# Modeling Historical Shifting Cultivation in Europe

A Proxy-Driven Spatial Analysis

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# ABSTRACT

As Europe experienced profound industrialization over the past centuries, its landscape and agricultural practices were also profoundly changed. Exploring the dynamic relationship between the ancient practice of shifting cultivation (SC), land use, and the forces of industrialization, this study sheds light on the fascinating interplay between human activities and the changing environment. This thesis examines the historical dynamics of SC in Europe since the Industrial Revolution, using proxy indicators and geospatial analysis in QGIS. By modeling the potential locations and extent of SC and considering factors such as population density, elevation, urban built-up area, and biome type, the study provides valuable insights into the changes in SC suitability over a 250-year timeframe. The findings reveal a significant decline in SC suitability across Europe, with central Europe experiencing the most pronounced decrease, influenced by higher population density and urbanization. However, in regions with lower population density levels, other factors such as market integration and private industrial land acquisitions also played a role in the decline of SC. The implications of this research are crucial for land management, conservation, and policy-making. The obtained results highlight the importance of implementing sustainable land use practices and policies that take into account future trends such as population density and urbanization growth. While SC has ceased in many parts of Europe, its relevance remains significant in developing countries. The insights gained from this study can inform land management approaches in these regions, where SC continues to play a vital role in agriculture and livelihoods. By integrating proxy indicators and utilizing QGIS, this study offers a comprehensive assessment of the changing suitability of SC across Europe, contributing to a broader understanding of the dynamic connections between human activities and the environment.

# 1. INTRODUCTION

Human effects on the environment have reached a point of severity which has led to multiple scientists to start using the term ‘anthropocene’ to refer to a new geological era in which humans are the main drivers of environmental change on our planet (Stoermer & Crutzen, 2000; Ruddiman, 2013). This effect can be clearly visualized by looking at the land use of our planet: about half of the Earth’s habitable land is currently used for agriculture (Unnerstall, 2022). This has resulted from thousands of years of population growth and agricultural development. One agricultural practice that has been widely used over the course of our history is that of shifting cultivation, which is the central concept around this research.

Shifting cultivation (SC) is a widely used agricultural technique which starts with the clearing and burning of a natural patch of vegetation. Then crops are temporarily cultivated on this cleared land, with the ashes providing nutrients for the soil, until the land is abandoned and allowed to recover into its natural state in what is called fallowing. During the fallow period, the cultivator moves to a different natural patch of land on which then the same process is repeated. Often the farmer will move back to the initial patch after its nature and soil quality are regenerated, and will use this land for cultivation again. The SC practice and its different stages are illustrated in figure 1:

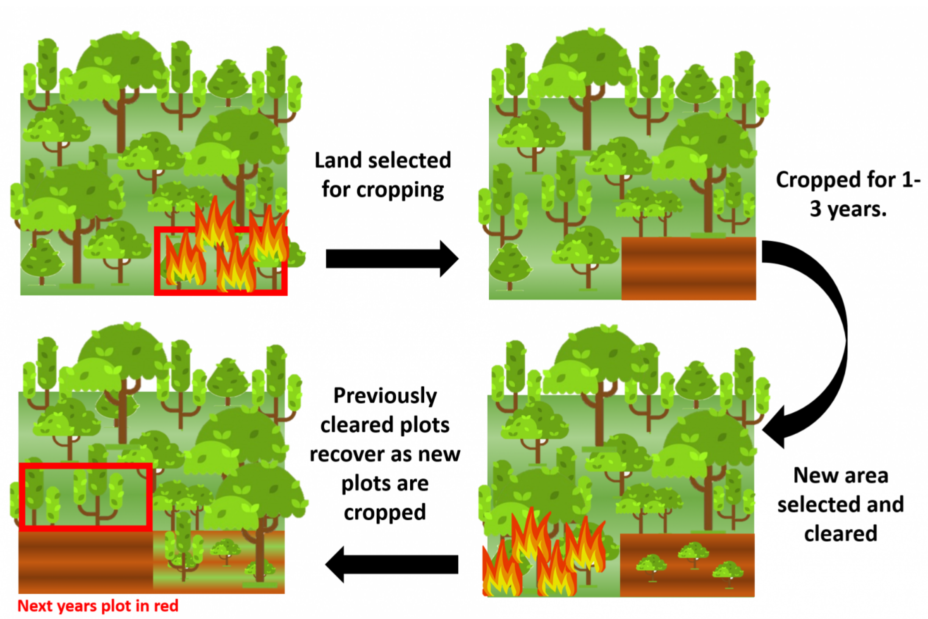


Figure 1: Visualization of the shifting cultivation practice [Grantham Centre].

