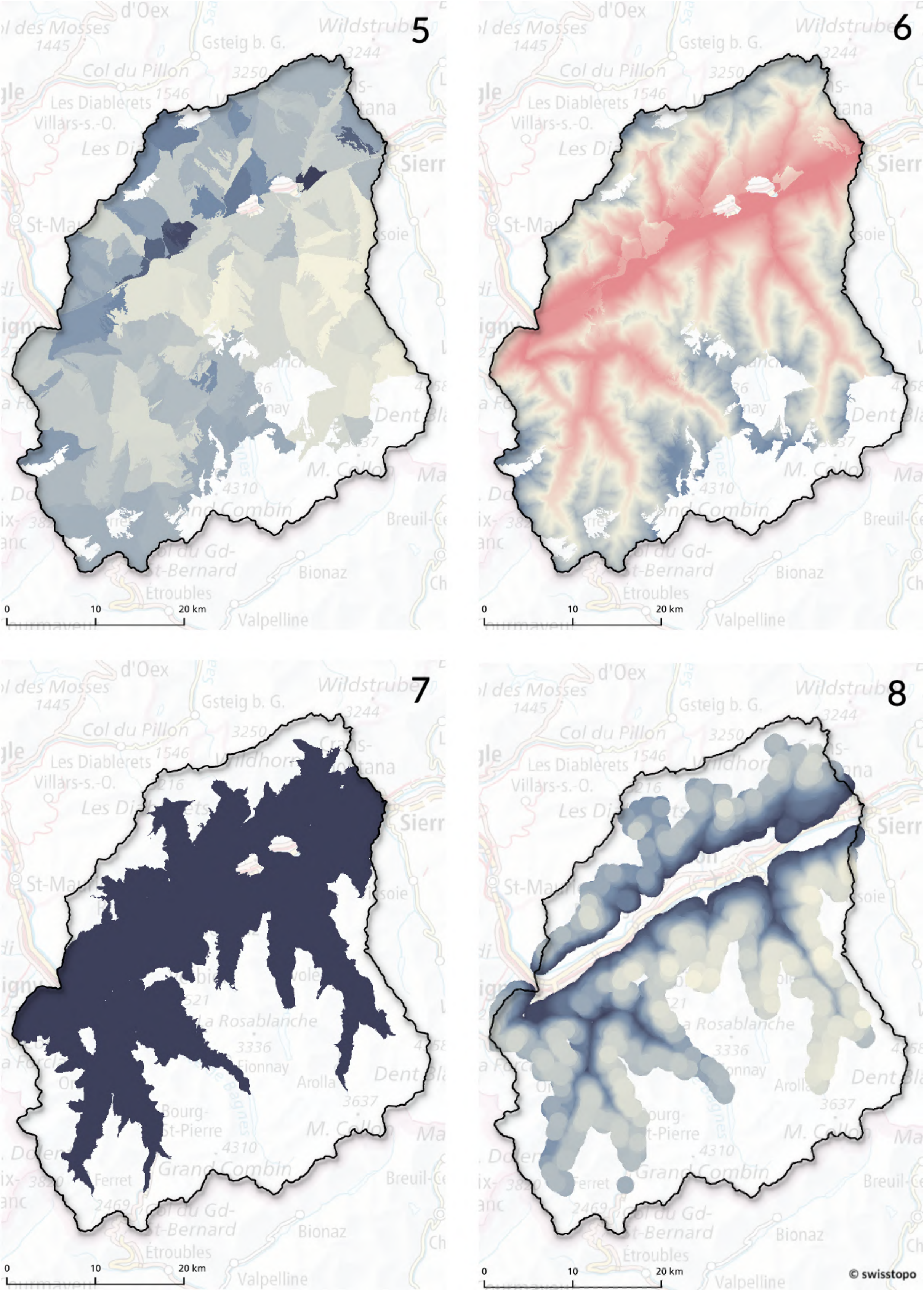


Figure 4.12: Selected individual steps of the workflow from Szerencsits.

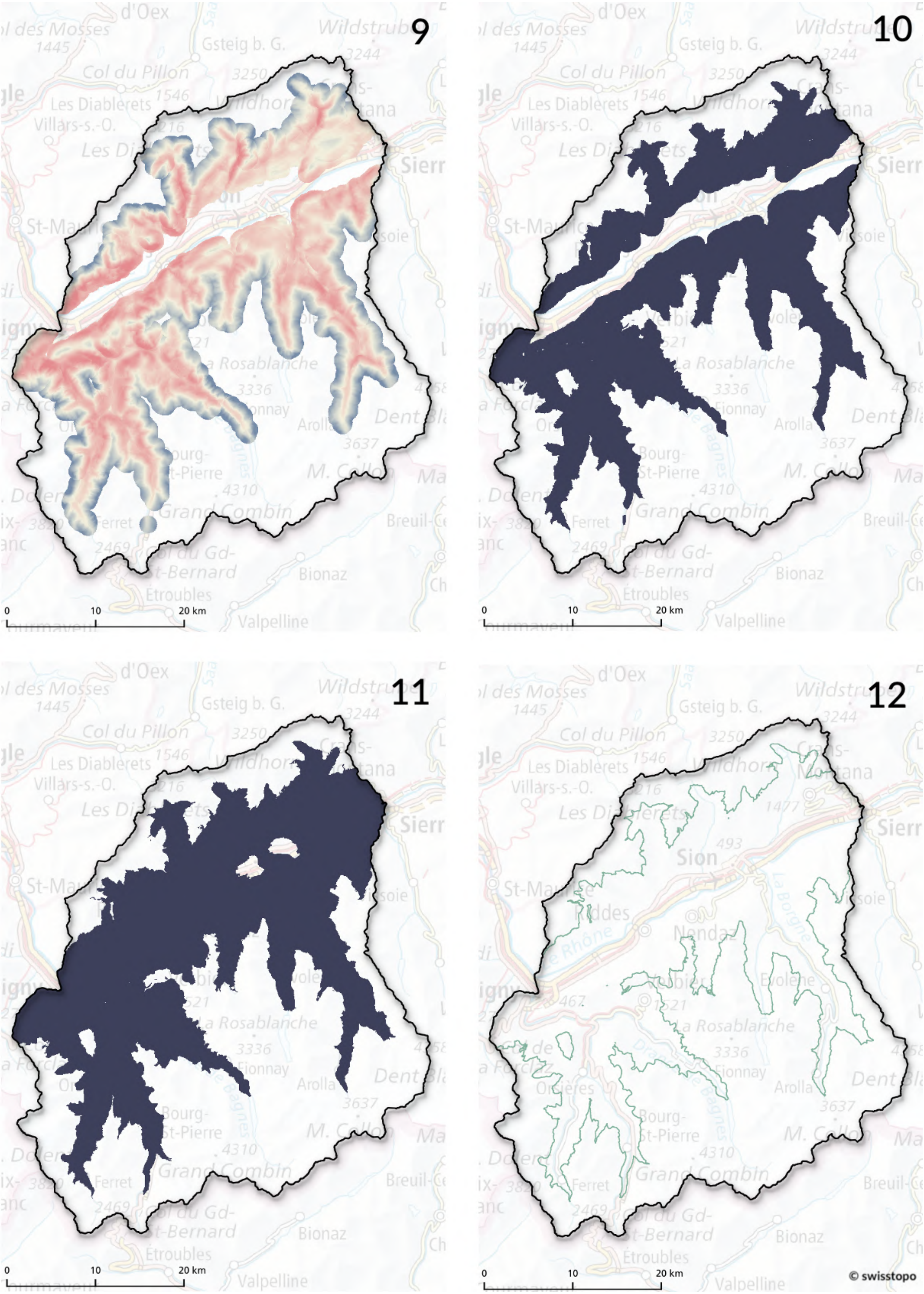
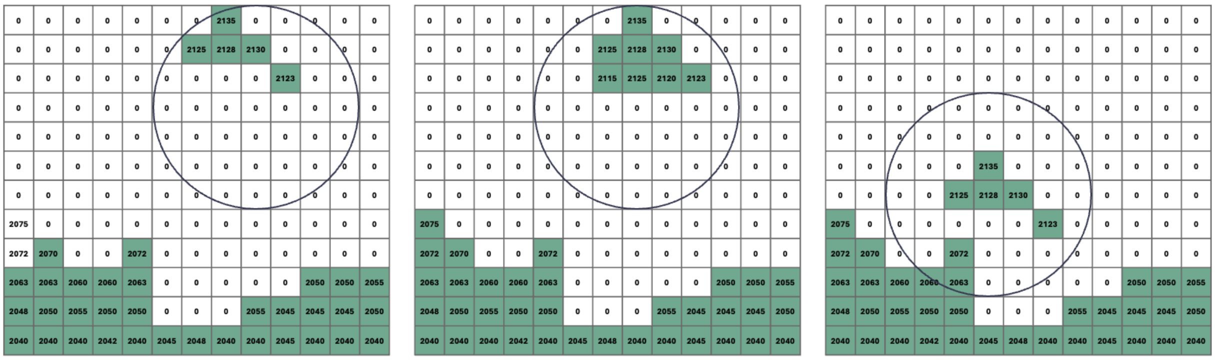


Figure 4.13: Selected individual steps of the workflow from Szerencsits.

4.4 Nguyen, 2025

This treeline model is the last part of the doctoral thesis from Nguyen (2025). In the first part, the author uses deep learning to derive forest cover maps from optical imagery, which is then used as input for the treeline model. Thus, this model is different to the previous three without using the typical forest or tree cover sources in Switzerland. The forest data is also much more detailed with a 1 m and later in the process 5 m resolution. Nguyen uses two datasets as input, a forest composite derived from five years (C_{fine}) and one from nine years (C_{coarse}). Each year has a forest cover prediction raster (forest or no forest) and a vote raster (1-4). The vote raster contains a measure of certainty for each pixel, stemming from the deep learning model. The pixel from each year with the highest vote is then taken. It was not stated how it was decided when two years have equal votes but different predictions. Unsurprisingly, this occurs most often around forest boundaries. I chose to take the more recent year in such cases. For both composites the elevation data is added, followed by moving window operations. Equally as in Paulsen and Körner, 1750 m is defined as minimum treeline elevation and all areas below are not considered. The resolution for the next step is resampled to 5 m, for computational reasons I used 10 m, which did not lead to any observable differences. The composite map was resampled to match the elevation data resolution using the majority method, where each pixel is assigned the value of the most common class within a 5×5 window. This means a pixel is classified as forest if at least 13 of the 25 pixels in the window are forest. It was not stated what method was used in the thesis.

The operations Nguyen uses are different from the previous: the author uses a circular disk instead of a rectangle as window, the 89.8 percentile elevation instead of the maximum elevation and small windows with radiuses of 50 m and 300 m, compared to 1000 m (Szerencsits, 2012) and 10 km (Gehrig-Fasel et al., 2007). The 89.8 percentile function ignores forest patches that are smaller than 800 m² and further than twice the radius away from larger forest patches. This step only works if all non-forest cells have the value 0 or some other dummy value. If non-forest cells are set to 0, the percentile calculation includes all cells in the window (as opposed to if they were NA). If forest covers only a small fraction of the window, most values are 0, pushing the 89.8th percentile below the actual forest elevation. This effectively excludes isolated small forest patches from defining the treeline elevation. If a small patch lies within 2x the window radius of a larger forest, the window will capture cells from both, exceeding the 800 m² threshold and producing a valid percentile. Only truly isolated small patches are filtered out. 800 m² is the minimum size of closed forest in the swissTLM3D product from swisstopo, thus the 89.8 percentile is precisely chosen. Figure 4.14 shows an illustration of this mechanism.



0	0	0	0	0	0	0	2135	0	0	0	0	0
0	0	0	0	0	0	2125	2128	2130	0	0	0	0
0	0	0	0	0	0	0	0	0	2123	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0	0	0	0	0
2072	2070	0	0	2072	0	0	0	0	0	0	0	0
2063	2063	2060	2060	2063	0	0	0	0	0	2050	2050	2055
2048	2050	2055	2050	2050	0	0	0	2055	2045	2045	2045	2050
2040	2040	2040	2042	2040	2045	2048	2040	2040	2045	2040	2040	2040

0	0	0	0	0	0	0	2135	0	0	0	0	0
0	0	0	0	0	0	2125	2128	2130	0	0	0	0
0	0	0	0	0	0	2115	2125	2120	2123	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0	0	0	0	0
2072	2070	0	0	2072	0	0	0	0	0	0	0	0
2063	2063	2060	2060	2063	0	0	0	0	0	2050	2050	2055
2048	2050	2055	2050	2050	0	0	0	2055	2045	2045	2045	2050
2040	2040	2040	2042	2040	2045	2048	2040	2040	2045	2040	2040	2040

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	2135	0	0	0	0	0	0	0
0	0	0	0	2125	2128	2130	0	0	0	0	0	0
2075	0	0	0	0	0	0	2123	0	0	0	0	0
2072	2070	0	0	2072	0	0	0	0	0	0	0	0
2063	2063	2060	2060	2063	0	0	0	0	0	2050	2050	2055
2048	2050	2055	2050	2050	0	0	0	2055	2045	2045	2045	2050
2040	2040	2040	2042	2040	2045	2048	2040	2040	2045	2040	2040	2040

Figure 4.14: If forest cover within a window is too small and isolated the elevation of the 89.9% percentile will be 0 (left). If it is larger (middle) or closer to other forest (right) the percentile will be elevation of forest cover. Non-forest cover cells have to be set to 0 or some other dummy value.

The 50 m window is used to derive what the author calls upper forest elevation, the two 300 m window to derive the timberline elevation. It is unclear why the author refers to the term timberline in this instance, since the timberline is usually the lowest boundary within the researched papers in Chapter 2 that used this term. The two consecutive windows are used because it is computationally less intensive than a single larger window. In a last step, the two products are combined in the same way as in Szerencsits's method, deriving the treeline. Since Nguyen only used forest as input, the final product most likely refers to what I defined as forest line. Workflow and intermediate steps can be seen in Figure 4.15, Figure 4.16 and 4.17.

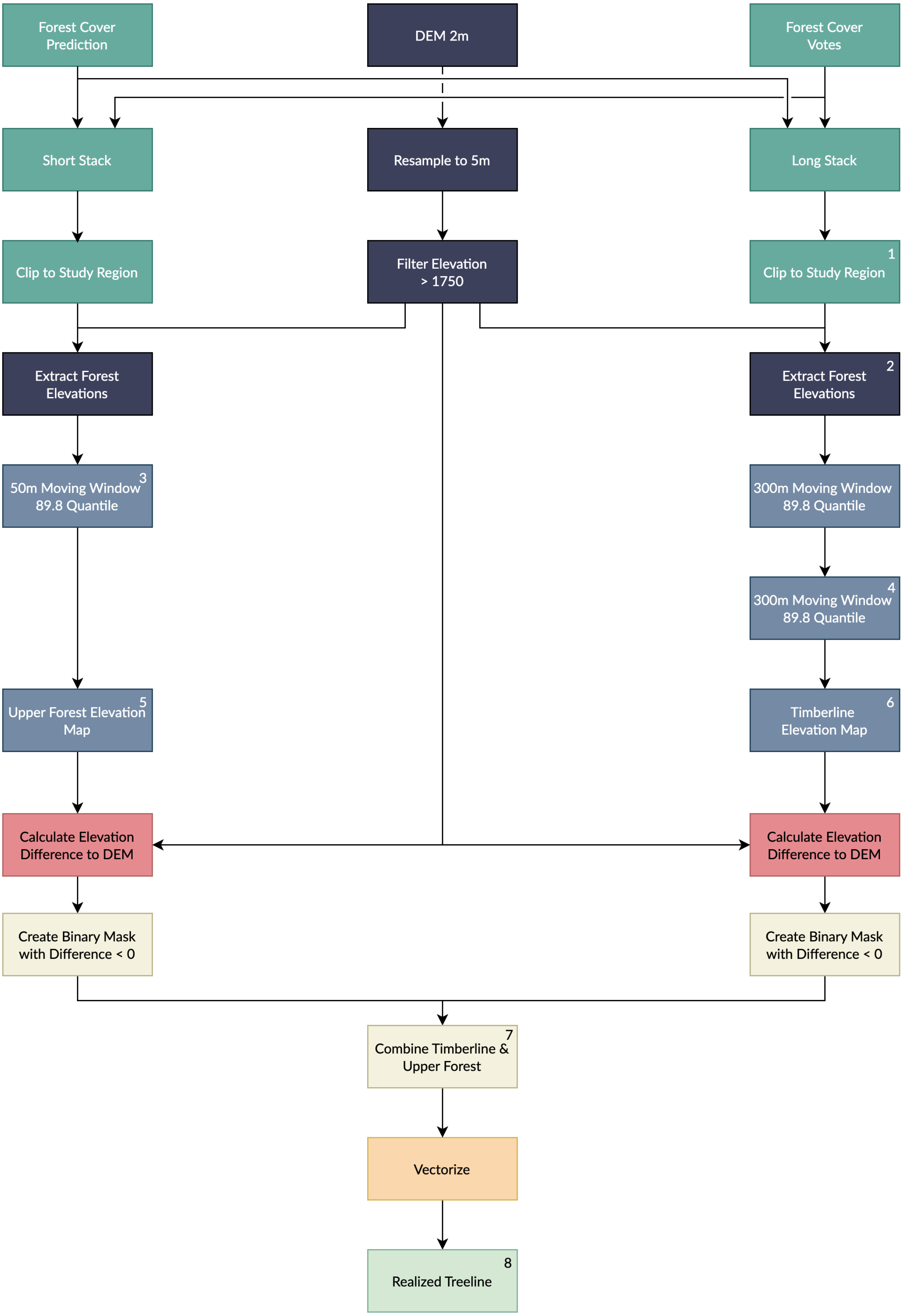


Figure 4.15: Workflow of the method from Nguyen. Source: Own figure.

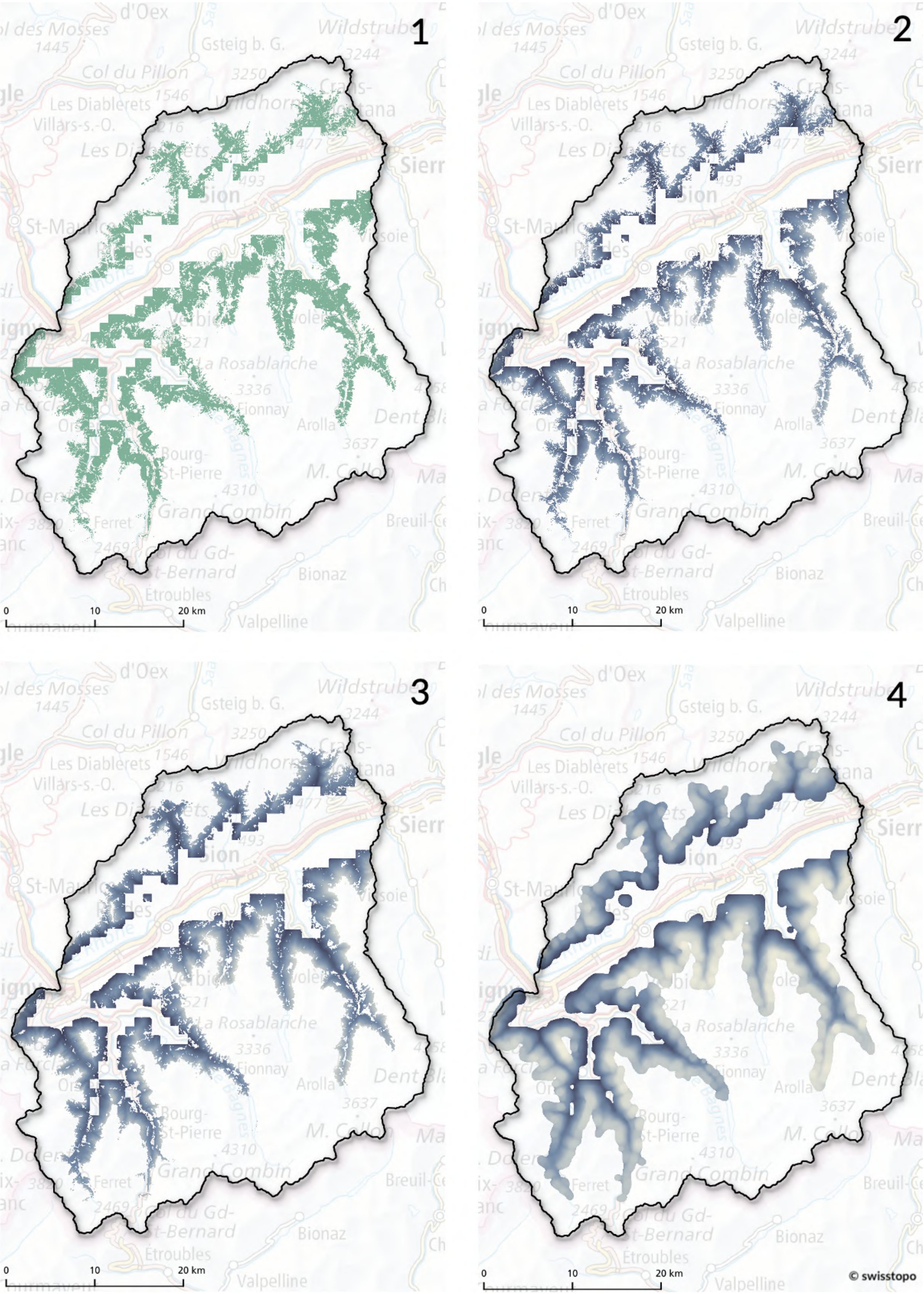


Figure 4.16: Selected individual steps of the workflow from Nguyen.

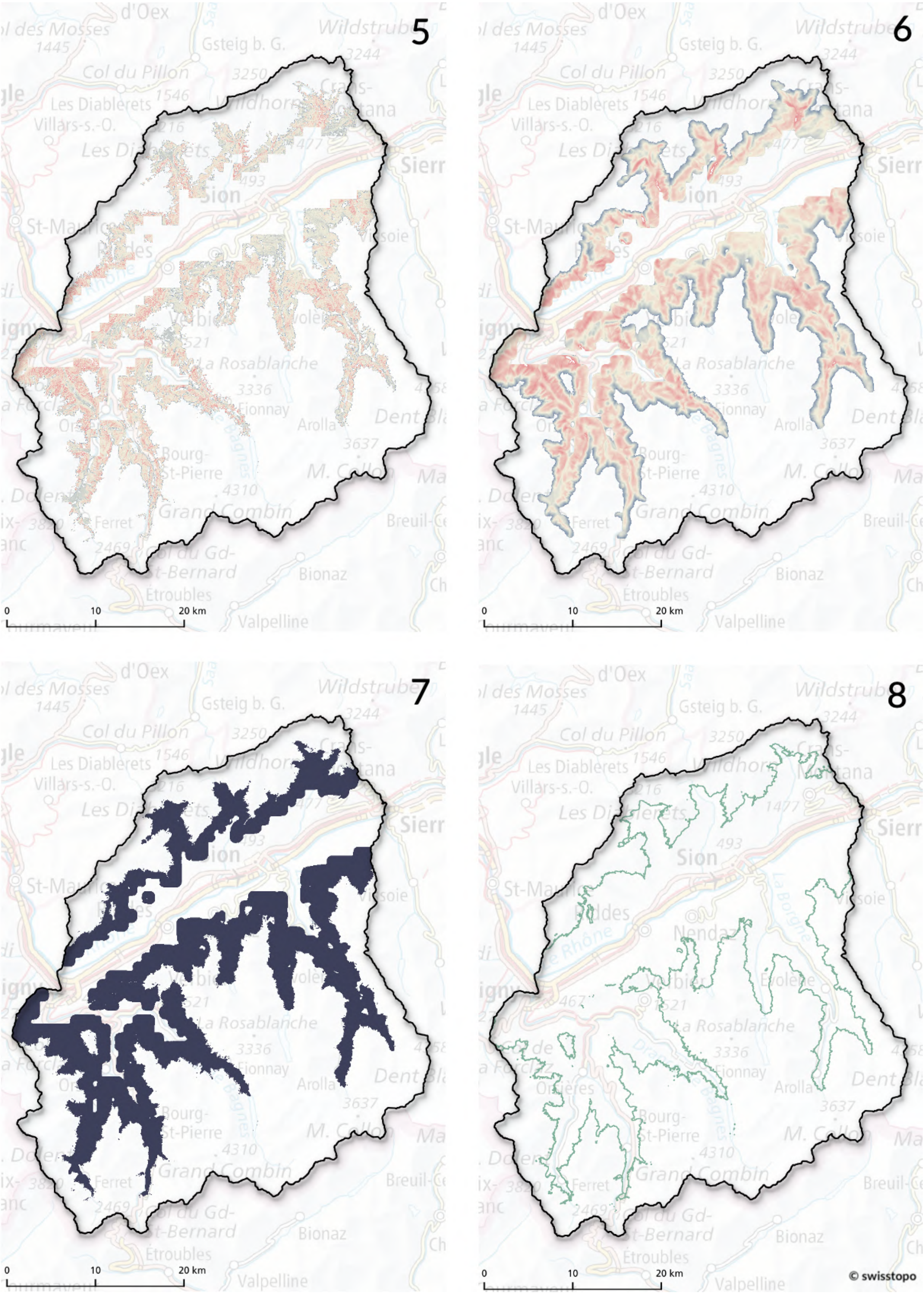


Figure 4.17: Selected individual steps of the workflow from Nguyen.

4.5 Summary

The four reproduced approaches differ in input data, data resolution, choice of spatial unit and the statistical metric used to extract maximum forest elevations. Paulsen and Körner and Gehrig-Fasel et al. use forest categories from the Arealstatistik as input and a maximum forest elevation within large spatial units. While Paulsen and Körner use a fixed 100 km² grid, Gehrig-Fasel et al. use a moving window of the same size to estimate the maximum forest elevation within. Szerencsits extends this workflow first by combining data from the Arealstatistik with land cover data from the SMV25 product. Szerencsits then uses the idea of fixed spatial units from Paulsen and Körner to estimate maximum forest elevation, but with much smaller and topography related units and combines this with the moving window approach from Gehrig-Fasel et al. but also with a higher resolution of 1000 m. The same procedure is separately applied to forest and tree cover, resulting in a forest line and a treeline. Nguyen uses high-resolution forest cover from deep learning models and also applies a moving window approach. Two different window sizes are combined and refined by not taking the maximum forest elevation but the 89.8 percentile. Table 4.4 provides a short overview of the input data, methods and output products of the four reproduced papers. Chapter 5 analyses and compares the results from these reproductions.

Table 4.4: Summary of input data and output products for the four treeline modelling methods.

Input Data	Method Summary	Output Product
Paulsen & Körner, 2001		
Arealstatistik, DHM25	Max elevation per 10×10 km grid	Forest line
Gehrig-Fasel et al., 2007		
Arealstatistik, DHM25	Max elevation per 10×10 km moving window + interpolation	Forest line (local & regional)
Szerencsits, 2012		
Arealstatistik + Swiss Map Vector 25, DHM25	Max elevation per slope zone; Max elevation per 1000 m moving window	Forest line and Treeline
Nguyen, 2025		
Deep Learning forest composite, swissALTI3D	89.8 percentile elevation per 50 m and 300 m moving window	Forest line

Chapter 5: Results

5.1 Original Methods

The results of the four reproduced methods are analysed in several ways. First, they are described and compared qualitatively by examining individual characteristics. Then, a quantitative analysis follows, consisting of three parts: pixel-wise classification frequency, treeline elevation histograms and elevational distance between treelines. Each quantitative analysis is conducted under three data conditions: original input data as used in the respective papers, harmonised input data — swissTLM3D closed forest — and harmonised input data including both closed and open forests. This approach aims to disentangle methodological differences from those caused by varying input data and to assess the sensitivity of treeline positions to the definition of forest cover.

The methods of Paulsen and Körner, Gehrig-Fasel et al. and Szerencsits were replicated for the majority of the Swiss Alps. Due to computational constraints and limited input data availability[1], the method of Nguyen was only applied to a part of the Canton of Valais. Testing different regions showed no substantial differences in the results, thus, I selected one representative region for the comparative analysis presented here. For the qualitative characterization in the next section, I considered the modelled treelines over the entire Alps for the three other methods, as this broader spatial coverage provides examples of edge cases and variability that may not be captured by the smaller study region alone. The resulting four treelines are shown in Figure 5.16 at the end of 5.1.1.

5.1.1 Qualitative Analysis

Paulsen and Körner, 2001

The authors used 100 km² grid cells as spatial units to determine treeline elevations. This means that if no forest cell is present in a 100 km² grid cell, the entire cell will be neglected, as there is no treeline elevation for this cell. While this is methodologically correct — there cannot be a treeline where there are no trees — it can lead to abrupt, unrealistic treeline sections that are dependent on grid size and grid position as shown in Figure 5.1. Something similar occurs at the boundary between grid cells with large elevation differences. Here, the treeline is not cut-off but 'jumps' large elevations in a straight line, basically following the cell boundaries until it reaches the maximum elevation in that cell. To a small degree, this can be observed in many transitions between two cells with small differences in treeline elevations, major effects are demonstrated in Figure 5.2. In the case where a treeline ends at the back of a valley, with a grid boundary close by, the treeline can also be sort of cut-off and shortly reappear in the neighbouring cell, if that cell has a higher treeline elevation (see Figure 5.3). Also, due to the large resolution of the grid the highest forest pixel can be located far away and set the treeline high up in distant lateral valleys within the grid cell where forest and trees are completely absent. Figure 5.4 shows such a situation. By taking the elevation of the single highest forest point, the method is also prone to outliers — for example, if a small patch of trees grows much higher than surrounding forest due to favourable local conditions. However, in a more recent publication of one of the authors, it is argued that small cohorts of trees are still a robust proxy for the treeline (Körner and Hoch, 2023). Thus, while generally a susceptibility to outliers is considered a flaw, it seems like it is actually desired in this case.

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[1] Nguyen kindly provided me with input data — the forest prediction and votes — for the Canton of Valais.

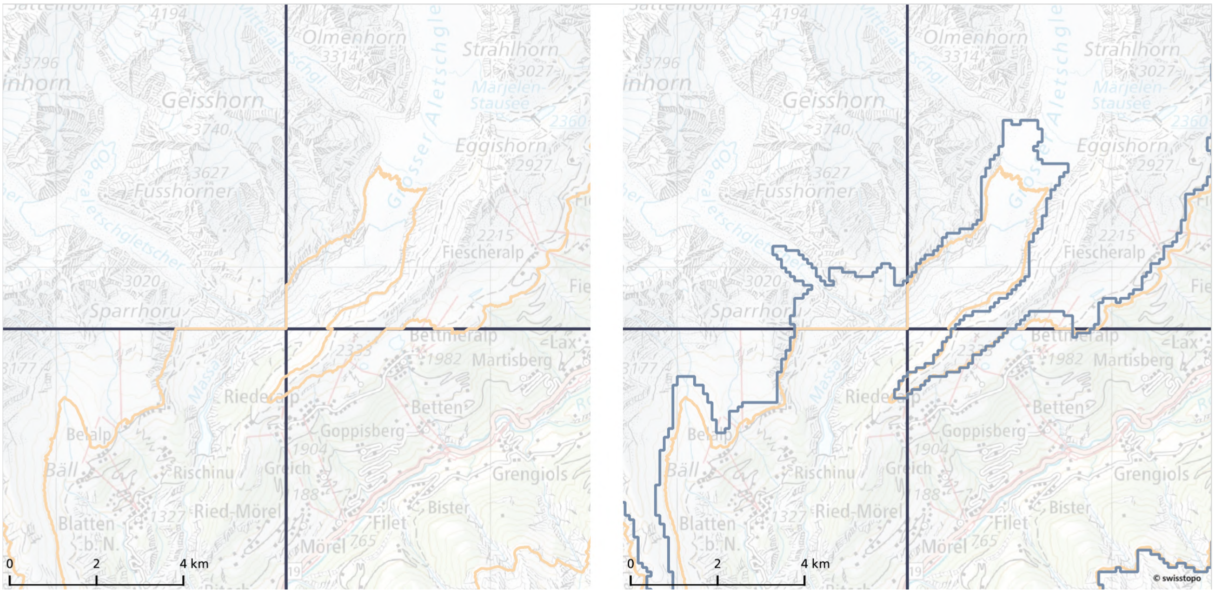

Figure 5.1: Within a grid cell with forest cover, the treeline of Paulsen and Körner follows the treeline elevation for this cell but as soon as the line heads into another grid cell without a treeline elevation, it is 'cut-off' at the boundary (left). The result from Gehrig-Fasel et al. shows how the treeline could look like if it was not cut-off (right).

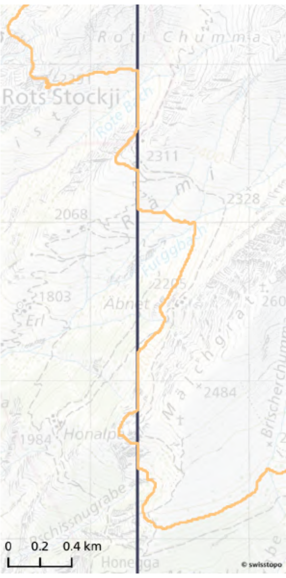

Figure 5.2: The treeline elevation in the left grid is 122 m higher up than in the right grid, causing the treeline to 'jump' the difference in elevation at the grid boundary, in this case several times.

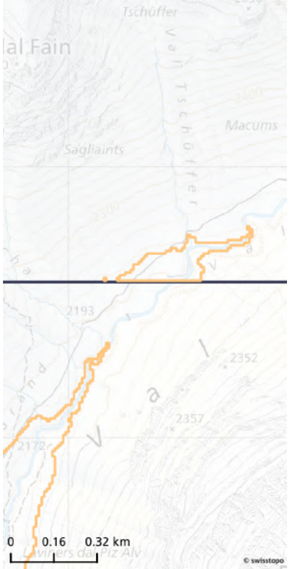

Figure 5.3: The treeline terminates towards the end of the valley as elevation increases. Because the neighbouring cell has a higher treeline elevation, the treeline reappears there until the elevation again exceeds its limit.

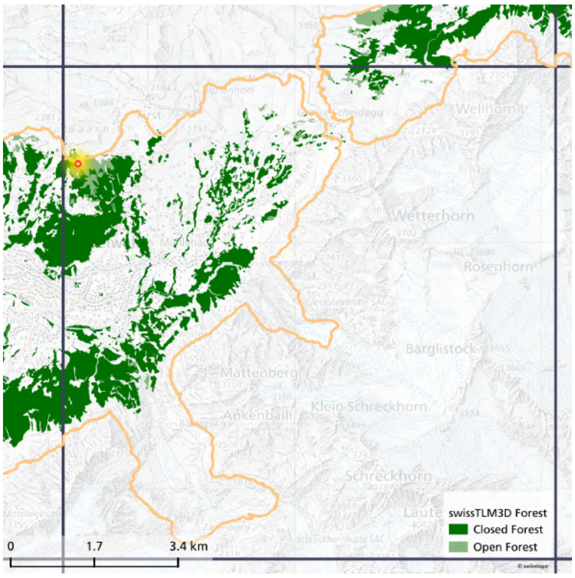

Figure 5.4: The maximum forest elevation point sets the treeline height for the whole cell, leading to a treeline far from actual tree or forest occurrence in two lateral valleys, where rocky terrain may prevent forest establishment.

Gehrig-Fasel et al., 2007

The same effect of the sudden jumps in treeline elevation at grid cell boundaries can also be observed in this method, as shown in Figure 5.5, because the interpolation results in one treeline elevation per 100 km² grid cell. While the method is different, the cause is likewise the equally large grid. As discussed in Section 4.2, it is not entirely clear how the interpolation was carried out. If the resolution was indeed higher than the stated 10 km, the outcome would be different. But if a single elevation value sets the treeline for an area of 100 km², such characteristics are bound to happen. However, the effect occurs much less frequent than in Paulsen and Körner, which may be because the values that determine the treeline elevation result from an interpolation with less steep gradients between neighbouring cells. Figure 5.6 indicates this. The interpolation also prevents cells without treeline elevations, as opposed to the method of Paulsen and Körner.

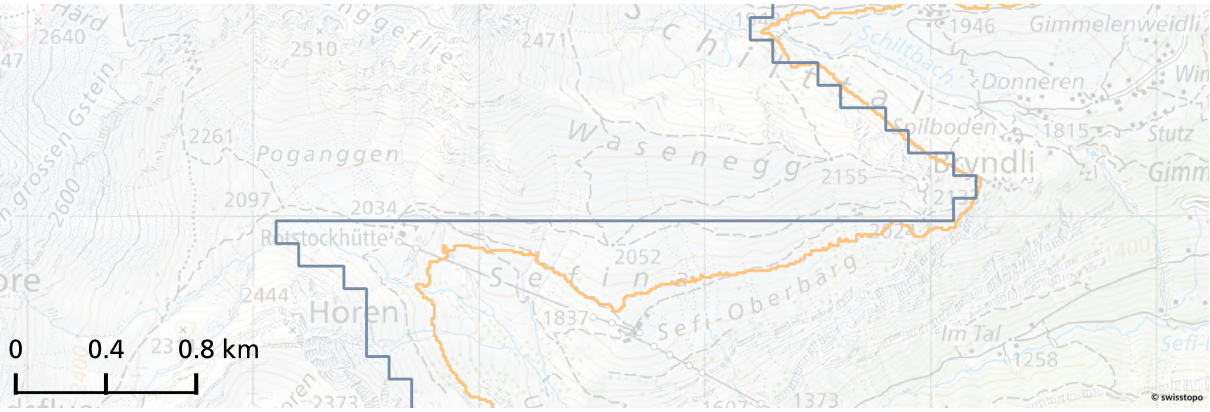

Figure 5.5: The treeline of Gehrig-Fasel et al. is 'cut-off' at the treeline elevation cell and follows the boundary until it reaches the elevation of the other cell, which is 213 m higher. The treeline from Paulsen and Körner does not have a cell boundary with a steep elevation gradient at this location and follows the elevation naturally.

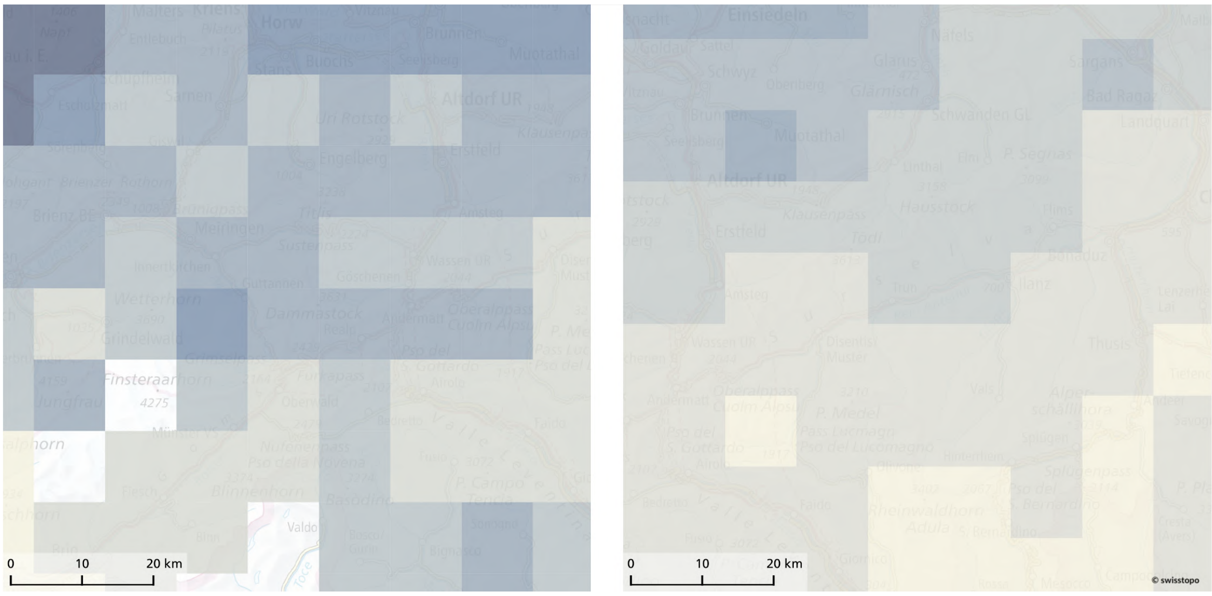

Figure 5.6: Treeline elevation of Paulsen and Körner (left) is less continuous than for the same extend of Gehrig-Fasel et al. (right). Both rasters use the same colour classification.

Szerencsits, 2012

The data for the final product of the treeline of this paper is online available, which allows me to compare it to my replication, however, only the treeline product, not the forest line. The treeline is used to illustrate key characteristics of this method, but it is excluded from the subsequent quantitative analysis as it is the only "real" treeline (derived from actual tree cover data) whereas the other represent forest lines. A minor but immediately visible difference is that the original treeline lacks the typical stair-step pattern from raster processing (see Figure 5.7), suggesting the author applied some smoothing or simplification algorithm. Also, my vectorised treeline contains inner rings (sometimes described as doughnut holes) the original does not. Since inner rings do not make sense conceptually, they may have been removed by the author without mentioning it. The two lines are sometimes very similar and sometimes completely different. The input data that I used was not the same as the author did for two, already indicated reasons. First, while the used products are still available — Arealstatistik 1992/1997 and Swiss Map Vector 25 (SMV25) — their categories are not always the same any more and the landscape has also changed. While it is possible to access the Arealstatistik data points from 1992/1997, significantly older versions of SMV25 are not openly accessible. Thus, I had to use a recent version. Swisstopo gently provided me with a table to match the old and new categories, but as previously mentioned, *Baumreihe* and *Gebüschreihe* were merged into *Gehölzfläche* and Szerencsits used *Baumreihe* but not *Gebueschreihe* so I might be underestimating forest cover by not including *Gehölzfläche*. Further, by introducing swissTLM3D as the new topographic model in 2011, there are now significantly more individual trees in the dataset, according to swisstopo, making it difficult to determine whether differences stem from imprecise method replication or from changed input data.

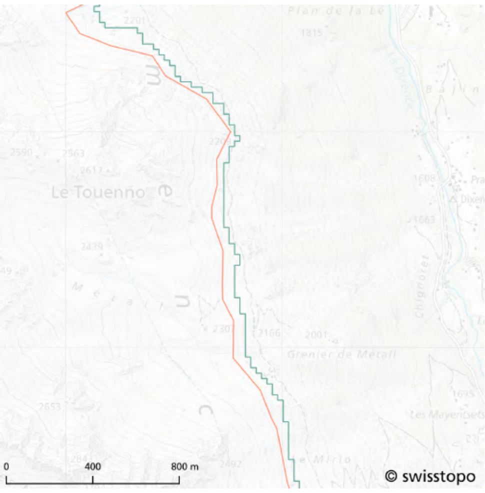

Figure 5.7: Comparison of the two treelines, the original with a smoothed lined, the replicated with the stair-step pattern stemming from raster processing steps.

While Szerencsits uses much smaller spatial units than the previous two methods, these units can still cause unrealistic shapes. Figure 5.8 shows how the moving window analysis can lead to such examples. The moving window operation assigns each cell the highest tree elevation within a 1 km radius. In continuous tree cover, neighbouring trees naturally have similar elevations, so transitions between influenced areas are smooth. However, with sparse tree cover, isolated high-elevation trees can create circular artefacts. As indicated by the circle in Figure 5.8, once the treeline contour reaches the moving window boundary, it begins to follow the circular perimeter instead of the topography, until it reaches the lower elevation set by more distant trees. Figure 5.9 shows another such instance. The round course of the treeline clearly stems from the moving window around it. In this case the tree outlier is an error in the source dataset, as the tree is completely isolated with an elevation of 2546 m, 400 m higher than the next tree within that slope zone and would place that tree amongst the highest trees in the entire alps[2]. The treeline of the slope zone analysis follows the topography more naturally, but the isolated tree on top of the hill sets the treeline elevation in the surrounding area much higher. The author mentioned removing erroneous data, so this was maybe mitigated by identifying such points and rerunning the method.