This common practice has been the subject of much debate regarding its effects on deforestation and on the carbon cycle: many contradicting papers exist that give different answers to whether SC can be considered a sustainable practice. Studies such as the one conducted by Borah *et al.* (2018) highlight the fact that in recent times SC has been expanding into primary old growth forests, which is leading to the fast degradation of these ecosystems and is strongly altering the carbon cycle through deforestation. However, other studies oppose this point of view by arguing that the effects of SC depend mostly on the length of the fallow period. Lawrence *et al.* (2010) mention that when the fallow period is respected, and thus not shortened in order to rush cultivation, forests can recover and thus the practice of SC can be considered sustainable, especially in comparison to other traditional forms of agriculture such as monoculture. Moreover, Ickowitz (2006) stressed that the general shortening of fallow periods that most researchers base their claims on is based on false assumptions. As Thrupp puts it in their research (1997), SC is not one single system, but it consists of hundreds of systems of varying practices (mainly varying in the practice of fallow). For this reason, he refers to SC as "the most complex and multifaceted form of agriculture in the world". This study acknowledges the complexity of SC, and respects Thrupp's narrative: this practice can not simply be deemed good or bad as there are multiple ways of carrying it out. This research thus focuses on expanding our knowledge on past SC and not on settling this ongoing discussion about its sustainability.

The complexity of SC also translates into uncertainty regarding the geographic modeling of this practice. Land use and land cover classifications through remote sensing often disregard SC as it is highly complicated to capture something with such a dynamic nature and spatially complex structure (Heinimann *et al.*, 2017). This is the main reason why there is such a lack of research and existing databases on SC modeling, which is even more the case for historic reconstructions. Modeling of past shifting cultivation has seldom been conducted and is often plagued with uncertainties (Klein Goldewijk & Verburg, 2013). This gap in knowledge should be filled for many reasons, including not only enhancing our understanding of SC, but also providing a more complete picture of historical land use and land cover. While the practice of SC has largely ceased in Europe, it remains widespread in many developing nations within tropical regions (Hoang *et al.*, 2021). This discrepancy is largely due to differing societal and economic pressures, as well as variations in local environmental conditions. Hence, since SC is still broadly used around the globe, and as mentioned previously it has a great effect on the carbon cycle as well as on both biodiversity and soil quality, its study should be prioritized in order to make land cover research more complete. Furthermore, exploring the historical distribution of SC allows to create links for potential implications of this practice for past and present socio-ecological systems. For instance, historic recollection allows us to find correlations between this practice and carbon emissions and sequestration. In this way, this research contributes to sustainability by providing a much-needed base to assess the impact SC has had and might have on our planet.

The few studies that have explored the geographic distribution of SC have limited their focus to a certain region; for instance, Hörnberg *et al.* (2015) researched past SC limiting their focus on northern Sweden. However, no previous research has extensively modeled this or created a database/mapping of any sort. Moreover, the vast majority of the existing studies have explored the historic SC cover in tropical regions. This is well justified as SC is mostly practiced in tropical regions with dense forest coverage. However, it has also been practiced in forested areas of temperate regions for thousands of years. This study seeks to fill this specific gap in knowledge: it recognizes the scientific relevance and need for more comprehensive modeling of SC, and aims to model the potential locations and extent of this practice in Europe from the Industrial Revolution to the present using proxy indicators. It then seeks to understand how these potential locations and extents have changed over time. This leads to the following research question:

- How can we model the potential locations and extent of shifting cultivation in Europe from the Industrial Revolution to the present using proxy indicators?

While the main purpose of this research is to develop a model for potential historic shifting cultivation extent in Europe, the following subquestion has been elaborated to further explore the topic:

- How and why have the potential locations and extent of shifting cultivation in Europe changed over this period according to the developed model?

# 2. THEORY / CONCEPTS

The Socio-Ecological Systems (SES) framework is used to frame the key concepts of this research, examining the relationship between human activities in the environment, with a focus on modeling the potential locations and extents of SC. Moreover, it recognizes that human societies are embedded within and dependent upon the natural environment, and that changes in one system can have profound impacts on the other. The framework emphasizes resilience and adaptability, and it facilitates the finding of synergies or trade-offs in socio-ecological practices such as farming (Partelow, 2018), or specifically shifting cultivation.

An important concept to define for this research is that of agroecology. Tittonell (2015) defined it as "the use of ecological principles for the design of agricultural systems". It is thus an approach that combines biodiversity conservation with social knowledge to promote sustainable and resilient agriculture. Within the SES framework, it is the ideal form of agriculture as it recognizes and prioritizes both ecological and social dynamics.

Further expanding this concept within the context of the SES framework and considering the practice of shifting cultivation leads to the separation of agroecology into two parts: the social and the ecological aspect. As to the social aspect, the most important concept to consider for this research is that of food security. McDonald (2010) defines it as "the idea that all people at all times have access (including physical, social and economic access) to sufficient, safe, and nutritious food necessary to lead active and healthy lives". Understanding and addressing food security allows for a comprehension of the impacts of shifting cultivation on communities, livelihoods, and overall societal well-being, providing a holistic perspective within the SES framework.

The environmental aspect of agroecology can be addressed with the concept of ecosystem services. This is an appropriate way of viewing the concept under the SES framework, since in this way ecosystems are looked at as capital assets and their use to humans is highlighted (Brauman & Daily, 2008): in this way the protection of the environment makes sense both from a biophysical and a cultural perspective. The ecosystem services that are most relevant to the practice of shifting cultivation are biodiversity conservation, carbon sequestration, and soil health (Klemick, 2010; Wood *et al.*, 2016). Biodiversity conservation recognizes the importance of preserving diverse species and ecosystems which may be affected by shifting cultivation, ensuring ecological balance and long-term sustainability. Carbon sequestration highlights the potential of shifting cultivation to capture and store carbon dioxide, mitigating climate change by reducing greenhouse gas emissions. Soil health addresses the crucial role of maintaining fertile and productive soils, promoting agricultural productivity and minimizing erosion. The fallowing period included in shifting cultivation practices (if the required length of it is respected) is said to help minimize the exhaustion of soil and its nutrients (Singh *et al.*, 2017). Hence, these three subconcepts together provide a comprehensive understanding of the environmental aspects crucial for sustainable shifting cultivation practices.

For this study, the focus lies approximately on the time from the Industrial Revolution onwards (the earliest modeling will be done for the year 1750). This time frame is chosen as a practical decision for two key reasons: firstly, data availability, particularly compatible with QGIS, greatly improves for this period, thus facilitating a more comprehensive analysis. Secondly, the Industrial Revolution brought along a crucial turning point in agricultural practices, with a transition from subsistence farming (which SC is an example of) to more industrialized, large-scale operations (Allen *et al.*, 1994). Thus, the epoch of the Industrial Revolution and beyond is of great importance in understanding the trajectory and extent of SC within Europe.