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[2] This tree is likely part of a rather amusing, systematic error within the swissTLM3D dataset, that falsely recognizes stations of t-bar ski-lifts as trees because the stations have a similar structure like trees crowns.

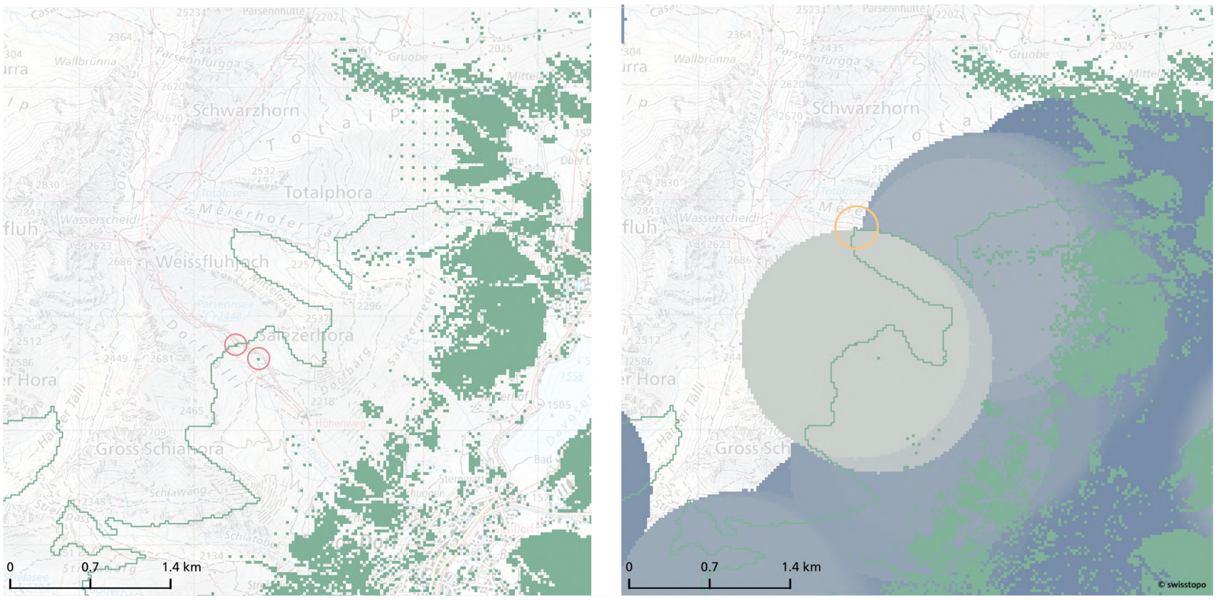

Figure 5.8: The moving window operation explains the unusual course of the treeline. Two isolated, highly elevated trees set the treeline elevation within the window significantly higher than the surrounding area. The circle indicates where the treeline starts to follow the window boundary rather than the topography.

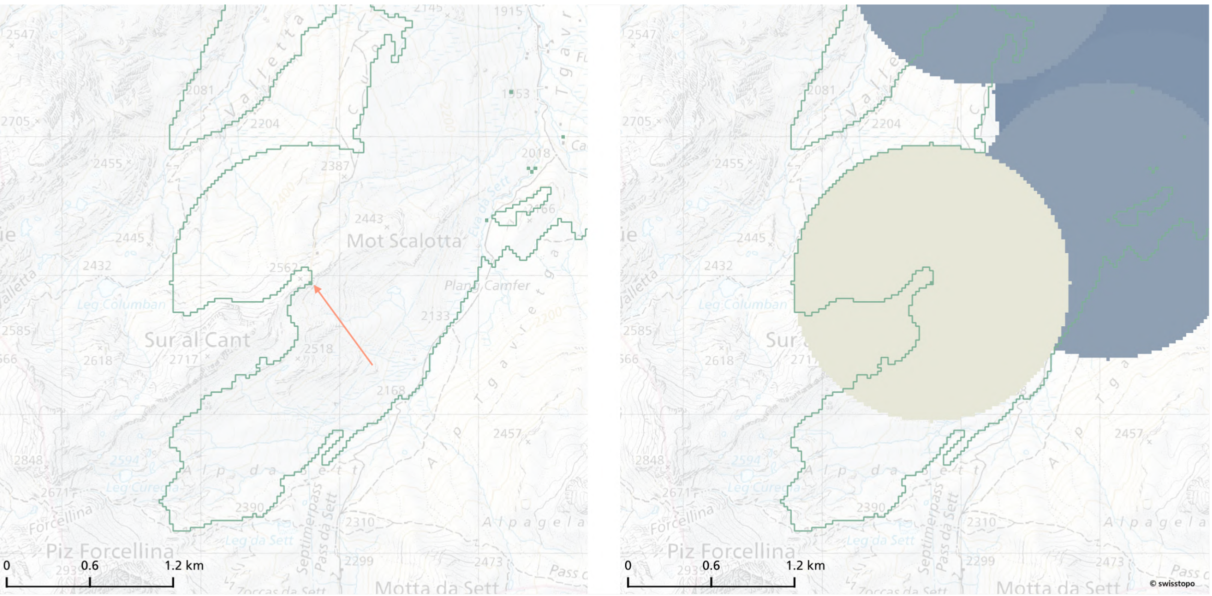

Figure 5.9: The tree outlier at 2562 m leads to a circular treeline, caused by the moving window operation, which sets the treeline much higher than the surrounding windows. When the treeline reaches the end of the moving window, it starts to trace its boundary until it reaches the lower elevation set by the moving window of trees further down the valley.

Similarly to the treeline following the grid boundaries in Paulsen and Körner and Gehrig-Fasel et al., it sometimes follows the slope zone polygons in this method, as in Figure 5.10. The difference here is just the spatial unit. This effect cannot be observed in the published dataset. Since the author did not further describe how the small slope polygons were subsequently merged into larger ones as mentioned in 4.3, it is not clear if that difference is a result of different algorithms, the initially mentioned smoothing or something else.

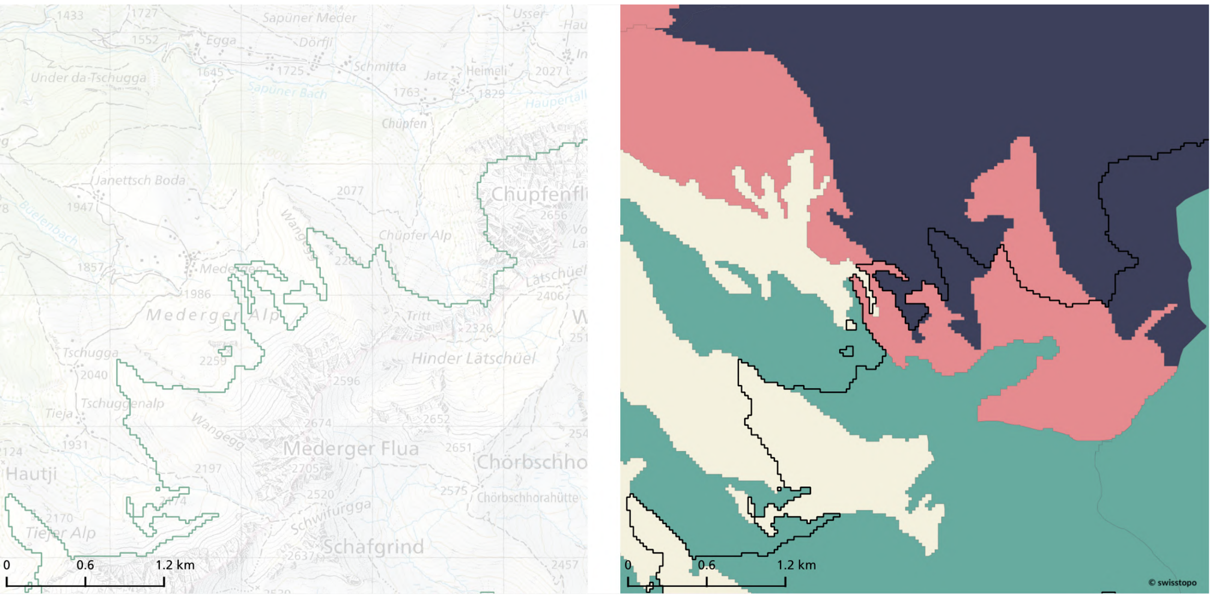

Figure 5.10: Neighbouring slope zones with significant differences in treeline elevation can result in the treeline following the slope zone boundaries. In this case, a difference of 100 m is sufficient to yield the effect.

The merging algorithm can significantly influence the resulting slope zones. Figure 5.11 illustrates the slope zones produced by two distinct approaches. While this does not necessarily affect the final treeline in all cases, it certainly could, as 5.10 showed.

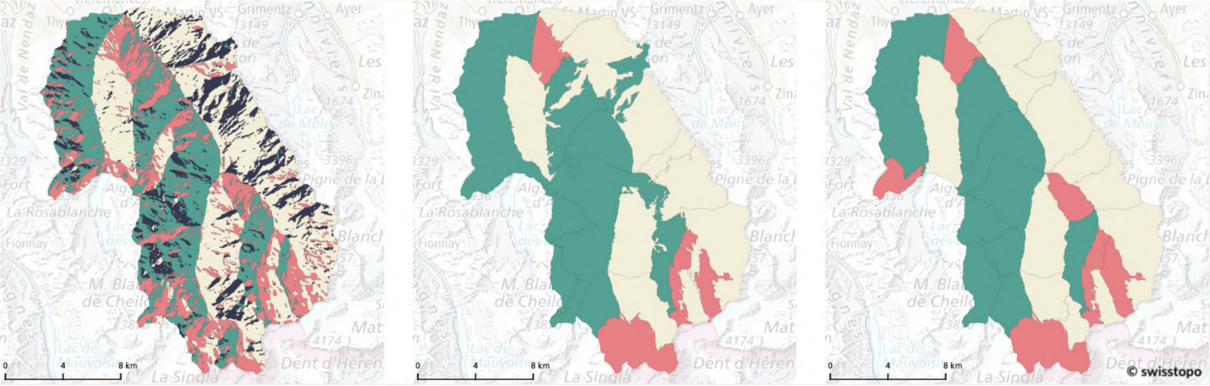

Figure 5.11: Stepwise integration of polygons smaller than 4 km² by area (middle) or by longest shared boundary (right) lead to significantly different slope zones.

Nguyen, 2025

While this method disregards patches smaller than 800 m² — the minimum size of a patch to be classified as forest according to swisstopo criteria — there are plenty of isolated treeline patches left in the final result, as shown in Figure 5.12. This can happen to any method with a small enough moving window or if forest patches are heavily scattered. The comparison of the two moving window rasters in Figure 5.13 shows how smaller windows create more fine-grained results, leading to such isolated patches. While such treelines patches are methodologically correct, they are conceptually illogical. There cannot be a treeline on a slope at 2200 m and then another one further up at 2250 m on the same slope. Then, the lower line is not the uppermost line and should

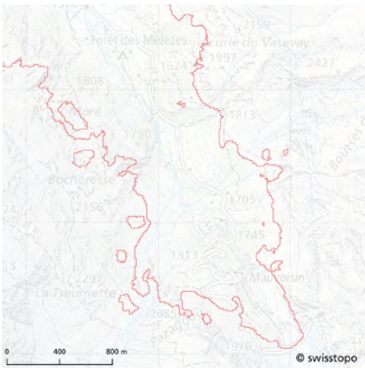

Figure 5.12: Treeline patches above the main treeline.

not be classified as treeline or otherwise the upper is not classified as forest and thus will not have a treeline. The opposite effect with small holes below the treeline, equally as in the replication of Szerencsits, can also be observed in Figure 5.12, but these could much more easily be filtered out.

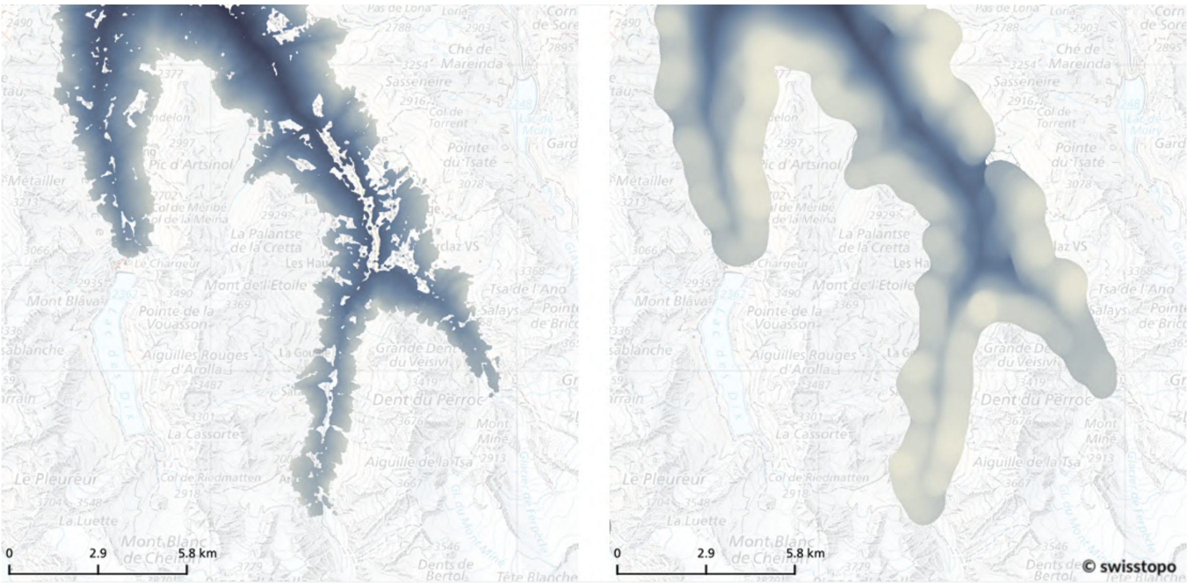

Figure 5.13: The moving window with size 50 m (left) coupled with spread out forest leads to much more fragmentation than the 300 m window (right).

The increased sensitivity to local forest patterns occasionally produces counter-intuitive configurations where two distinct treeline elevations appear along the same flow line. Such artifacts (Figure 5.14) result from the method's small search window, which captures local forest edges rather than regional trends. In areas with missing forest cover—near settlements or sparser vegetation—Nguyen's treeline drops several hundred meters, creating concave shapes. Other methods smooth this effect through larger spatial units (Figure 5.15).

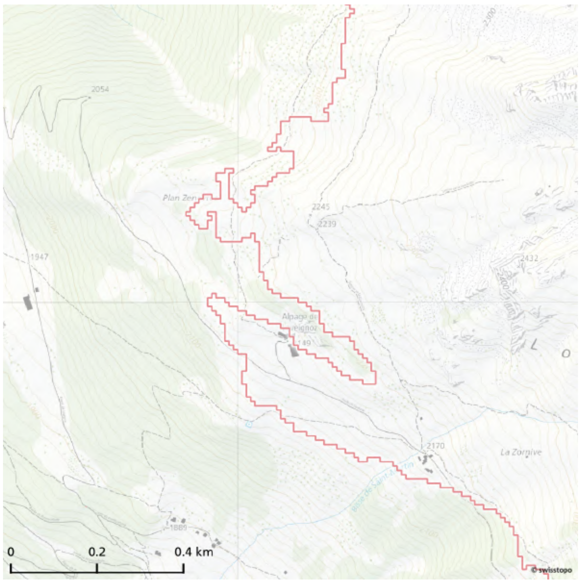

Figure 5.14: If a person would follow the flow line along this slope, at some point, they would be below and above the treeline at the same time, which clearly stands in contrast to how the treeline is conceptually defined.

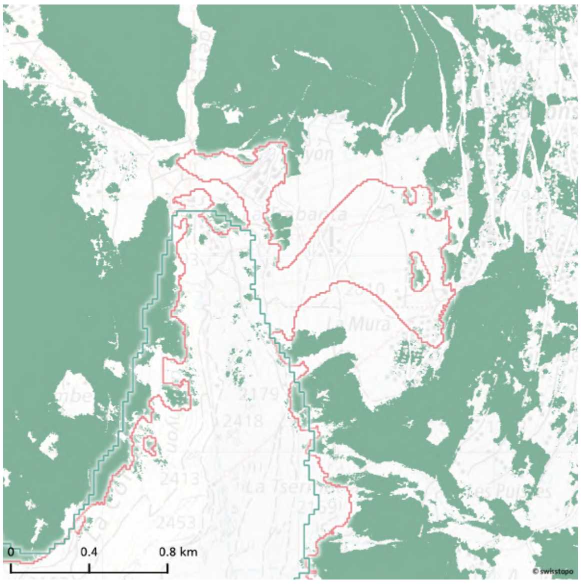

Figure 5.15: Nguyen's treeline creates a concave shape as the forest cover is sparse, where the treeline of Szerencsits appears more regular.

These qualitative observations show that all methods produce artifacts caused by their spatial units and parameters, but do not reveal the extents of (dis)agreement. This is covered in the following section through a pixel-wise comparison, elevation histograms and an elevation-based buffer analysis. As indicated at the start of the chapter, Figure 5.16 shows the resulting treelines of the four methods.

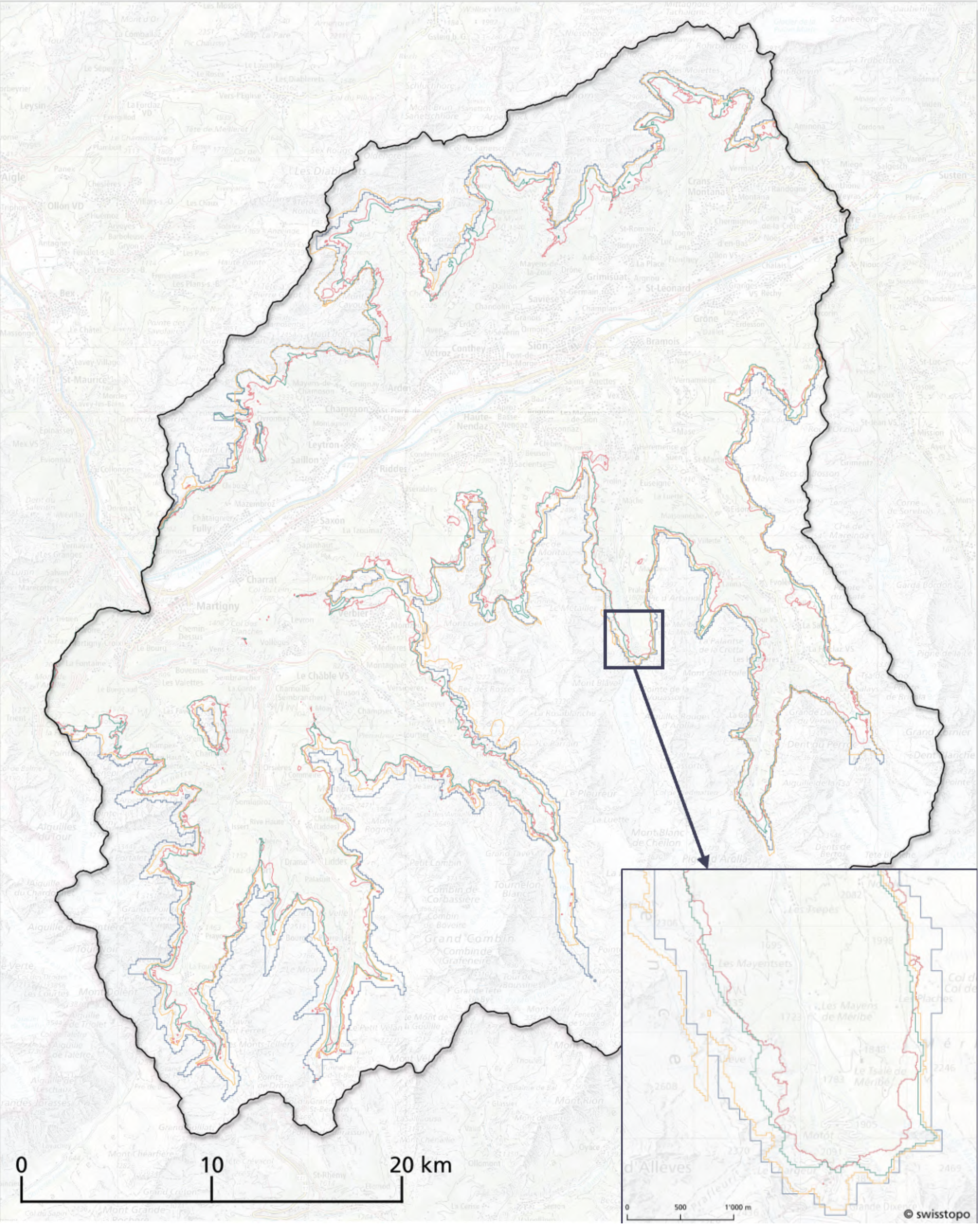

Figure 5.16: Result of the replication of the four methods: Paulsen and Körner, Gehrig-Fasel et al., Szerencsits, Nguyen.

5.1.2 Quantitative Analysis

Pixel-wise Comparison

In order to quantify and visualise uncertainty and vagueness, I conducted a pixel-wise comparison of the four methods. This method of evaluating uncertainty is similar to Sexton et al. (2016), where the difficulty in estimating global forest cover is addressed. They compared estimates of using eight different remotely sensed datasets. For each pixel, they counted how many datasets classified it as forest, producing a map with values 0–8, where 0 means no dataset classified the pixel as forest and 8 means all datasets did, giving a measure of forest cover (un-)certainty.

For the results derived here, I have to adopt the logic slightly, as it hardly makes sense to classify the results into treeline and no treeline. One way is to use the intermediate binary rasters that classify the pixels into above and below the treeline and count the number of times a pixel is below (or above) the treeline. This way a visual measure of uncertainty can be demonstrated similar to Sexton et al. (2016). It shows in what areas the four methods agree on the treeline elevation, where they are dissimilar and by how much (vertical distance). This uncertainty visualisation is shown in Figure 5.17. Pixels with a value of 2 represent maximum discrepancy, where two methods classify the area as below the treeline and two as above.