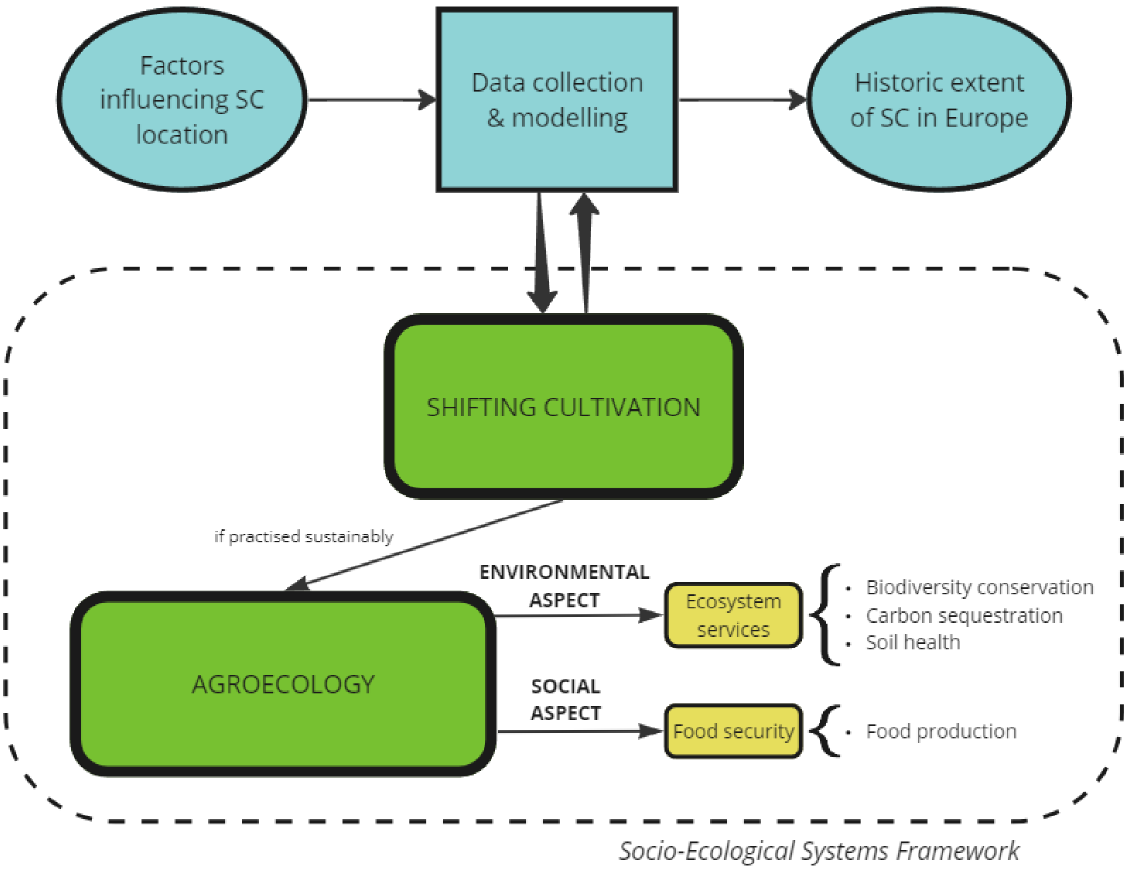


Figure 2: Conceptual framework used for this thesis. Own elaboration.

The practice of shifting cultivation is embedded within several sustainability concepts, which highlights the importance of its understanding and quantification. The conceptual framework portrayed in figure 1 was created with the intention of visualizing where shifting cultivation stands within the broader context of sustainability, while considering the scope of this research. A Socio-Ecological Systems (SES) framework is used for this, since this allows for the consideration of the two aspects of sustainability that are considered relevant to this study: the social and ecological aspect.

The sustainable practice of SC should follow the basic principles of the agroecology concept. Following the principles of agroecology, and in accordance with the used SES framework, a sustainable SC practice should thus cover the social aspect by ensuring food security through sufficient food production, and should cover the environmental aspect by maintaining ecosystem services well-functioning and intact. This includes considering the previously-mentioned subconcepts of biodiversity conservation, carbon sequestration, and soil health.

However, the objective of this study is not to explore the sustainability of the SC practice. This research has the objective of quantifying and mapping the trends in historical SC suitability. Thus, by modeling this trend, this research creates a much-needed base for a more in-depth understanding of SC and its implications for the mentioned (sub)concepts related to sustainability. Hence the two-sided connection in the framework between data collection & modeling and the concept of shifting cultivation: (proxy) data is collected from available SC knowledge, and a model is created based on this that will further broaden the SC concept. The data collection and modeling are further fed by the factors influencing SC location, which will become known after conducting the planned literature review and by analyzing existing GIS databases. The result of this data collection and modeling will be a dynamic representation of potential locations and extents of SC in Europe from the Industrial Revolution to the present.

# 3. METHODOLOGY

In this research a comprehensive methodology is employed that integrates an extensive literature review, proxy identification and development, GIS-based modeling, model validation, and an in-depth analysis of results. The methodological process can be visualized in Figure 2:


Figure 3: Visual representation of the methodology. Own elaboration.

## 3.1. LITERATURE REVIEW

To start with, an extensive literature review was conducted. The primary resource for this review was the Google Scholar academic database. However, some of the articles utilized were sourced from grey literature. Throughout this process, ensuring the credibility of all sources was of utmost importance. The main areas of focus were (in this order) the general understanding of SC, its current state, the discourses around the sustainability of the practice, and its historical use, with a particular emphasis on Europe. The main objective of this literature review, apart from getting a better understanding of this agricultural practice, was to learn about methods to model and map SC and to identify potential proxies that influence the occurrence of SC, particularly in temperate regions. Furthermore, case studies of historical SC in Europe were also sought, which would be used later in the process to validate the model. In this way, more than 30 relevant articles were analyzed.