The same pixels can also be interpreted as indicating the most likely location of the treeline, as they mark the transition zone between areas where the majority of methods classify a pixel as above the treeline (value 1) and areas where the majority classify a pixel as being below (value 3). Figure 5.18 shows that second uncertainty visualisation. The pixel-wise comparison reveals spatial patterns in the agreement between the methods, reflecting both topographical influences and methodological characteristics. The comparison reveals areas of almost complete agreement, areas with large discrepancies and a consistent elevational hierarchy between the methods throughout the study region. The method from Nguyen almost consistently sets the lower end of the uncertainty estimates for the treeline, followed by Szerencsits and Paulsen and Körner while Gehrig-Fasel et al. mostly shows the highest elevations. This is not surprising since the former two both use much smaller search windows (50-300 m and 1000 m, respectively) compared to Gehrig-Fasel et al. and Paulsen and Körner with spatial resolutions of 10 km. The lower treeline estimates of Nguyen's method provides significantly lower estimates of the treeline especially in areas with fragmented forest cover.

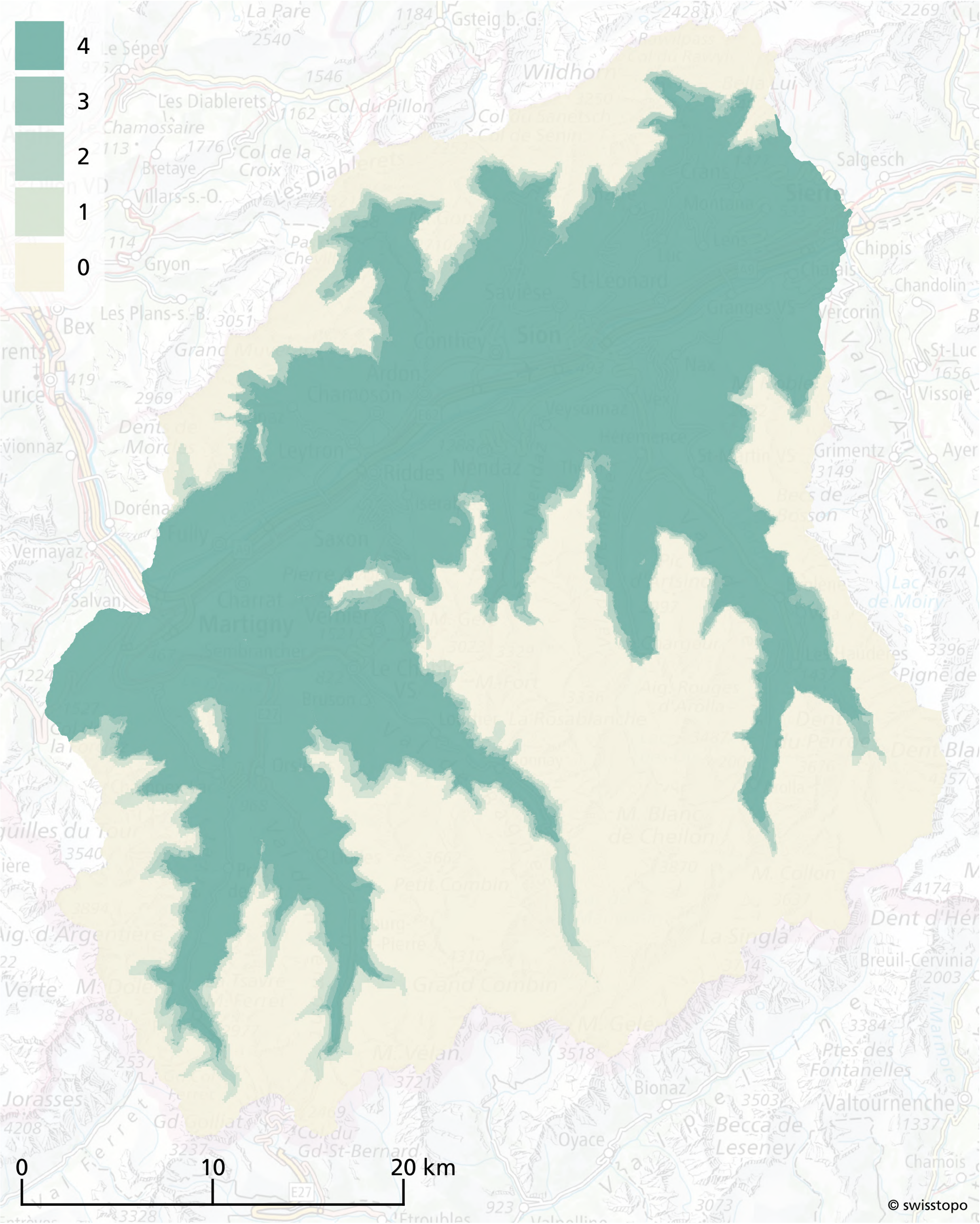

Figure 5.17: Pixel-wise comparison displaying how many methods classify a pixel as below the treeline.

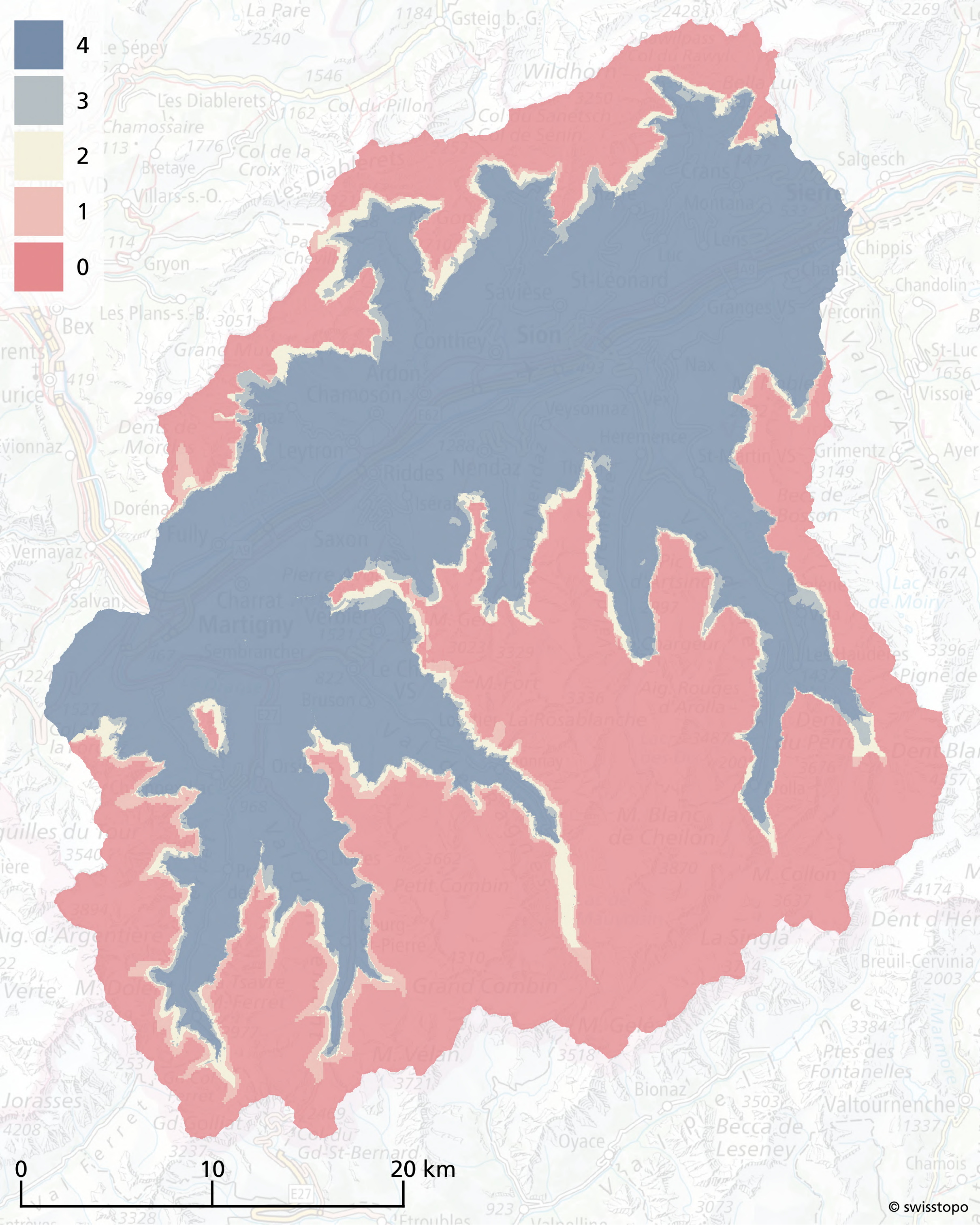

Figure 5.18: The same map as in Figure 5.17, differently coloured. Blue indicates more methods classify a pixel as below, red as above the treeline, with value two as the transition zone.

In Figure 5.19, the methods with the three largest scales form a consistent treeline, leading to a regular, stepwise transition within ~240 m elevation, while the Nguyen method responds to local forest fluctuations and provides isolated lower estimates leading to a large area of less agreement spanning over an elevation of ~600 m. In Figure 5.20, the methods pair into two groups (Nguyen & Szerencsits and Gehrig-Fasel et al. & Paulsen and Körner), each agreeing on the treeline elevation, leading to a larger transition or disagreement zone with value 2. These examples reveal a scale-dependent pattern: agreement between methods is highest where forest cover is dense and continuous, while patchy or fragmented forest produces diverging estimates as finer-scale methods respond to local gaps that coarser methods ignore. But due to the large resolutions of two methods, this pattern can also be disrupted with one of the treelines of the two methods reacting to a single higher elevation patch of forest.

The map also shows fragmented patches and not just continuous bands of elevation, which has two already discussed causes. Small moving window approaches respond to local forest geometry and produce spatially heterogeneous results, including patches of treelines as seen in Nguyen's results, where isolated patches of forest within the analysis window are classified as below the treeline even though the surrounding areas are above it. Grid-based methods can produce artificial discontinuities of the treeline between neighbouring cells. Figure 5.21 shows this effect caused by Gehrig-Fasel et al.

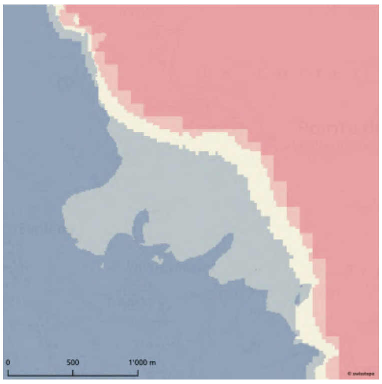

Figure 5.19: Forest cover along this slope is disrupted by a anthropogenic activity, which is only captured by Nguyen's treeline.

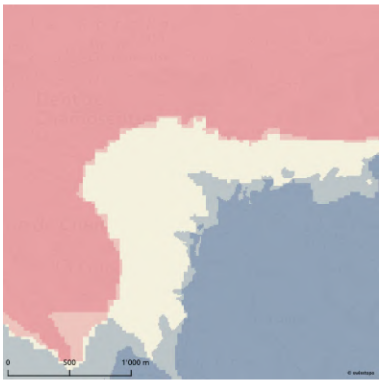

Figure 5.20: The treeline elevation of the coarser two methods is set by higher elevated forest further away, whereas that of the finer two methods by nearby forest.

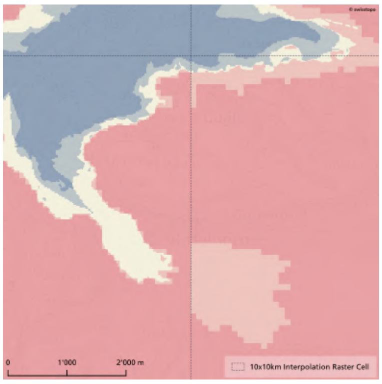

Figure 5.21: The 10x10 km resolution of the interpolation from Gehrig-Fasel et al. with a steep gradient in elevation leads to a 'jump' in treeline elevation.

Topographic effects strongly influence the matching patterns: the largest deviations occur in flatter terrain, where gentle elevation differences cause disagreement about the treeline to extend over larger horizontal areas. Consequently, the transition zones (values 1–3) are significantly wider in areas with flat topography, so these are less likely true larger deviation between the methods and more simply the geometric projection of the elevation-based discrepancy onto flat slopes. The most extreme example can be seen in Figure 5.22 where an increase of one meter in elevation will extend around 5000 m vertically into the back of the valley. There is no forest cover at all in that part of the valley, but since the methods of Gehrig-Fasel et al. and Paulsen and Körner use the same treeline elevation for a much larger region, the treeline extends all the way into the valley. The difference around the Lac de Mauvoisin reservoir between the methods is also clearly visible in Figure 5.16.

Conversely, some areas show very little variation between the models, typically at steep slopes with continuous forest and clearly defined upper edges that all methods model similarly, despite their different spatial scales. However, the reason for this agreement depends on the method. As previously discussed, the coarser two methods measure the highest forest elevation within a large area and set the treeline to this height, regardless of other forest cover within the area. The more fine-grained methods will place the treeline always much more closer to actual forest. This means that on a slope where all four methods roughly agree on the treeline elevation, there must be forest within some proximity. In other words, the more widespread forest grows up to the elevation that is possible within a region — indicated by the maximum forest elevation — the more the four models tend to agree.

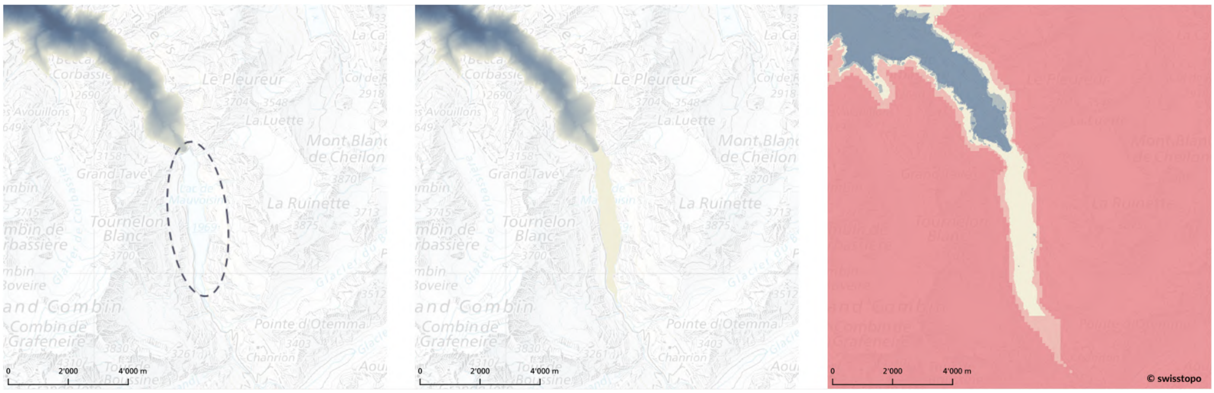

Figure 5.22: The area around the Lac de Mauvoisin reservoir (circle) yields the largest value two zone, because of the sudden increase in area as soon as the height of the dam is reached. The left two figures show the difference in area between two DEM's clipped with a maximum elevation of 1969 and 1970 respectively. Meaning that a treeline with an elevation of 1969 would extend several km into the back of the valley with just a 1 m increase in elevation.

Calculating the area of each transition zone shows that zones 1 and 2 (where one or two methods classify pixels as below the treeline) each cover 35% of the total transition area. Zone 3 covers slightly less at 28%, reflecting that Nguyen's method often produces considerably lower treeline elevations than the other three

Histogram

The elevation distributions of the four treelines provide further insight into their characteristics and allow for a quantitative comparison within the study region. The histograms are shown in Figure 5.23.

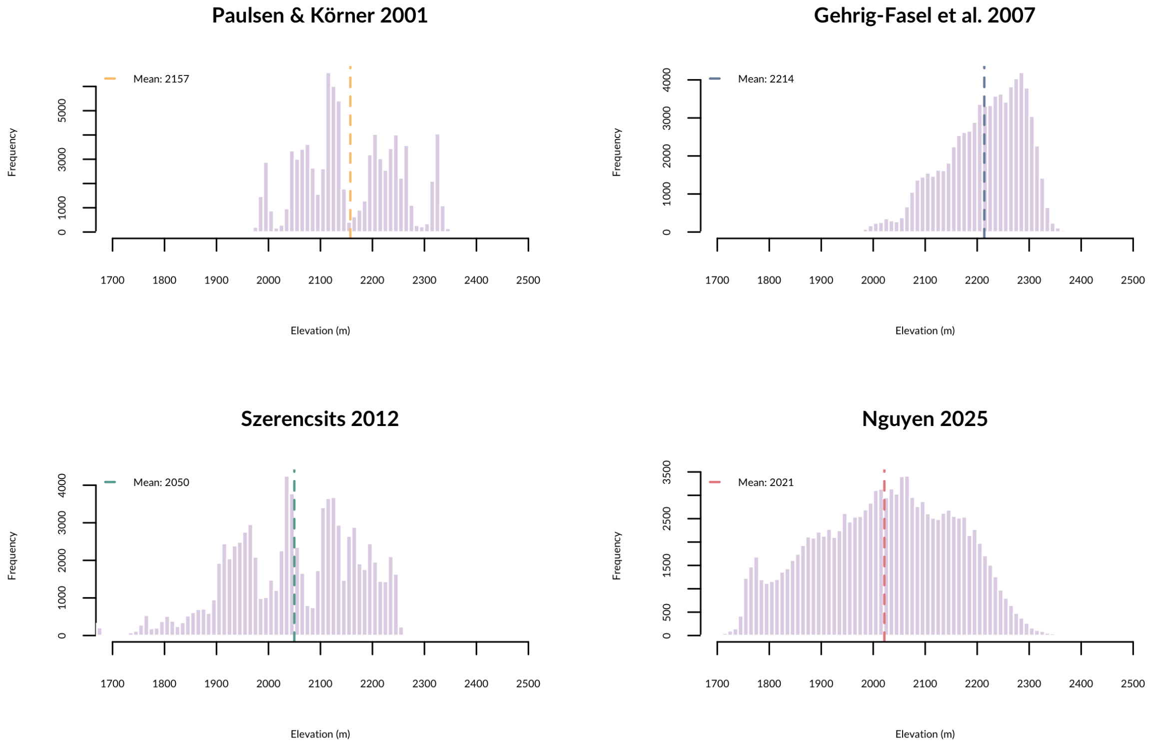

Figure 5.23: Histogram of the treeline elevation values of the four methods.

The approach of Gehrig-Fasel et al. produces a significantly more gradual distribution than Paulsen and Körner or Szerencsits. This is predictable from a methodological point of view: the interpolation step smooths discrete input points to form continuous surfaces and naturally produces intermediate elevation values. The other two methods, which identify maximum elevations within discrete spatial units (grid cells and slope zones), produce more clustered or multimodal distributions, as they select actual observed forest elevation rather than interpolating between them.

Nguyen, which uses a small search window with a 89.8th percentile instead of the maximum elevation, shows much greater range in elevation than the other three methods. This broader distribution reflects the method's sensitivity to local forest structure. By using small moving windows and a percentile rather than the maximum, the treeline closely follows actual forest cover. In contrast, methods with larger windows maintain high treeline elevations even where forest drops locally, as long as some high-elevated patches remain within the window, leading to fewer lower elevations. The reason why this histogram has a higher total number of values is partly because of the higher resolution, leading to a more meandering and thus longer overall treeline, resulting in more pixels when rasterised.

The method of Paulsen and Körner and Gehrig-Fasel et al. produce the fewest different treeline elevations, as they use only one treeline elevation per 100 km². Szerencsits lies in-between, with a spread smaller than Nguyen, but larger than the other two methods. Both Gehrig-Fasel et al. and Paulsen and Körner barely contain elevations below 2000 m, whereas Szerencsits has some and Nguyen has plenty. This goes back to the observed elevational hierarchy of the four methods. A comparison of the mean elevation confirms that visual hierarchy with Nguyen having the lowest mean (2021 m), followed by Szerencsits (2050 m), Paulsen and Körner (2157 m) and Gehrig-Fasel et al. with the highest value (2214 m).

Elevation-Based Buffer

The pixel-based comparison shows that the deviations are more pronounced in flatter terrain, but horizontal distance is not very telling in mountainous environments because a small horizontal distance can represent vastly different elevations depending on terrain steepness. As shown previously, a few horizontal meters on a steep slope can span over 50 m in elevation, while hundreds of meters across a plateau may remain within a narrow elevation band. An elevation-based comparison therefore provides a more meaningful measure of agreement for treelines, which are fundamentally defined by their elevational position.

The elevation-based buffer works by creating a spatial buffer around each treeline where elevation is similar to the treeline's elevation. First, treeline cells are encoded by adding 5000 to their elevation values to mark them in the DEM (any distinct enough number would work). Then, using a circular moving window, the algorithm checks each cell of the raster: it identifies if there are any treeline cells within the window (values 5000+) and if so, extracts their elevation and determines if the centre cell's elevation falls within a specified threshold. If this condition is met, the cell gets marked as part of the buffer. This creates a buffer that accounts for elevation instead of horizontal distance. Since the study region is artificially limited, the lowest points such as valley entries are removed from the analysis as these are not actual treelines but merely artifacts where the rasterised polygons close at the study area boundaries.

The higher the elevation threshold, the larger the moving window needs to be. The problem is that the required window size is not known beforehand, as it depends on topography, which varies with each cell. If it is too small, it will not contain all cells within the elevation threshold; if it is too large, it will start to include cells that are within the threshold but far away, for example on the other side of a valley where the elevation rises and falls back within the threshold. Since the goal is simply to quantify how similar the treelines are in elevation, the threshold used to calculate the percentage of one treeline within x meters of another can be somewhat arbitrary, as long as the window is large enough to capture all values.

This method is adapted from Goodchild and Hunter (1997), which is directed at the problem of measuring positional uncertainty. They developed a method to estimate the distance from one linear feature to another such that 95% (or some other desired percentile) of one feature is within this distance of the other. The purpose here is not positional uncertainty, as I do not have a reference treeline, but rather, similarity. The method works by selecting different distances and measuring how much of one feature is within the other and then iteratively changing the distance to arrive at the desired percentile. Because there is no reference treeline, I will conduct a pairwise comparison of all four lines. Finding the distance to match the desired percentile for each comparison involves a lot of computation so I switched the logic by simply estimating how much of one treeline lies within x meters of elevation of another. I chose a value of 100 m in elevation and a moving window of 1000 m. 100 m correspond to estimates of elevational spans of the treeline ecotone (Elliott, 2017; Tinner, 2013) and they proved to be a fitting threshold through testing different values. A significantly larger buffer would simply include all other treelines and a significantly smaller buffer would barely include enough to make a meaningful assessment.

Szerencsits also selected 1000 m as moving window size — although for a different purpose — mentioning it should be small enough not to have the effect of including values on opposing slopes or nearby ridges. But in rare cases, the buffer still reaches on the other side of a ridge if it is close enough to the top, as shown in Figure 5.24.

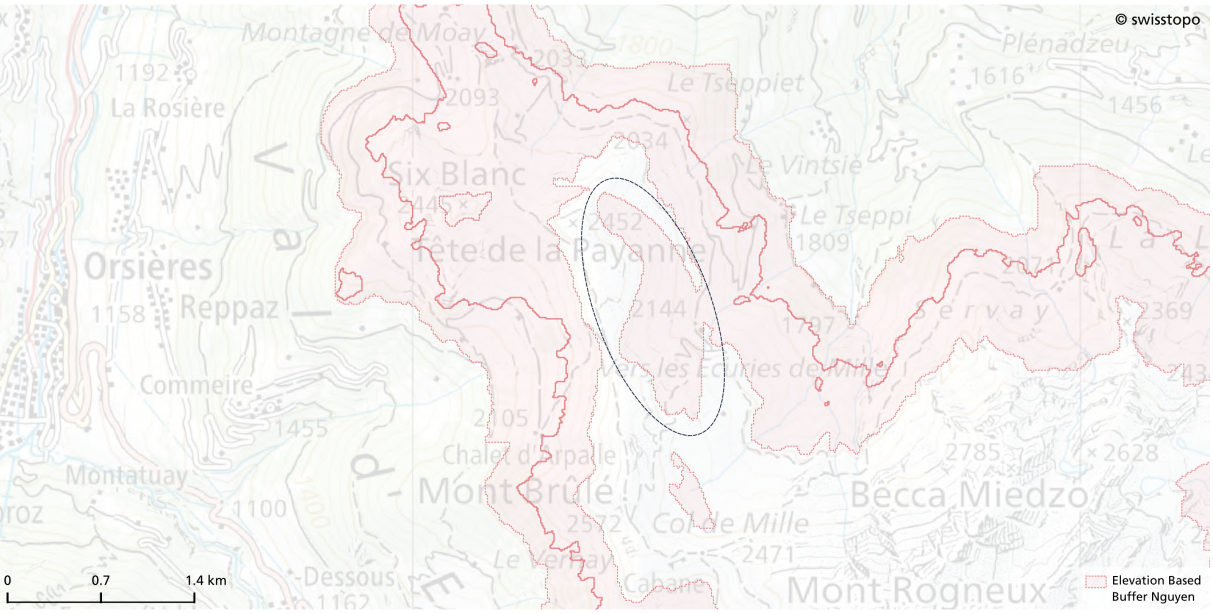

Figure 5.24: Elevation-based buffer extends to the other side of a ridge as the elevation starts to drop again, falling back into the 100 m elevation threshold while still being within the 1000 m of the buffer.

While 1000 m mostly seemed to be just small enough — apart from the rare occurrence of the above effect — it is not a large enough to achieve the necessary buffer in very flat terrain. This is negligible as long as the other three treelines are still within that buffer, but there are cases where they were not within the buffer and lead to a lower overlap result. Figure 5.25 shows two such situations.

Since the terrain that the treeline naturally follows is mostly much steeper, this problem is limited to a few specific locations and the parameter size represents a reasonable compromise. Also, the study region is large enough that both effects are unlikely to affect the calculations significantly, but they should still be noted. Figure 5.26 shows the elevation-based buffer of the four methods on a zoomed in area.

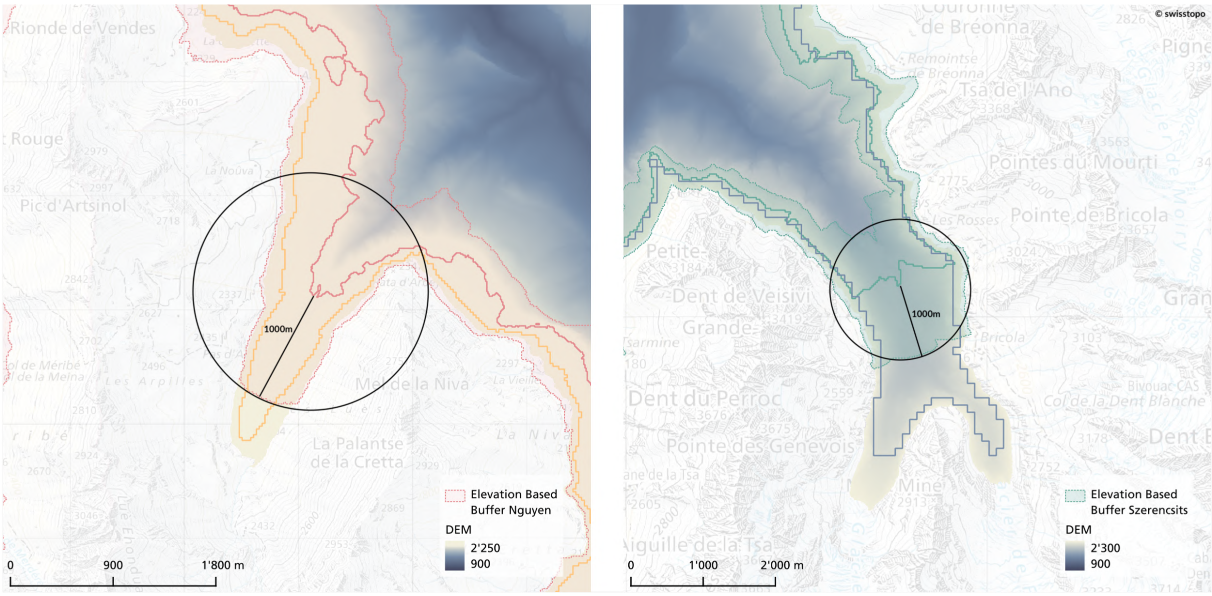

Figure 5.25: The two scenes show how the elevation-based buffer is bounded by the 1000 m search window, while the elevational distance of 100 m extends these 1000 m because the terrain is very flat. The treeline of Paulsen and Körner is within those 100 m of elevation, but not within the buffer. The same on the right side but with the buffer of the treeline from Szerencsits and the treeline of Gehrig-Fasel et al..

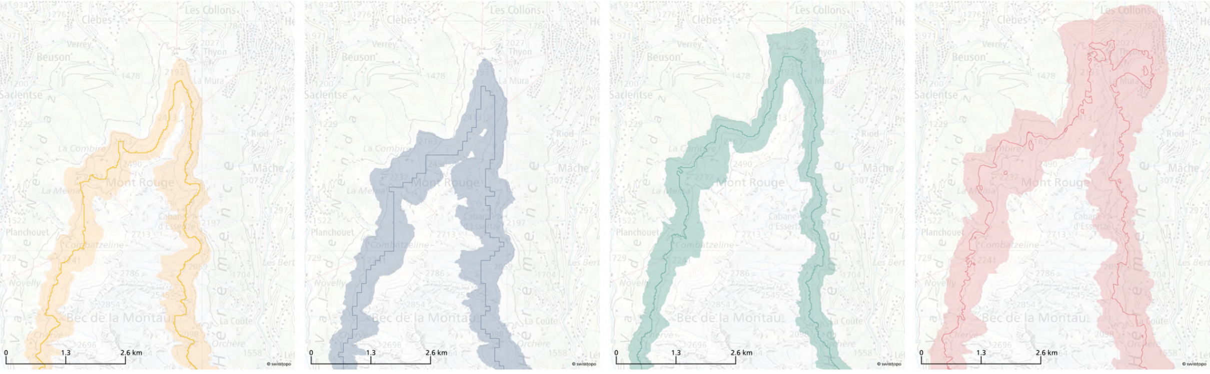

Figure 5.26: Elevation-based buffer of Paulsen and Körner, Gehrig-Fasel et al. and Szerencsits, Nguyen.

The pairwise elevation-based buffer comparison is presented in Table 5.1. The results confirm the elevational hierarchy observed in previous sections in a more robust way and provide a statistical measure of elevational similarity between the four methods. The table reveals the pattern identified earlier: Paulsen and Körner and Gehrig-Fasel et al. show mutual agreement of 74% and 86% within ±100 m elevation, while Szerencsits and Nguyen demonstrate even stronger agreement at 98% and 86%.

Table 5.1: Elevation-based buffer overlap between treeline methods (%). Values indicate the percentage of the row method falling within ±100 m elevation buffer of the column method.

	Paulsen-Körner	Gehrig-Fasel et al.	Szerencsits	Nguyen
Paulsen-Körner	–	86%	68%	86%
Gehrig-Fasel et al.	74%	–	43%	68%
Szerencsits	66%	47%	–	98%
Nguyen	54%	38%	86%	–

Further, the limited overlap between Nguyen and Gehrig-Fasel et al. shows the significant difference between the highest and lowest two treelines with more than 60% of Nguyen's treeline being lower than 100 m in elevation than Gehrig-Fasel et al.

One aspect appears counter-intuitive: the treelines of Gehrig-Fasel et al. and Paulsen and Körner overlap more with Nguyen's buffer than with Szerencsits'. In fact, all three other methods show relatively high overlap percentages with Nguyen's buffer. This can be explained by the nature of Nguyen's final treeline product, which consists of numerous treeline patches that sometimes extend significantly higher in elevation than the main treeline. While the histogram analysis largely discounts these patches due to their limited spatial extent, the elevation-based buffer method with a relatively large 1000 m search window, can substantially expand the buffer area in locations where such high-elevation treeline patches exist.

Figure 5.27 shows how significant the influence of these small patches can be. It raises the same conceptual question encountered previously: how should such occurrences be handled? These treeline patches are not errors in either the method or the data nor a methodological flaw of the buffer approach. Yet, they produce results that conceptually challenge conventional treeline definitions. They represent valid forest occurrences at elevations well above the main treeline, but their inclusion fundamentally questions what the treeline represents. Thus, the overlaps of the other treelines within the buffer of Nguyen should be considered with caution.

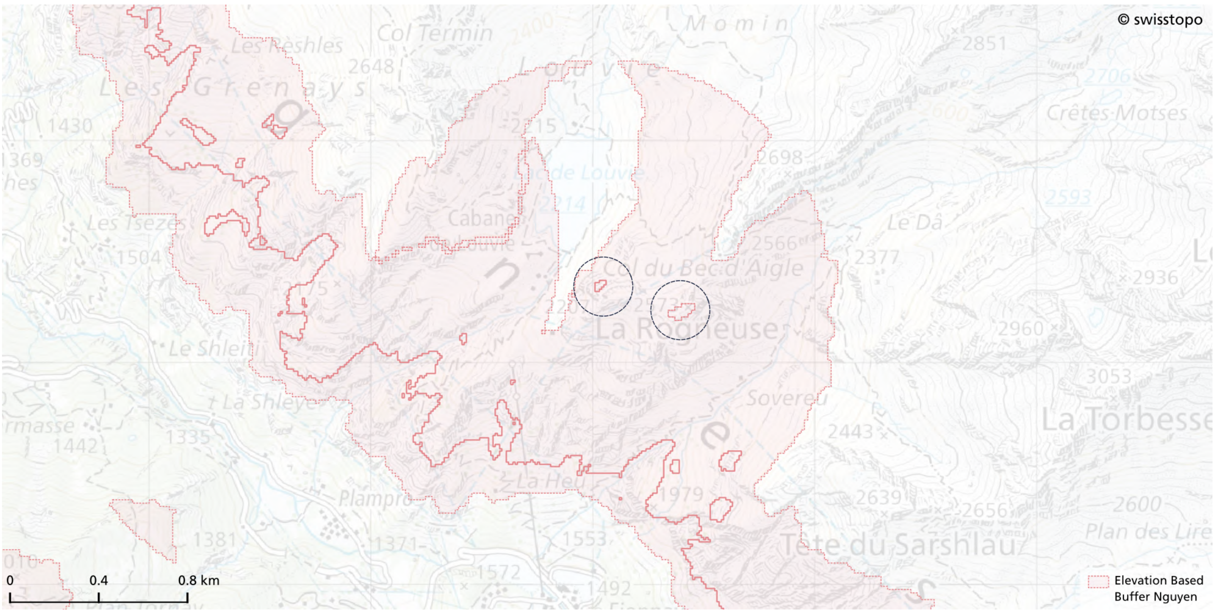

Figure 5.27: The small treeline patches in the middle of the scene, high above the main treeline, increase the buffer around the treeline of Nguyen by large margins.

The results from the quantitative analysis — revealing significant differences between the treelines — either suggest that rather large disagreement in the methodologies of how the treeline should be modelled exist or that simply different types treelines were modelled — as discussed in Chapter 2 there exist plenty of types. In order to assess how much these results are influenced by their input data, the next section shows the results of the same methods using harmonised input data.

5.2 Sensitivity to Input Data

5.2.1 Qualitative Analysis

Compared to the original product, the method of Paulsen and Körner produces a slightly higher overall treeline when using harmonised input data, with also regions where the line is lower or similar. The input data is not fundamentally different, however, because the method assigns a single treeline elevation to each 100 km² cell based on maximum forest elevation, even a small patch of present or missing forest can raise or lower the treeline across the entire cell.

The largest difference in treeline elevation between two identical cells is 160 m, Figure 5.28 shows this occasion. The results from Gehrig-Fasel et al. seem nearly identical between the two input datasets. The original treeline is sometimes slightly higher, sometimes slightly lower. While the forest cover from the original input data (Arealstatistik) generally extends to higher elevations than the swissTLM3D closed forest cover, this discrepancy has limited effect on the output. Due to the maximum elevation approach, it is sufficient for a single patch of forest within the 100 km² cell to reach a given elevation to set the treeline to that height for the entire region. For example, if forest cover within a cell in the original data is continuously present at around 2400 m but forest cover of the harmonised data generally only reaches 2300 m, the treeline elevation remains unchanged as long as at least one small patch of forest still occurs at 2400 m within that cell. The interpolation step may also flattens differences between the results.

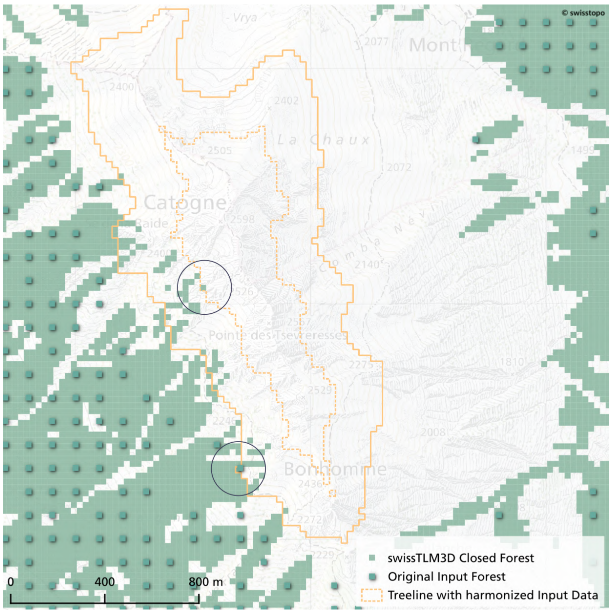

Figure 5.28: The circled pixel indicate the highest elevated forest cover, which sets the elevation of the treeline for this region. The difference between the two pixels (i.e. forest cover) is 160 m, which is then also the difference to the original treeline.

Whereas the impact of the resolution was negligible with the original data, as discussed in 4.2, it becomes significant with the new input data. The original input forest cover had a resolution of 100 m, but the swissTLM3D dataset is a much more detailed vector dataset. This means the process of how the vector is rasterised and the resolution becomes significant, especially when single small patches of forest can influence the treeline elevation for large regions. I rasterised the vector dataset with default parameters, where a cell is classified as forest cover if its centre falls within a polygon. This can lead to parts of forest not being included, especially smaller patches. Another common method classifies all cells that contain any forest polygon as forest cover. However, this means that tiny parts of forest touching a cell will set the entire cell as forest cover. Clearly, the size of the cell is therefore also relevant. While such aspects may seem like unimportant data processing decisions at first glance, it can influence the treeline elevation significantly, as demonstrated in Figure 5.29. This is not limited to the method of Gehrig-Fasel et al. but occurs in all methods that include rasterisation steps.

The method of Szerencsits produces treelines that are almost consistently higher throughout the study region when using harmonised input data, in some cases substantially so. While there are areas where both treelines follow a similar course, the harmonised version generally lies at higher elevations. This is because the swissTLM3D closed forest tends to extend higher than the original input data (Arealstatistik + SMV25). Due to the maximum elevation approach, even small patches of forest at high elevations can raise the treeline within a search window or slope zone. Figure 5.30 shows an example of this effect.

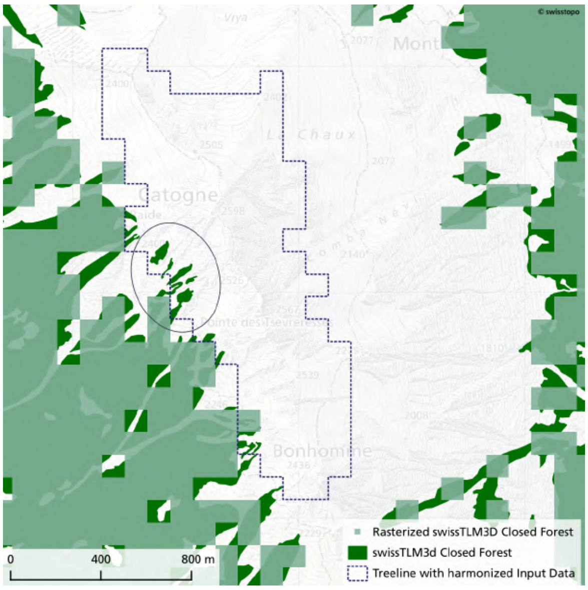

Figure 5.29: Smaller patches of forest cover are not included in the rasterisation of the vector dataset. A smaller resolution or a different rasterisation method that includes these patches would increase the treeline by ~67 m.

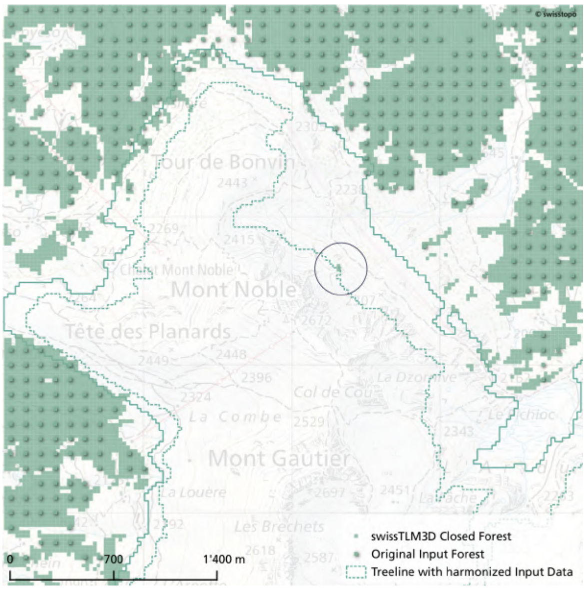

Figure 5.30: The small patch of forest in the swissTLM3D dataset, sets the treeline significantly higher than the rest of the closed forest within the area.

The results from Nguyen are similar between the two datasets, with some locations showing virtually no difference. Overall, the treeline tends to be lower when using harmonised input data. This is because the swissTLM3D dataset used in this section includes only closed forest, whereas the original deep learning-derived forest cover also captures more open forest structures, resulting in forest presence at higher elevations in the original dataset.

5.2.2 Quantitative Analysis

Pixel-wise Comparison

Using original input data, the differences between the methods appeared relatively balanced, with similar proportions of pixels in transition zones 1, 2 and 3. However, when using harmonised input data, transition zone 3 becomes substantially larger, revealing a more pronounced divergence between the method from Nguyen and the remaining three approaches. This shift is driven by movement from both ends: Szerencsits and Paulsen and Körner converge towards Gehrig-Fasel et al. from both ends, while Nguyen shifts downward. As described above, the harmonised input data causes Szerencsits to produce consistently higher treeline estimates, bringing it closer to the two coarse-scale methods. Meanwhile, Nguyen shifts notably lower due to the restriction to closed forest in the swissTLM3D data in this step, compared to the forest cover derived through the deep learning approach. Since the method operates at a fine spatial scale, it reacts sensitively to these changes in forest cover, amplifying the downward shift. While the magnitude of this decrease is smaller than the upward shift of Szerencsits, the combined effect increases the gap between Nguyen and the other three methods. For Gehrig-Fasel et al., the original forest cover tends to extend to higher elevations than the swissTLM3D closed forest, yet this has limited impact on the results.

Table 5.2 shows the distribution of the transition zones, indicating that the differences between the three methods of Paulsen and Körner, Gehrig-Fasel et al. and Szerencsits decreased, while it increased slightly in relation to the method of Nguyen when harmonising the input data. Figure 5.31 shows a location where this is pattern is visible. The total area of disagreement increased by roughly 20%, showing that the overall differences (at least in horizontal distance) between the highest and lowest treelines are larger when using harmonised input data.

Table 5.2: Distribution of transition zone area for original and harmonised input data. Values indicate the number of methods classifying a pixel as below the treeline. Percentages are calculated relative to the total transition area (values 1–3).