During the literature review, the focus was not solely on the term ‘shifting cultivation’. Other commonly used synonyms for the practice, such as ‘slash-and-burn’ and ‘swidden cultivation’, were also included in the search criteria. The inclusion criteria for this search, such as publication date or geographic scope, were quite ample. For this research, it was best not to filter results through publication date as the needed data was mainly historical, and was meant to capture the historical evolution of SC practices. Hence, any ‘old’ research can be considered just as relevant as present-day research.

## 3.2. IDENTIFICATION AND DEVELOPMENT OF PROXIES

With the literature findings serving as the main base, several conditions that favour shifting cultivation were identified. The feasibility of translating these conditions into quantifiable GIS parameters was also assessed. Certain proxies were deemed unfeasible for different reasons: soil quality was considered as a proxy as literature showed soils are usually depleted in areas where shifting cultivation was practiced, but this can be for many other reasons as well than because of SC; the same applies for the presence of charcoal in soil, which can indicate SC but also any other type of fire; crop type was considered, as certain crops were grown almost exclusively through SC in the past, but there is no precise data to be used for what crops were grown where in history.

The literature review findings served as the main foundation for identifying conditions that could hint at past SC. The feasibility of converting these conditions into measurable GIS parameters to be used as proxies was examined. However, certain potential indicators were deemed unfeasible for various reasons. For instance, soil quality was considered as a potential indicator, as literature indicates soil depletion is common in areas where SC is practiced (Majewski & Tchakerian, 2007). But this depletion could be due to a variety of factors, not just the practice of SC. Similarly, the presence of charcoal in the soil could suggest SC (Tomson *et al.*, 2021) as well as any other fire-related activities. Crop type was also considered, since specific crops were predominantly grown through SC in the past (Sigaut, 1979). However, precise historical data regarding which crops were grown where is lacking, making this an unfeasible proxy.

Other proxies were considered to potentially have a significant effect on the occurrence of SC, as well as deemed feasible to use. For instance, research suggests that a rugged topography and a certain elevation greatly favor the emergence of this agricultural practice (Sigaut, 1979; Majewski & Tchakerian, 2007), both in tropical and in more temperate regions. Moreover, van Vliet *et al.* (2012) state that SC becomes much less predominant in landscapes with access to integrated markets, thus establishing a direct relation with population density and urbanization. Lastly, the type of ecosystem, just like the type of vegetation, greatly influences the occurrence of SC (Heinimann *et al.*, 2017). Therefore, four proxies were finally used in this research, which are shown in Table 1:

Table 1: utilized proxies together with the source of the databases.

| **Proxy** | **Database source** |
|---|---|
| Elevation | Copernicus European Digital Elevation Model - European Space Agency (2022) |
| Biomes | A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate - Prentice *et al.* (1992) |
| Population density | HYDE 3.2. - Klein Goldewijk (2017) |
| Urban built-up area | HYDE 3.2. - Klein Goldewijk (2017) |

The selection of proxies employed for this study is visually represented in the following four figures. These representations showcase how each individual proxy appears within the QGIS environment. It is important to note that some of these proxies required additional processing to adapt them to the specific needs of this study. The maps allow for a comprehensive view of the spatial properties of each selected proxy.