	Original		Harmonised	
Value	Area (km^2)	%	Area (km^2)	%
1	63.4	35.5	46.3	21.7
2	65.0	36.4	48.6	22.8
3	50.2	28.1	118.4	55.5
Total	178.6	100.0	213.3	100.0

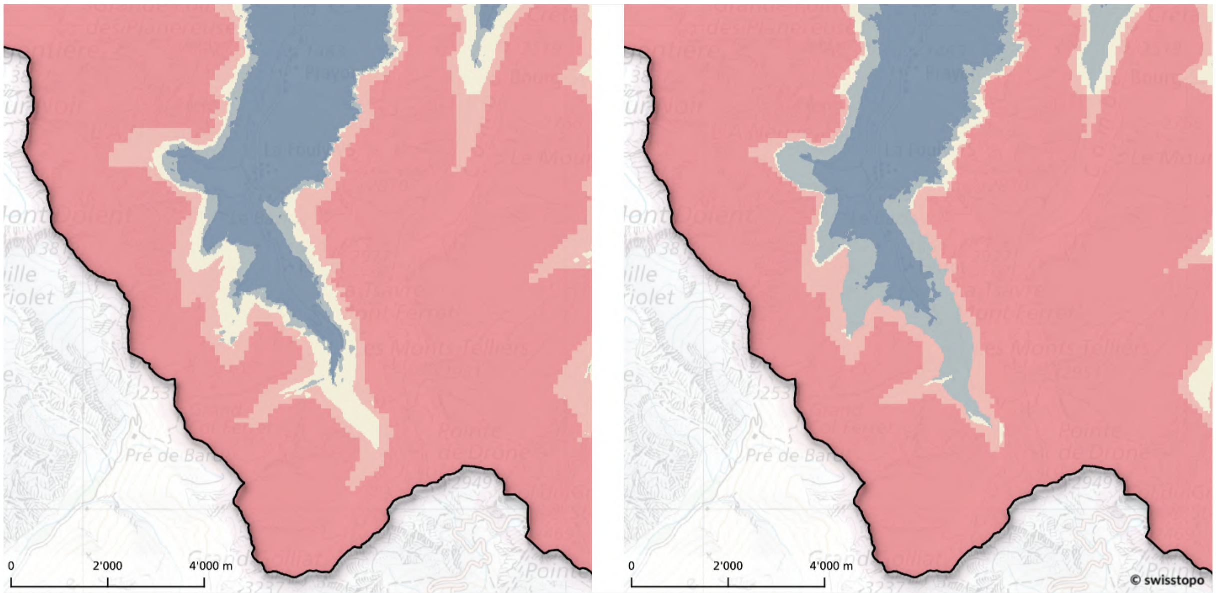

Figure 5.31: Left image shows the pixel-wise comparison with original, the right with harmonised input data. As the treeline of Szerencsits increases in elevation the difference to the methods of Gehrig-Fasel et al. and Paulsen and Körner decreases, while the difference to Nguyen increases.

Histogram

The histograms in Figure 5.32 confirm the elevation shifts observed in the previous sections. While Paulsen and Körner show an increase from 2157 m to 2201 m, the mean of Gehrig-Fasel et al. shifts only marginally downward from 2214 m to 2197 m. The most pronounced shift occurs with Szerencsits, rising from 2050 m to 2144 m. Unlike the coarser methods, this approach reacts significantly to even a few additional high-elevation forest patches in the swissTLM3D data. The mean treeline elevation of Nguyen decreases from 2021 m using original input data to 1963 m using closed forest from swissTLM3D, reflecting the exclusion of open forest (in comparison to the derived forest cover through the deep learning approach). Their histogram also shows a striking peak at around 1750 m, which results from the methodological step that caps the treeline at this elevation. With the original input data, relatively few pixels fell below this threshold and the lowest values gradually tapered off similar to the upper end of the histogram. With harmonised input data, however, significantly more pixels fall below the threshold and are artificially pushed up to 1750 m, causing a pronounced spike in the histogram. Paulsen and Körner also use this threshold, but their method produces no treelines below 1950 m in this study region, so the same effect does not occur. Beyond these effects, the nature of the histograms does not change considerably between input datasets.

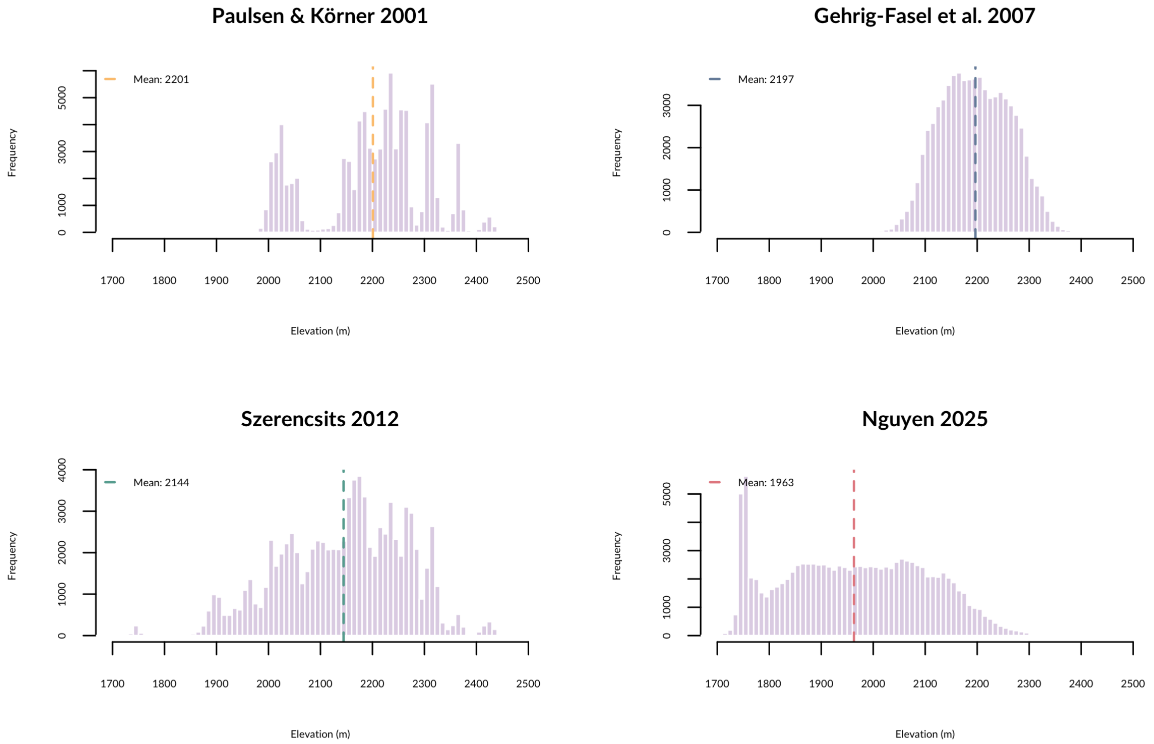

Figure 5.32: Histogram of the treelines with harmonized input data.

Elevation-Based Buffer

The matrix shown in Table 5.3 again confirms the observations from the previous sections. The three methods of Paulsen and Körner, Gehrig-Fasel et al. and Szerencsits converge and display a much greater overlap within each others elevation buffers. For example the treeline of Szerencsits is now 80% within the treeline of Gehrig-Fasel et al., compared to just 43% previously. The treeline of Nguyen is only 14, 28 and 39% within the buffer of the other three methods and only Szerencsits is still more than 50% within the treeline of Nguyen, even though their buffer might be overestimated as discussed in 5.1.2.

Table 5.3: Elevation-based buffer overlap between treeline methods (%). Values indicate the percentage of the row method falling within ±100 m elevation buffer of the column method.

	Paulsen-Körner	Gehrig-Fasel et al.	Szerencsits	Nguyen
Paulsen-Körner	–	95%	83%	43%
Gehrig-Fasel et al.	84%	–	80%	48%
Szerencsits	78%	85%	–	75%
Nguyen	14%	28%	39%	–

The results using harmonised input data differ notably from those using original input data. The treelines of Paulsen and Körner, Gehrig-Fasel et al. and Szerencsits now converge and appear quite similar, while Nguyen's remains distinctly different.

5.3 Sensitivity to Forest Definition

5.3.1 Qualitative Analysis

The treeline of Paulsen and Körner shows a slight increase in elevation, which is methodologically expected. When open forest cover is added to closed forest, the treeline either stays the same or increases. In areas without open forest, the treeline is expectedly identical to the previous version. For Gehrig-Fasel et al., it shows similar effects, with one region showing a stronger increase in elevation. This is explained by the interpolation step, which introduced treeline elevations not stemming from actual uppermost forest. In this particular part of the valley, the closest maximum forest elevation point, presumably used as input for the interpolation, is quite far away. Such effects question the interpolation step even more or require a more precise justification for why interpolation was included. Apart from this, the changes with new input forest cover are comparable between Paulsen and Körner and Gehrig-Fasel et al.

In contrast to Paulsen and Körner's approach where one small patch of significantly higher elevated open forest will impact 100 km^2, Szerencsits's treeline will only increase locally around the same patch, where locally means within the same slope zone or moving window. The treeline of Szerencsits otherwise does not change substantially within the study region and generally only increases around areas where open forest reaches significantly higher elevations compared to closed forest. Since some slope zones are large — the largest within the study region covers 53 km^2 — such effects could also extend more widely, but it was not observed in this case and a mean area of 12 km^2 and a minimum area of 4 km^2 (see 4.3) prevent this effect to widespread.

The treeline changes in Nguyen require closer inspection than the other methods, but at finer scales, many small changes become visible. Since this method operates at a small scale, it reacts to very minor changes in forest cover, but it never differs as much as the other methods because the changes are even more local than those in Szerencsits's approach. If the open forest consists of only small, higher elevated patches, the method results in more of the previously discussed treeline patches, instead of a higher elevated main treeline (see Figure 5.33).

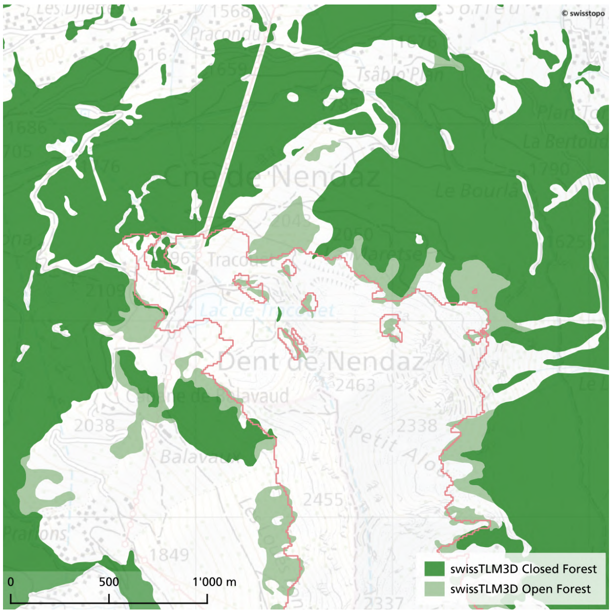

Figure 5.33: The main treeline is only altered by connected parts of open forest, whereas isolated patches lead to treeline patches.

5.3.2 Quantitative Analysis

Pixel-wise Comparison

Figure 5.34 shows the pixel-wise comparison of the four treelines using swissTLM3D closed and open forest as input. The right image displays the difference to the previous section where only closed forest was used. The figures give a spatial overview of the above discussed changes, showing that some areas have barely changed at all across all methods and few have changed by more than one value. These areas mostly correspond to slopes where more higher elevated open forest is present, as Figure 5.35 displays. Table 5.4 shows the distribution of the uncertainty zones, showing that the changes across the entire study region are rather minor.

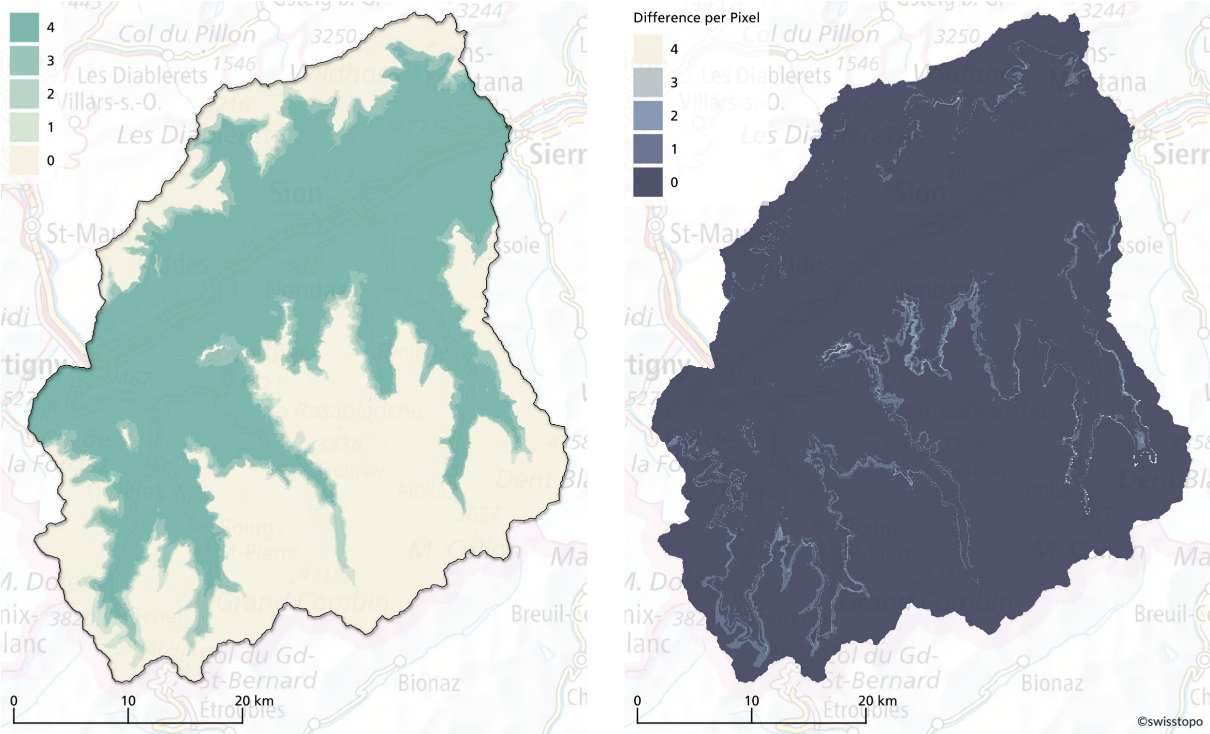

Figure 5.34: Left: Pixel-wise comparison using swissTLM3D closed and open forest cover. Right: Difference to the pixel-wise comparison using just closed forest.

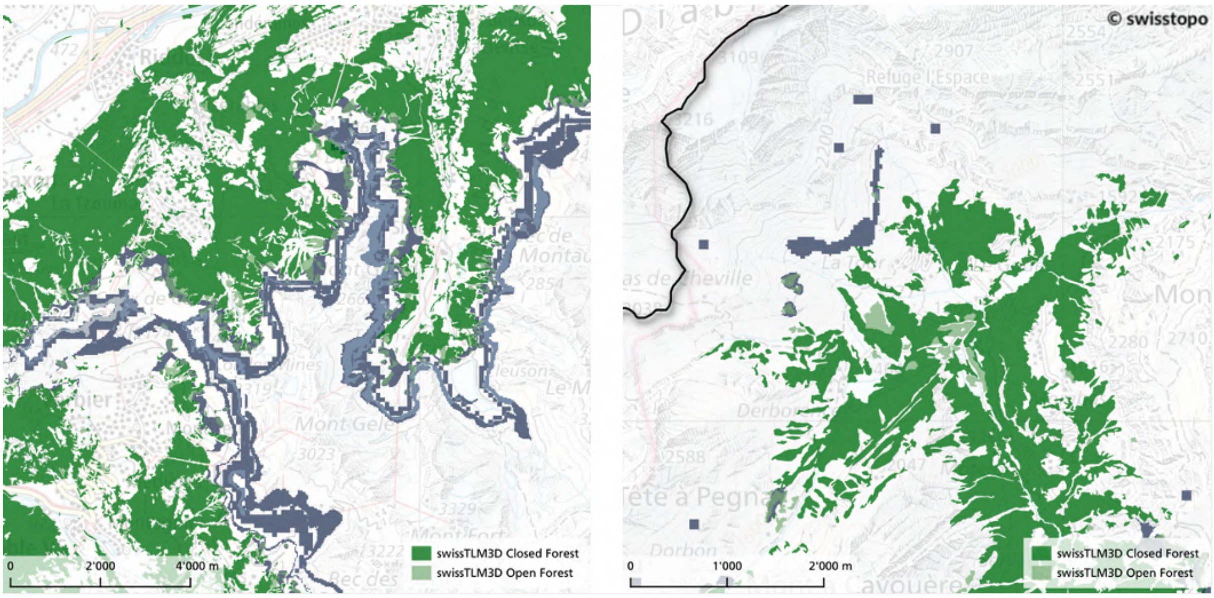

Figure 5.35: The left area shows significant change, because of more higher elevated open forest, as opposed to right area.

Table 5.4: Distribution of transition zone area for swissTLM3D open and open & closed forest cover as input data. Values indicate the number of methods classifying a pixel as below the treeline. Percentages are calculated relative to the total transition area (values 1–3).

	swissTLM3D Closed Forest		swissTLM3D Closed & Open Forest	
Value	Area (km²)	%	Area (km²)	%
1	46.3	21.7	50.7	24.4
2	48.6	22.8	53.7	25.8
3	118.4	55.5	103.3	49.8
Total	213.3	100.0	207.7	100.0

Histogram

Figure 5.36 shows the histogram for the results using open and closed forest cover. Compared to just closed forest, unsurprisingly, all means increase by 26-39 m with Szerencsits and Nguyen having slightly lower increases, which is caused by their more local responses to changes in forest cover, as compared to the other two methods.

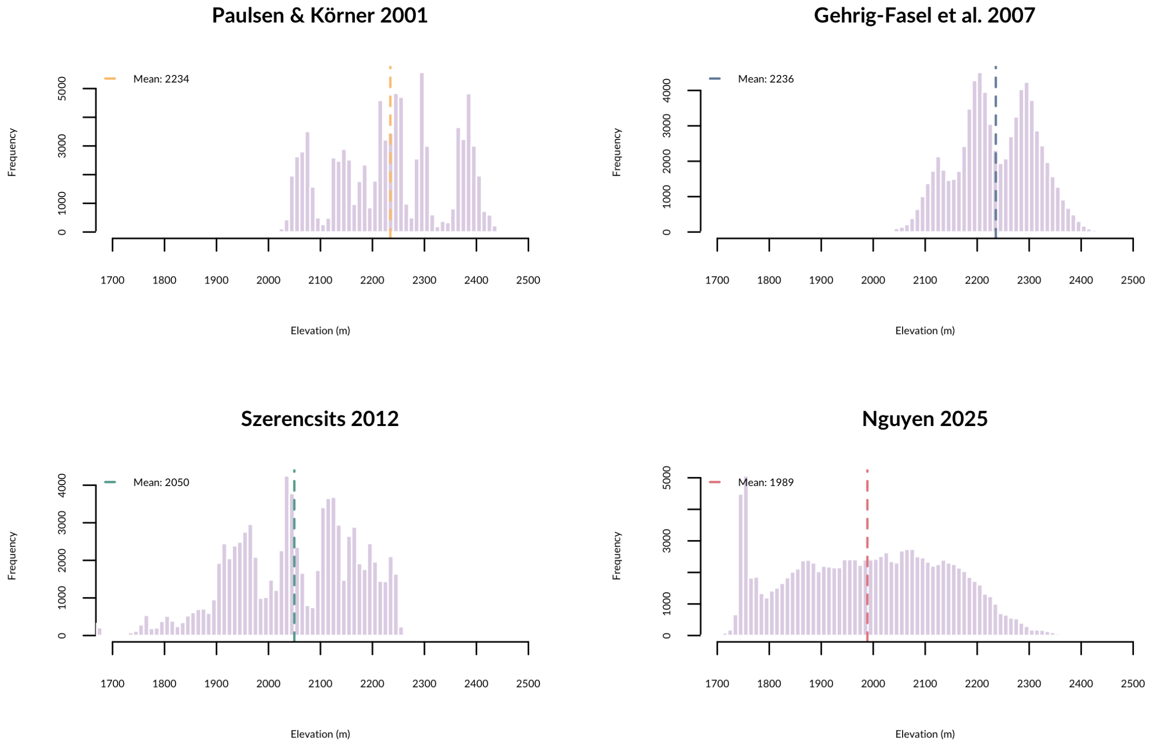

Figure 5.36: Histogram of the treeline elevations using swissTLM3D closed and open forest as input.

Elevation-Based Buffer

The elevation-based buffer comparison (Table 5.5) is mostly identical to the same comparison of the treelines using only closed forest cover. The most change occurs between Szerencsits and Gehrig-Fasel et al. where the latter is only to 69% within 100 m elevation of the former, as compared to previously 80%. This is likely due to some of the mentioned changes of the treeline of Gehrig-Fasel et al. The rest is very similar, as the previous sections already suggested. While the observations in this section are rather straightforward, they demonstrate how the treeline position can change by using a different definition of forest.

Table 5.5: Elevation-based buffer overlap between treeline methods (%). Values indicate the percentage of one method (row) falling within ±100 m elevation buffer of another (column).

	Paulsen-Körner	Gehrig-Fasel et al.	Szerencsits	Nguyen
Paulsen-Körner	–	92%	81%	42%
Gehrig-Fasel et al.	86%	–	69%	42%
Szerencsits	78%	77%	–	77%
Nguyen	13%	26%	39%	–

5.4 Results Synthesis

The preceding sections demonstrated substantial variability in how treelines can be modelled. The results showed many different characteristics of the four reproduced methods, some introduced simply through methodology, such as treelines artificially cut off at cell boundaries or following spatial units like slope zones and others of conceptual nature, such as treelines positioned in areas unlikely to support tree growth and far from any actual forest cover. Through qualitative observations and multifaceted statistical measures, the analysis revealed how diverse the spatial delineation of treelines can be depending on these conceptual and methodological decisions. The results documented impacts of dataset errors, showed spatial variability in the degree to which the four methods differ from each other and demonstrated how much of these differences depend on input data characteristics by rerunning the same methods with harmonised datasets. The sensitivity analysis further revealed how the four methods respond differently to varying definitions of forest cover, with some methods reacting strongly to the inclusion of open forest in certain areas while others showed only local change.

To synthesize these findings into a comprehensive representation of the treeline ecotone, the four methods were applied using three forest definitions from swissTLM3D data: closed forest only, closed and open forest and closed, open and shrub forest. This progression corresponds to the hierarchical structure of the treeline ecotone framework discussed in Chapter 2: from the forest line (closed forest) through the treeline (including open forest formations) to the shrubline (including shrub forest). Using official Swiss forest classifications from swisstopo ensures consistency across all three levels and represents the full range of official forest cover types in Switzerland. The resulting 12 boundaries (4 methods × 3 forest definitions) are shown in three figures, illustrating a range of possible variety of treelines across the ecotone. First, all twelve boundaries are superimposed (Figure 5.37), then combined using the pixel-wise comparison approach from Section 5.1.2, producing an uncertainty gradient ranging from 0 to 12, shown in Figure 5.38.

This combination of the four methods across varying forest definitions provides an approach for visualising uncertainty within treeline models, capturing the cumulative effect of methodological diversity and definitional ambiguity within a single representation. The map reveals areas where all approaches converge (values near 0 or 12) as well as extensive transition zones where boundaries diverge (intermediate values). Finally, Figure 5.39 shows a visualisation where the intermediate values are highlighted, similarly as in Figure 5.18.

These results raise several questions to be addressed in the upcoming discussion: What are the advantages and disadvantages of each method? What causes the large variety of resulting treelines? How do these results correspond to different parts of the earlier established framework of the treeline ecotone? How do they relate to how authorities understand the treeline in practice? And fundamentally, do certain aspects of these results actually represent uncertainty or is it vagueness? The following discussion examines how these results relate to different conceptualizations of the treeline in scientific and practical contexts. It further evaluates method suitability, explores aspects of vagueness and discusses reproducibility.

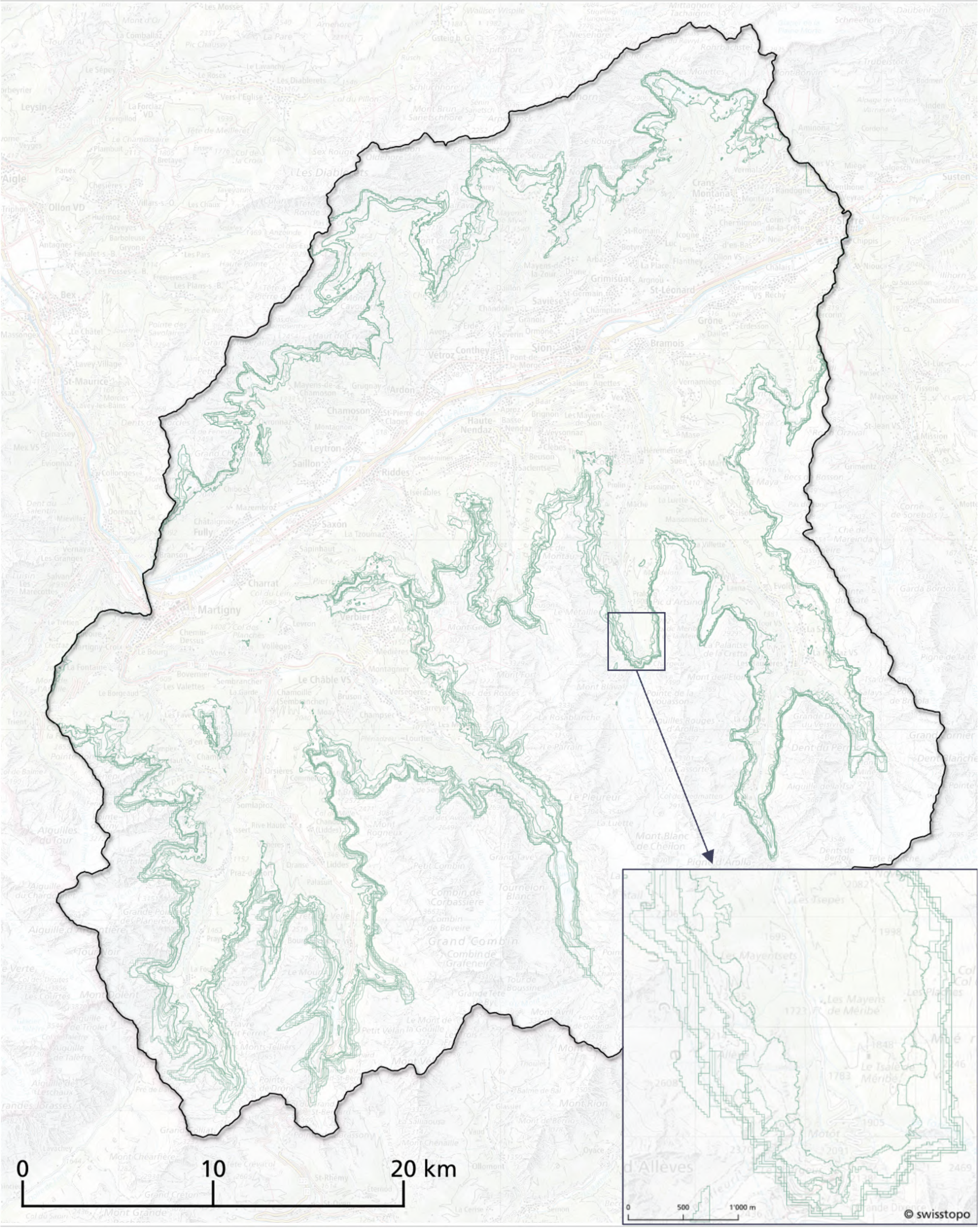

Figure 5.37: All twelve treelines derived by running the four methods using three different input datasets.

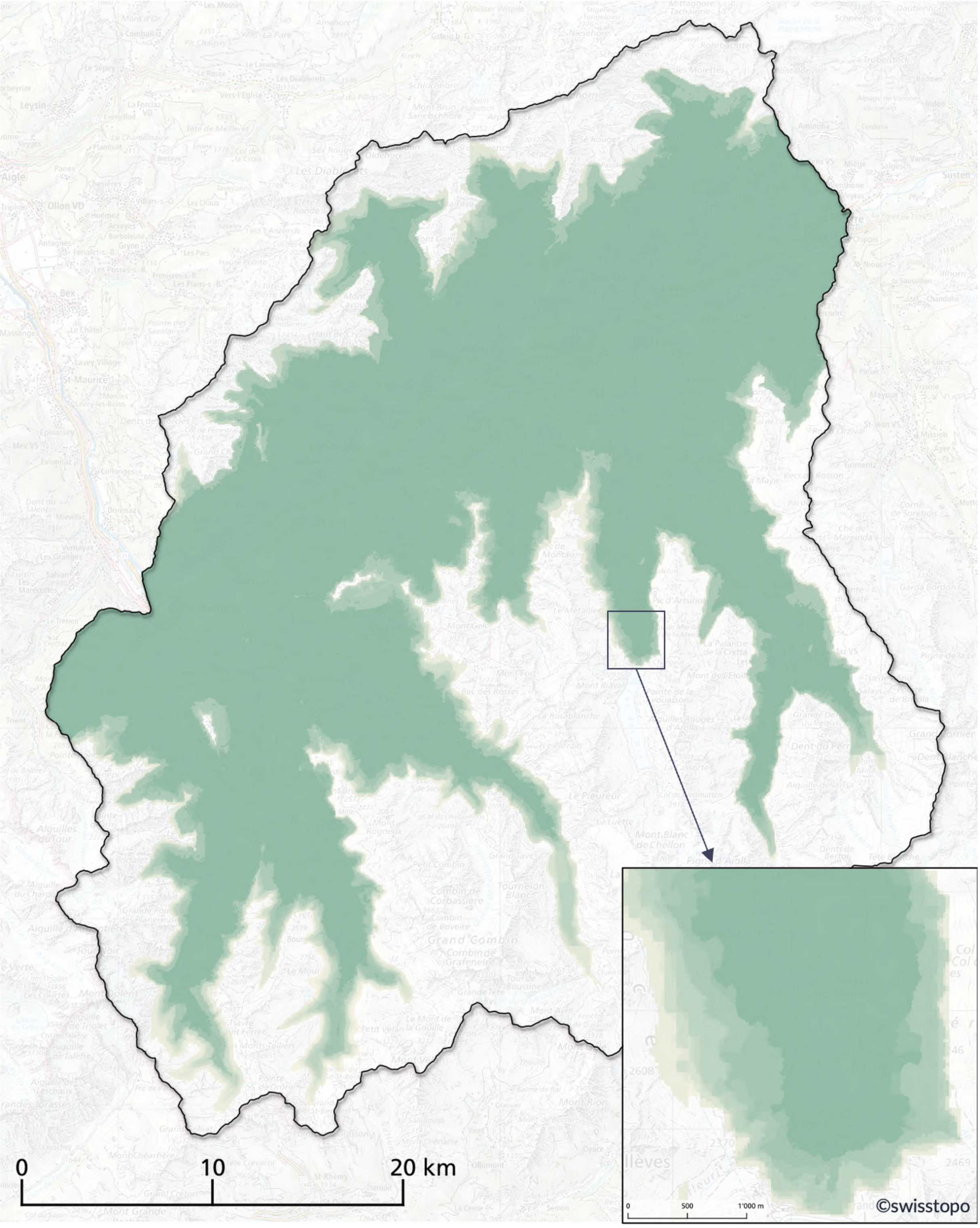

Figure 5.38: Pixel-wise comparison across the twelve treelines: The darker the values, the more methods classify a location as below the treeline. The inset map is used to show the transition in more detail, at a random location.

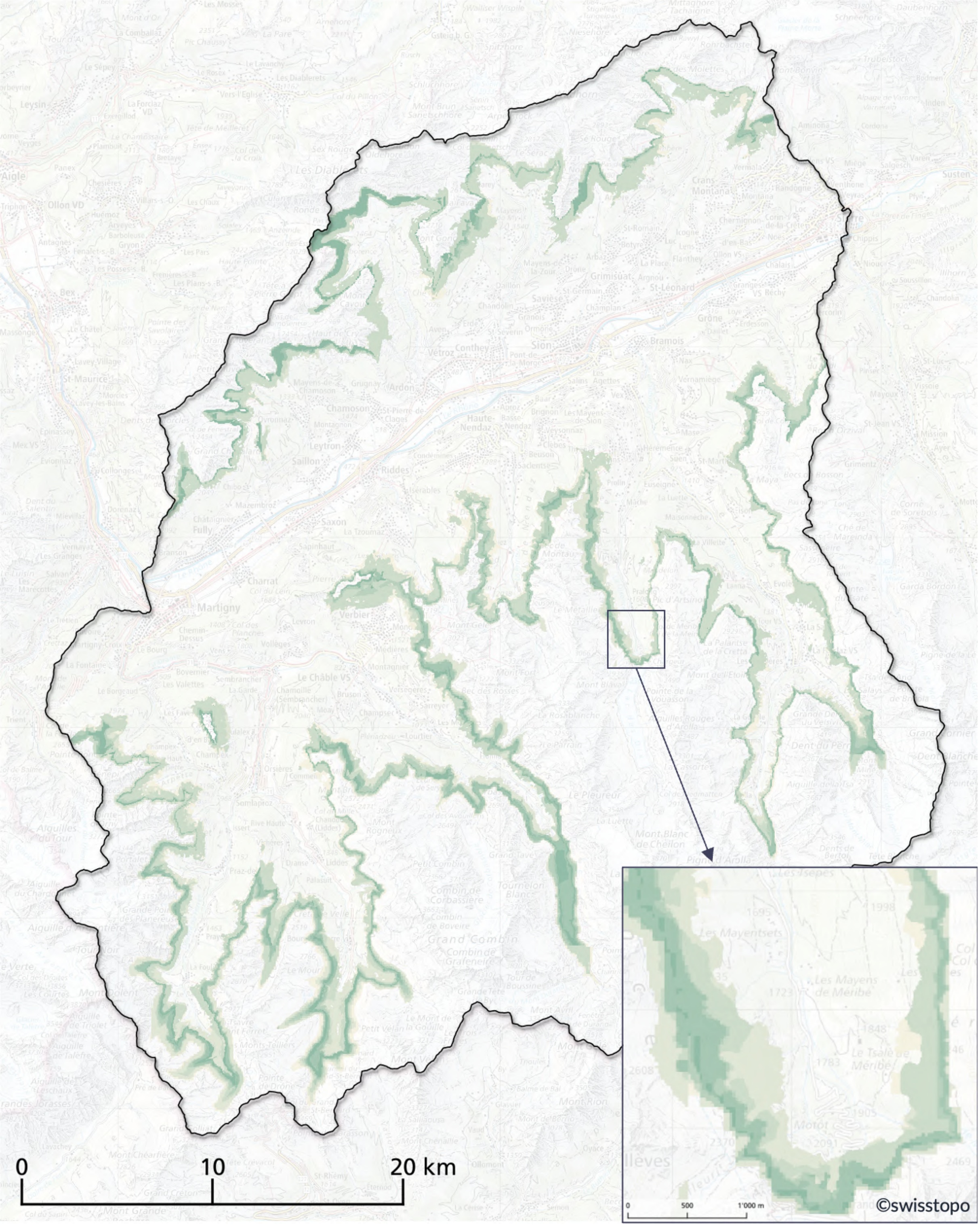

Figure 5.39: Another pixel-wise comparison across the twelve treelines: The darker the values, the more disagreement within the twelve treelines occurs, indicating the transition of the consensus of being above to below the treeline. The inset map is used to show the transition in more detail, at a random location.

Chapter 6: Discussion

In this thesis I established a terminology framework for the treeline ecotone, synthesizing definitions from over 30 papers to clarify the often inconsistent usage of terms such as forest line, treeline or timberline. Beyond the scientific literature, I gathered examples of how the term treeline is applied in Swiss laws and regulations, indicating how definitional ambiguity may lead to practical issues. I then selected and reproduced the methods of four papers that modelled the treeline in Switzerland and built a workflow that allows testing these methods with original and harmonized input data. Finally, the results of this reproduction were critically analysed and compared and I created three different visual representations of the treeline, demonstrating the variability between delineations of the treeline.

In this chapter, I will synthesize these achievements with the research questions stated in Section 1.2 and situate them in both scientific and practical context. I will examine what the methodological comparison reveals about the nature of treeline definitions, discussing aspects of uncertainty and vagueness. I will then evaluate the strengths and shortcomings of the methods and address the visualisation of vagueness. Further, aspects of reproducibility concerning the four papers will be discussed. Finally, I acknowledge the limitations of this thesis.

6.1 Synthesis of Findings

While the definitional ambiguity around the term treeline as discussed in Chapter 2 and 3 already introduced issues — addressing RQ1 — the results from reproducing four selected methods confirms that these definitional inconsistencies translate directly into divergent spatial representations. To assess the results and usability for different contexts, we must first clarify what each method actually modelled in relation to the definitions established in Chapter 2, providing a framework of the treeline ecotone.

Paulsen and Körner and Gehrig-Fasel et al. modelled the climatic forest line, although calling it the climatic treeline. It is obvious that their focus was on forest and not trees when looking at their input data, which consists only of forest cover. The terminological mismatch goes back to the previously discussed usage of the much more popular term treeline, that the authors refer to. By identifying maximum elevations where forest occurs within large spatial units (100 km^2), both approaches deliberately ignore local topographic or geological conditions that might prevent forest growth and aim instead to capture the purely climatic limit. Paulsen and Körner explicitly note that the difficulty of that task — modelling the climatic treeline based on observations — is to distinguish the potential elevation limit from upper forest edges that were (most often) anthropologically depressed. They assume that the scale of their method is large enough to filter out such local disturbances.

Contrary to that, Nguyen explicitly modelled the actual forest line, calling it the realized treeline in reference to the ecological concept of the fundamental and realized niche (Körner, 2021a). Her method was specifically designed to capture the actual uppermost forest edges as they currently exist. This includes areas depressed by anthropological activity, unsuitable topography or any other disturbances as discussed in 2.1.2. She did not include any data about individual trees, despite suggesting the contrary with the terminology.

The results showed substantial differences between her method and the two climatic treeline approaches with mean elevation differences of 136 m and 193 m respectively. As many other authors noted, forest was anthropologically pushed down significantly throughout the majority of the alps, leading to a clear difference in elevation between the climatic and the actual treeline, which corresponds with these results. There were also locations where this difference was minor, possibly indicating slopes where natural treelines still exist or regrew.

Yet more ambiguity is introduced with the method of Szerencsits. The author states his results should approximate the potential forest and treeline, while also respecting local site conditions. This raises a conceptual question: if Paulsen and Körner's and Gehrig-Fasel et al.'s methods explicitly exclude local conditions, can Szerencsits be modelling the same line, while simultaneously respecting such conditions? The substantial differences between these methods suggest they are not capturing the same concept. Yet, the author still uses the same term — potential treeline — to describe his results. What then is the potential treeline that takes local conditions into account? What adds more confusion is that Szerencsits (2012, p. 15) does not compare his forest line, but his treeline to the results of Paulsen and Körner, stating "the maximum values (of Paulsen and Körner's forest line) are lower than what was found in this study for the treeline". The author mentions Paulsen and Körner using the uppermost tree in each cell, which contradicts the description of their workflow. Paulsen and Körner only used forest categories from the Arealstatistik, which does not provide information about individual trees. There are categories like shrub forest or forest clusters and these extend higher than closed forest, but not as high as single trees. More importantly, Paulsen and Körner did not consider them. For these reasons, I compared Szerencsits's forest line to the results of the other methods in Chapter 5 which is conceptually consistent and it is unclear why Szerencsits did otherwise.

The question remains: are these differences between methods purely conceptual, stemming from different interpretations of what the treeline stands for or might they also reflect methodological imprecision? Although rather minor, differences between the treelines of Paulsen and Körner and Gehrig-Fasel et al. exist even though they seemingly model the same thing. Here, some observed differences can reasonably be attributed to methodological variation (e.g. fixed spatial units vs interpolated moving window) but also — as Section 5.2 showed — different input data. However, compared to Szerencsits's approach with significantly smaller, topography related spatial units, the differences cannot be reduced to methodological imprecision. They reflect different conceptualisations of what should be represented by the treeline: climatic limits, actual boundaries of trees or forests, or a hybrid incorporating both. This genuine ambiguity about what the treeline is—compounded by terminological inconsistency, conflation of distinct boundaries and frequent lack of explicit definitions—hinders meaningful comparison between studies and creates practical ambiguity. The comparison of these four methods exemplifies this definitional complexity, concluding RQ1.

Before addressing RQ2 regarding the suitability and limitations of specific modelling approaches, we must first examine the inherent indeterminacy of the concept itself. In other words: its vagueness. Only by understanding types of vagueness — addressing RQ3 — can we meaningfully assess method suitability.

In Section 5.1.2 I presented an approach to visualize uncertainty between methods proposed by Sexton et al. (2016) and extended it in Section 5.4 with differences in input data and forest definition. But upon having a closer look at the term uncertainty, it suggests that this might not be a case of such. Bennett (2010) defines uncertainty as lack of precision or knowledge about the world and the existence of a definite boundary between correct and not correct. This means, for example, that when we look at a person, we might estimate their height as somewhere between 150 and 200cm. The person has an exact height (e.g. 178.5cm), but we do not know it, because our judgement is imprecise, but we could theoretically measure it precisely. Here, the issue lies in our knowledge, not in the concept. In contrast, vagueness arises from a lack of definite criteria for a linguistic term (Bennett, 2010). Even if we know that the person's height is 178.5cm, one person might considers this a tall person, while another might not — because the concept tall has no precise boundary.

The occurrence of uncertainty and vagueness is not mutually exclusive and surely uncertainty is also present within these treeline models. For example the accuracy of the DEM or measurement errors within the estimation of individual trees are clear cases of uncertainty. Table 6.1 provides an overview of methodological aspects that introduce vagueness into the four modelled treelines. Beyond these methodological parameters, the very definition of forest (i.e their input forest cover datasets) varies between the methods. As Lund (2002) plainly showed, already the term forest (or tree) does not consist of a definite boundary, but of countless possible definitions, making it a vague term. All treelines — including the four reproduced here — depend directly on the terms forest or tree, making it an inherently vague term. Each of these decisions in Table 6.1 may be reasonable, yet arbitrary.

Table 6.1: Methodological decisions introducing vagueness in each treeline model.

Paulsen & Körner (2001)	**Gehrig-Fasel et al. (2007)**
- 10×10 km grid cell size - 1750 m minimum treeline elevation - 150 m mountain top filter	- Rasterization method - 150 m mountain top filter (assumed) - Rectangular moving window shape - 10 km regional moving window size - Max elevation function - Interpolation method
Szerencsits (2012)	**Nguyen (2025)**
- Rasterization method - Slope zone derivation - 4 km^2 threshold for slope zones - Circular moving window shape - 1000 m moving window size - Max elevation function	- Resampling method - 1750 m minimum elevation - Circular moving window shape - 89.8 percentile function - 50 m and 300 m window sizes - 800 m^2 minimum patch size

Nguyen defines a minimum elevation at 1750 m for the treeline, adopted from Paulsen and Körner. If closed forest on a slope follows roughly along an elevation of around 1750 m, the treeline will be forced precisely on that elevation regardless if the upper forest edge on that slope follows this elevation or not. The treeline elevation is differently estimated if the 89.8 percentile within a moving window is used, as opposed to the maximum or some other function. The 89.8% threshold is not randomly defined, but exactly such that forest patches smaller then 800 m² will be discarded. But the 800 m² are simply defined by swisstopo as minimum forest area. One could just as well argue that 750 m² or 850 m² is more fitting. Paulsen and Körner use a spatial unit of 100 km² in order to disregard local conditions. But why does exactly a size of 100 km² achieve that effect, compared to 50 km² or 150 km²? Of course, when modelling a geographic object with a GIS (or any other tool), one inevitably has to make such decisions, since any model is an abstraction of reality. And each abstraction is always is just that, as each model does not capture all attributes of the original they represent, but only those that seem relevant to its creator (Stachowiak, 1973). There is no objectively correct reduction from reality. Since the underlying concept is vague, each spatial delineation is one of many possible interpretations. To further explain these aspects, Bennett (2001) proposes a distinction between conceptual and sorites vagueness.

Conceptual vagueness refers to the absence of a single completely adequate definition of a certain conceptual term. It means that if we take some subset of all plausible interpretation of a term, we might end up with too strict a concept. If we take all plausible interpretation into account, we might end up with a concept that is too general. Some may allow to give a reasonable interpretation, but none will be representative of all interpretations. The different discussed methods to estimate a spatial delineation of the treeline are an example of such different interpretations, so are the general definitional inconsistencies within treeline research and in the context of Swiss laws concerning the treeline.

Sorites vagueness is the indeterminacy stemming from dividing some quantities, without specifying at which point a property starts to apply. The quantity may be measurable, but the concept itself lacks a sharp boundary. This type of vagueness corresponds to some of the previously shown aspects in Table 6.1 such as the elevational limit of the treeline or the size of a spatial units. Even if we agree that the highest elevated forest patch sets the treeline within a region, why should we settle for 100 km², instead of 99.9 km², or 99.8 km² or 99.7 km²? It is, in essence, the sorites paradox introduced in Section 3.3. As with uncertainty and vagueness both of these types are not mutually exclusive either. Bennett (2001) notes that natural terms are actually often affected by both, as is the case for the treeline. Vogt et al. (2012) argue that from an epistemic point of view such as Smith (1995, 2001) or Smith and Varzi (1997, 2000) indeterminate boundaries are, in principle, definable, but their exact position cannot be pinned down. Their vagueness stems from their fiat nature, bringing us back to bona fide and fiat boundaries as discussed earlier in 3.3.

I argued that climatic treelines — the physical limitation that prevents growth of forests or trees — are bona fide, existing independently of human cognition. Since Paulsen and Körner and Gehrig-Fasel et al. modelled the climatic treelines, their results should then represent bona fide boundaries. But their results were — although similar — not equal. Not in their original state, not with harmonized input data and not with varying definitions of forest. This is not surprising, because even when modelling a supposedly bona fide boundary, one has to make fiat decisions, that introduce vagueness. Nguyen's treeline is fiat from the outset, as the uppermost forest and any continuous line representing that limit is entirely a matter of definition, not a matter of physical necessity. Szerencsits's approach blurs the distinction between bona fide and fiat boundaries, by questioning what the potential treeline represents. Is it merely of climatic nature or is it a reasonable assumption that the growth of forest and trees is not only hindered by climatic parameters but also by the presence of unsuitable topography? This would then suddenly give the climatic and potential treeline different meanings. It suggests that all types of treelines, whether potential, actual, forest line or treeline, contain vagueness.

Given that vagueness is inherent to treelines, it is not possible to resolve it. Nevertheless, it can be made explicit. Rather than focusing on the most accurate definition or spatial delineation and presenting a single boundary, the disagreement or ambiguity itself can be visualised. Which brings us to the second part of RQ3, the visualisation of uncertainty and vagueness in the context of the treeline.

While uncertainty and imprecision and their visualisation have received considerable attention in Geography (e.g. MacEachren 1992) and other fields (e.g. Pang et al. 1997; Brodlie et al. 2012; Bonneau et al. 2014), the intrinsic vagueness of features and its visualisation have been largely overlooked (Bennett, 2001). The most common approach is applying fuzzy logic to represent vagueness (Gómez Álvarez and Bennett, 2017). Fuzzy logic is suitable for all sorts of features that include thresholds, as it allows to assign gradually increasing values using a membership function. This makes it an appropriate technique to deal with sorites vagueness and thus for many aspects mentioned in Table 6.1. Its usefulness is limited, however, when there is no underlying continuous dimension. It cannot capture categorical methodological choices or situations where several qualitatively different interpretations exist, such as when different treeline methods each place a boundary in different locations (Gómez Álvarez and Bennett, 2017). Thus, it is unsuitable to deal with conceptual vagueness and could not be applied to visualise different versions of the treeline as in this thesis.

Another approach is the egg-yolk model by Lehmann and Cohn (1994). This is a rather simple model for spatially vague objects and can equally be used to represent uncertainty (Bennett, 2010). It uses minimal and maximal extensions providing areas of determinacy (the egg-yolk) and indeterminacy (the egg-white). This could certainly be applied to different interpretations of the treeline by providing a region that contains all interpretations and one that contains none, giving regions that are surely below and above the treeline according to the available interpretations. The limitation of this approach is that it allows any possible course of the treeline within the indeterminate region, which would allow unrealistic courses. Additionally, we would lose all information in-between these regions, making it harder to explain the boundary of the regions. For instance, Nguyen's actual forest line extending the lower boundary of the indeterminate region far into a settlement might seem confusing without the information that only this approach supports that interpretation.

Bennett (2001) proposes another method to deal with conceptual vagueness: supervaluation theory. It works by combining a set of so-called precisifications for a feature. A precisification is a way of sharpening a vague term by fixing specific criteria. For example the vague term tall can receive the precisification '>180cm', or 'above average'. In this sense, the four methods from this thesis can be considered precisifications. More precisely, the twelve lines in Figure 5.37 are all precisifications of the term treeline. Opposed to a single line, a supervaluation approach is a more realistic formalisation that captures a whole set of views rather than a single, precise definition and keeps the information about each individual interpretation of the treeline. If a statement is true under all precisifications, it is called super true. In the context of treelines, this corresponds to two regions shown in Figure 5.38: All pixels where all twelve versions agree on being below or above the treeline, can be considered super true or in other words, depict a determinant region. The supervaluation approach is however limited to the extent that it is limited by the set of included interpretations. So any statement considered super true, might not be super true when considering further interpretations, in this case, other delineations of the treeline.

My thesis does by no means provide a complete set of precisifications of the treeline. In fact, no complete finite specification of the potential interpretations of a vague feature may even be possible (Bennett, 2001). However, completeness is not the goal. As long as the included precisifications are reasonable and cover a range of interpretations, the result is still more informative than a single crisp boundary without acknowledging its underlying arbitrary choices.

While supervaluation addresses conceptual vagueness through multiple precisifications, the same raster can also reveal something about sorites vagueness when visualized differently, as in Figure 5.39 compared to 5.38. It highlights the zone of maximum disagreement, where six methods classify a pixel as below and six as above the treeline. This is precisely the region where a person walking uphill would experience the sorites paradox most noticeably by asking at what point does 'below the treeline' become 'above'? Each precisification answers this sharply, but differently. The zone of maximum disagreement shows where this transition is most contested. In this region, half the methods classify a pixel as below the treeline and half as above, whereas just below the majority of the methods agree it is below and just above the majority agrees it is above. The supervaluation visualisation of the twelve treelines in 5.37 could be extended by combining it with fuzzy logic, addressing both sorites and conceptual vagueness. Each parameter introducing sorites vagueness per method could be varied across a range of values, producing fuzzy membership gradients rather than crisp lines. Combined with the different forest definitions (i.e. input data) and methods that capture conceptual vagueness, a more complete picture of treeline vagueness could be provided. However, I will leave this for future research.

In summary, the spatial delineation of the treeline involves both uncertainty and vagueness. Uncertainty arises from factors such as DEM accuracy and measurement errors. Vagueness manifests in two forms: conceptual vagueness, stemming from the absence of a single adequate definition, and sorites vagueness, arising from arbitrary thresholds and parameters inherent in any modelling approach. While uncertainty can in principle be reduced through better data, vagueness is inherent and should be acknowledged rather than concealed. The pixel-wise comparison and elevation-based buffer provide quantitative measures of disagreement between methods, while the supervaluation approach visualises zones of determinacy and indeterminacy across twelve interpretations, offering a more realistic representation than any single crisp boundary. This answers RQ3.

Having discussed various aspects of vagueness and its visualization, I finally turn to RQ2: what GIS-based methods are suitable for spatially modelling the treeline and what are their respective strengths and limitations? I first discuss the individual strengths and limitations of each method before returning to the broader question of suitability.

Paulsen and Körner's approach implements the logic that if forest can grow up to a certain elevation, it should also be able to do so in nearby locations where climatic conditions do not change drastically. Compared to purely physical models, this approach has the advantages that it only considers elevations where forest growth is actually possible and does this in a very simple and straightforward way. According to Körner (2021a), small forest cohorts are suitable proxies for the forest line. The derived treeline elevation however, is strongly influenced by the chosen spatial unit, the 100 km² grid. A different size, shape or placement of the unit will lead to different results and unrealistic boundaries between two grids as discussed in 5.1.1 are inevitable using fixed spatial units. The size of 100 km² as optimal spatial reference unit is contested by other researchers such as Eggenberg (2002). Further, setting a sharp boundary at 1750 m is subjective and in regard to the discussed issues around vagueness not unproblematic.

Gehrig-Fasel et al. follow the same logic as Paulsen and Körner, but the moving window is less rigid than fixed grid cells. The size of the moving window is again subjective and while they did test the effects of several different sizes for the local, they did not for the regional treeline. The approach partly solves the problem of unrealistic treeline courses at grid cell boundaries, but only partly as they also introduce a grid later on by interpolating over the derived maximum elevations, where treeline elevation again changes suddenly. But because of the interpolation the gradients are less steep. The interpolation step also creates artificial values that do not correspond to exact uppermost forest elevations any more and the existence of many different interpolation techniques, makes the selection of one subjective, especially since they did not further comment or explain this step.

Compared to these two methods, the approach of Szerencsits included topography, making the spatial units less artificial than rectangular cells. By combining it additionally with a moving window approach, the method is more robust than relying on just one derivation of treeline elevation. However, the generation of the slope zones also introduces aspects of subjectivity, since there are different possibilities to create them. The fixed threshold of 4 km² as minimum size as well as the moving window size fall into the same category of other decisions that are prone to sorites vagueness.

Nguyen's approach captures forest cover more accurately, using a higher resolution. Retrieving the treeline elevation using a percentile rather then the maximum makes it less prone to outliers and only considers forest patches that correspond to the minimum forest area defined by swisstopo. Again, the selection of the moving window size is subjective and the small scale of her approach leads to a relatively high number of disconnected treeline patches, which raise conceptual questions that remain unresolved.

There is no absolute answer on the suitability of these four GIS-based methods to model the treeline. No single 'best' method exists because, as the discussion on vagueness showed, there is no single 'correct' treeline. This does not display methodological shortcomings, but reflects the inherent vagueness of the concept treeline. Each method has distinct strengths and limitations and depending on the application a different approach may be suitable. Camping regulations in various Swiss communes or recommendations by the SAC may be most concerned about the protection of forest and would need an interpretation similar to Nguyen's approach of the actual forest line, whereas Mountain Wilderness may prefer Szerencsits's treeline to represent the uppermost individual trees. The BASPO uses the treeline as indicator for changing environmental conditions, which would imply a climatic forest or treeline as in Paulsen and Körner or

Gehrig-Fasel et al., but that would make it hard to locate the boundary on-site in cases where the climatic treeline is far above the uppermost forest or tree. The necessity of national parks to contain at least 25 km² of their area below the treeline could have different reasons, leading to different requirements of that treeline. Yet, none of these methods were designed for practical applications, but for ecological research questions. Some authorities also did not see a need for a further specification of the term. In short, each method offers trade-offs between simplicity, resolution and sensitivity to local conditions, and suitability depends on which interpretation the application requires. This answers RQ2.

While the suitability of one individual line to one individual application is indeed not given in all these cases, the comprehensive comparison and explanation of characteristics and limitations of these methods provides profound insights. Combined with the terminology framework and visualisation of vagueness, it contributes to a more accurate understanding of the innumerable appearances that the single term treeline can exhibit.

6.2 Reproducibility

Reproducibility of the researched methods was not an initial research question, but since the process of reproducing the methods is a major part of this thesis, it is worthwhile to evaluate it within this discussion. Reproducibility is defined as the ability to replicate results of a study using the same data and methods that were used by the original researchers (Kenneth Bollen , et al., 2015). It is deemed a minimum condition for scientific findings to be believable and informative. Goodman et al. (2016) describe three main types: methods reproducibility, results reproducibility and inferential reproducibility. I will only focus on the first type — providing enough methodological detail to let others repeat the study — as I cannot make a judgment regarding the latter two. Table 6.2 provides a listing of all aspects that contributed or hindered the method reproducibility of each of the four methods reproduced in this thesis. Following this, I will briefly discuss individual aspects of the reproducibility of each method.

Table 6.2: Reproducibility aspects of the four treeline modelling methods.

Aspect	Paulsen & Körner	Gehrig-Fasel et. al	Szerencsits	Nguyen
Input data clearly stated	yes	implicit	yes	yes
Input data available	yes	yes	partly	partly
Resolution specified	yes	no	yes	yes
Key steps fully described	yes	partly	partly	yes
Workflow illustration	no	no	yes	yes
Software mentioned	no	no	yes	yes
Results available	no	no	partly	no

Paulsen and Körner
The authors described the categories of the Arealstatistik they used, but only through definitions rather than explicit category codes. Identifying the correct categories required matching these descriptions to an older nomenclature. Data from the Arealstatistik is still available for past years and the method was otherwise straightforward to reproduce. Unfortunately no results were available, besides a figure of the treeline elevation per grid cell, which hindered a meaningful comparison.

Gehrig-Fasel et al.
Contrary to Paulsen and Körner, this paper named the category codes for the used input data from the Arealstatistik. The method was adequately described up to the interpolation step, besides not mentioning the resolution. It remains unclear why the interpolation was conducted in the first place and how exactly

it was carried out. The authors did not respond to a request of mine to explain the step in more detail. The only available result is a figure of the interpolated treelines, but with a resolution that does not match their description.

Szerencsits
While the author also named the category codes of the used data precisely, not all of it is openly accessible, since newer versions of one of the dataset (SMV25) with different categories were released, as already discussed in 4.3. A detailed workflow illustration made the replication mostly straightforward, but some key steps were not further described, including the generation of the slope zones, rasterisation steps and possible smoothing of the final forest and treelines. This paper is the only of the four that provided parts of the results — the treeline — which is still publicly available today.

Nguyen
This thesis is a bit of a special case, since it generated its own input data as preceding part of the thesis. While not publicly available, the author provided me with a subset of the data that allowed me to reproduce her method. Workflow illustration helped to understand the methods, but some steps were insufficiently described. The author however, answered all of my questions about the methodology personally. The analysis was carried out in Python, but no code repository was mentioned and no results are available. This may also be due to the thesis being recent, as the author noted that a final paper on the treeline analysis has not yet been published.

In conclusion, none of the four methods provided sufficient documentation for a full reproducibility. The final results were almost entirely unavailable, limiting the ability to validate reproductions. Workflow illustrations, where provided, significantly aided reproduction by complementing purely textual description. Older methods face additional challenges from changed or discontinued datasets, although, this is not the fault of the authors. Personal communication with authors provided valuable insights to specific steps within the procedure when documentation was lacking, but not all authors replied to requests. Method reproducibility remains undervalued and the scientific community would considerably benefit from greater attention to documentation, data sharing and code availability.

6.3 Limitations

While this thesis provides insights into treeline terminology, modelling approaches, and vagueness visualisation, several limitations should be acknowledged.

- Chapter 2 laid out the foundation of the terminology, that was used to decipher the ambiguous usage of the term treeline. This review was not conducted in a systematic manner. The selection of papers may be subjective, as it was done iteratively, starting from papers that seemed highly relevant within the field of treeline ecology. Different selections may lead to different conclusions on the terminology and definition of the treeline. By far the most cited author was Christian Körner, as he is one of the leading researchers of the field. This likely introduces some bias toward his research, but given his prominence in the field, this was difficult to avoid.
- In Chapter 3 I tried to provide a perspective of different authorities related to laws and regulations around the term treeline. Again, this was not a systematic approach, but rather done in a sort of snow-balling way. While the majority of contacted persons answered, the answers were sometimes brief and sometimes further information about the thesis may had led to more comprehensive answers. I felt that some of the people did not fully understand all of my points, which may have been clearer if I had requested interviews or phone calls. It still gave me an idea of inconsistencies around

the term and possible issues that could arise, but more comprehensive requests could surely provide better insights.

- The four methods that were reproduced in Chapter 4 were somewhat arbitrarily selected. While these four papers represent, to my knowledge, all observation-based treeline models developed for Switzerland, they build upon each other, limiting their methodological diversity. Including approaches from other regions might have provided a broader range of methods.
- For computational reasons and data availability of Nguyen's work, I did not run all four methods for the entire alps, but restricted the analysis to a study region. While I did not find substantial differences for the other three methods in other regions, I did not measure it quantitatively. Thus, it is possible that some quantitative measures would be different for the entire alps, in contrast to the ones presented here.
- A major limitation of this thesis is that I was not able to assure the reproduced results correspond to the original works. Only Szerencsits provided his results (partly), but even that was of limited use. Since the precise input data was not available any more, it is difficult to estimate which differences are caused by different input data or actual methodological deviations. Despite careful reproduction of the methods, errors across over 2500 lines of code remain possible.
- I developed an elevation based buffer to provide a more comprehensive quantitative comparison between the four methods, but as mentioned in 5.1.2, this approach has its limitations. Further improvement on this approach would be worthwhile to provide a more robust statistical measure to compare treelines and possibly other elevation based features as well.
- The literature on vagueness visualization that provided the basis for the preceding discussion is over 20 years old and the topic appears to have received little further development since then. Beyond a few authors such as Álvarez et al. (2018), not many researchers seem to actively pursue this area and actual implementations for spatial phenomena remain rare. I have attempted to provide an example of how such visualizations could look, but translating philosophical concepts into spatial representations that correspond to what the authors originally envisioned proved challenging. Furthermore, the visualization is limited by the four methods included. Other methods would produce different results, as would different input forest cover data. The visualization therefore does not show absolute regions of determinacy or indeterminacy, but only those relative to the included interpretations of the treeline.

Chapter 7: Conclusion

This thesis set out to investigate how the term treeline can be defined, how the treeline can be modelled using GIS-based methods and how aspects of vagueness arising from its spatial delineation can be visualized. I addressed this through a terminology review of over 30 papers, engagement with Swiss authorities, a reproduction of four modelling approaches and its visualisation.

The analysis revealed that no single definition of the treeline exists. The term encompasses multiple distinct boundaries—the forest line, treeline, and shrubline—which form a hierarchical structure within the treeline ecotone, as well as adjectival descriptions such as climatic or actual that further specify it. The issues arising from its definition are partly caused by insufficient effort to define it, but more importantly by the term's intrinsic vagueness. This vagueness can lead to misunderstandings, complicate scientific comparisons between studies and create ambiguity in practical applications. The finding is not that the term should remain undefined, but rather that any definition should acknowledge and reflect on the ambiguities the term inherently contains.

The comparison of four GIS-based methods showed that no single 'best' method exists for modelling the treeline — because no single 'correct' treeline exists. Different methods are suitable for different applications. Reproducing these methods was hindered by insufficient documentation, unavailable input data and missing results for validation, complicating the comparative analysis. Further limitations of these methods include arbitrary methodological decisions, but more fundamentally, the production of a single crisp line for an intrinsically vague phenomenon that does not acknowledge the arbitrary choices underlying it. The spatial delineation of the treeline introduces both conceptual vagueness — stemming from the absence of a single adequate definition — and sorites vagueness — arising from arbitrary thresholds and parameters. This intrinsic vagueness explains why feedback from authorities on the definition and purpose of the term was diverse and why treeline research exhibits such terminological variation. While philosophical frameworks for representing vagueness exist, actual implementations for spatial phenomena remain sparse. Nevertheless, this thesis presented three visualizations that aimed to capture the ambiguity of different approaches to spatially delineate the treeline, by identifying regions of less and more (in)determinacy.

Authorities using the term *Waldgrenze* in Swiss laws and regulations did not express an urgent need for more precise definitions, as the current ambiguity has not yet caused significant problems. However, the wide range of possible interpretations documented in this thesis demonstrates that practical issues could arise. Visual representations of treeline vagueness, as developed here, could help identify areas that may be problematic in enforcement contexts — the regions of indeterminacy — and those that are likely above or below the treeline according to all included interpretations. For scientific discourse, more explicit attention to terminology would enable more meaningful comparisons between studies and help make sense of divergent results.

This thesis contributes to the field by providing a terminology framework that synthesizes definitions across treeline research, by reproducing and critically comparing four modelling approaches with a workflow that allows testing under harmonized conditions and by connecting scientific definitions to practical usage in Switzerland. The visualization of vagueness offers an alternative to representing treelines as single crisp boundaries.

Future research could extend the visualization approach by combining fuzzy logic with supervaluation to address both sorites and conceptual vagueness simultaneously. More generally, actual implementations of visual representations of vagueness deserve greater attention, moving beyond purely theoretical treatments. Vagueness is not a flaw to be eliminated but a characteristic to be acknowledged. Flexibility in definition can have practical advantages, as several authorities noted. However, this flexibility should be made explicit rather than left implicit. Explicit terminological transparency — stating which definition is used and why — remains lacking in most studies and should become standard practice. Similarly, acknowledging the arbitrary choices inherent in any modelling approach would strengthen rather than weaken scientific work. Method reproducibility also remains undervalued and a greater attention to documentation, data sharing and code availability would be beneficial for the entire scientific community.

The treeline will remain a relevant concept for ecological research, climate change monitoring and legal frameworks. The question is not whether we can achieve a single more precise definition, but whether we are transparent about which interpretation we choose and why.

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Declarations

Personal declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis

AI declaration

Claude (Anthropic), ChatGPT (OpenAI) and Copilot (GitHub) were used to assist writing code. DeepL was used to translate between German and English. Claude and ChatGPT were used to assist with brainstorming, structuring optimisation, LaTeX syntax and to improve writing style. All text parts assisted by AI have been checked by me, the author of this text, and I take full responsibility of the text.

Zürich, 31.12.2025

Micha Franz

M.F