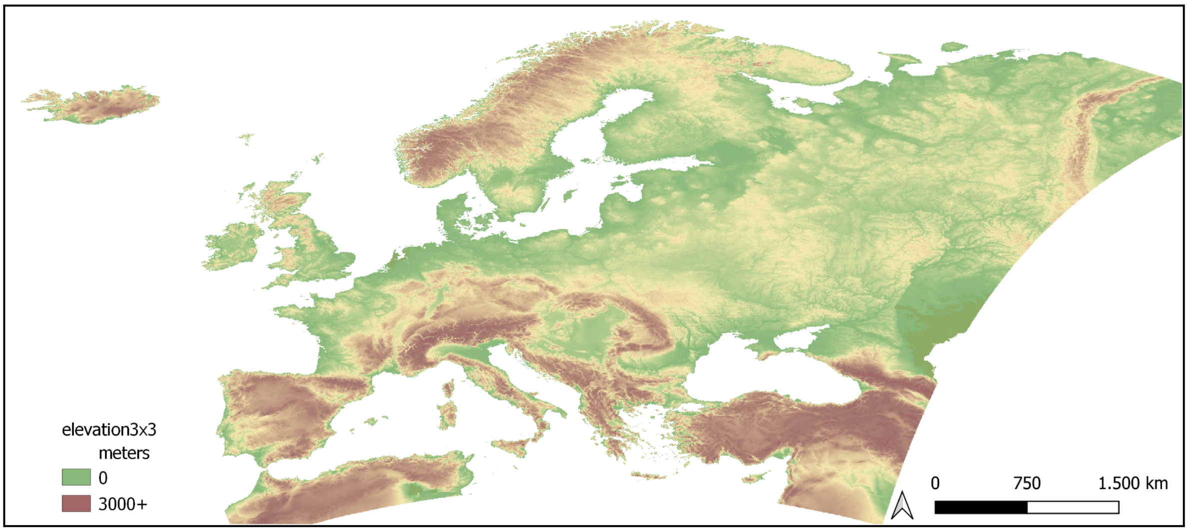


Figure 4: Map of the processed elevation proxy across Europe, georeferenced through QGIS.

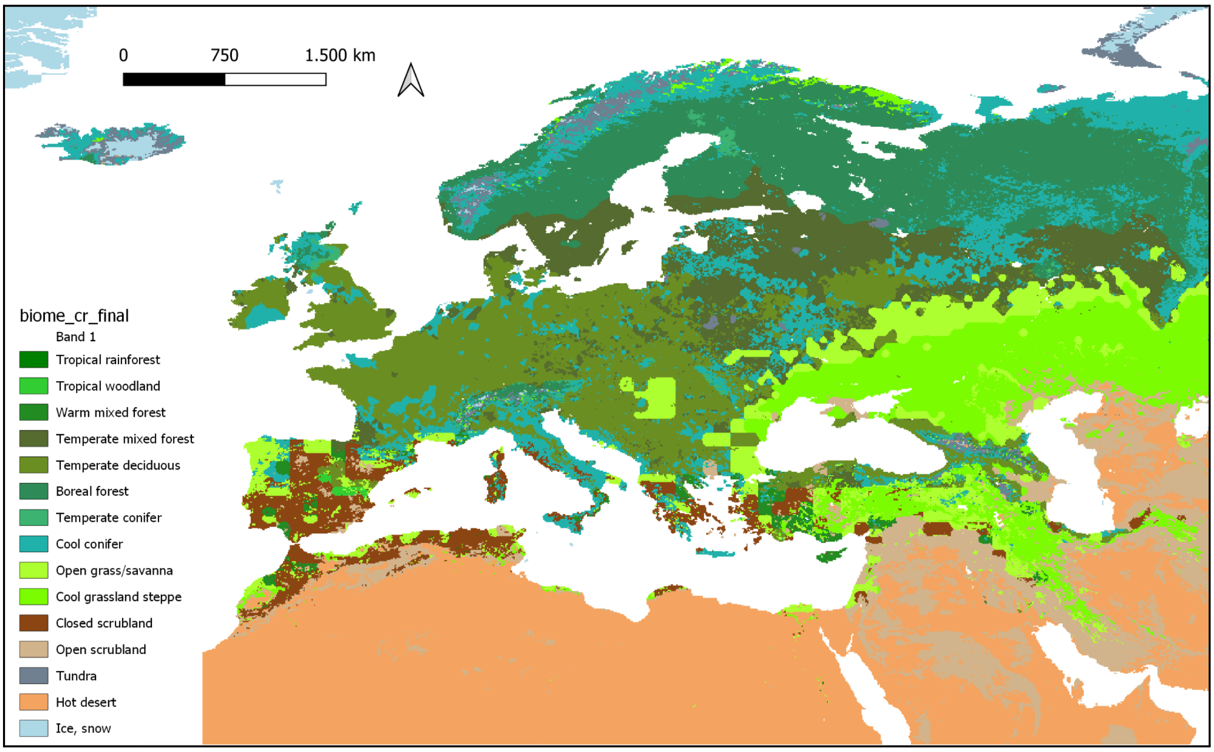


Figure 5: Map of the biome proxy, indicating different ecological zones across Europe.

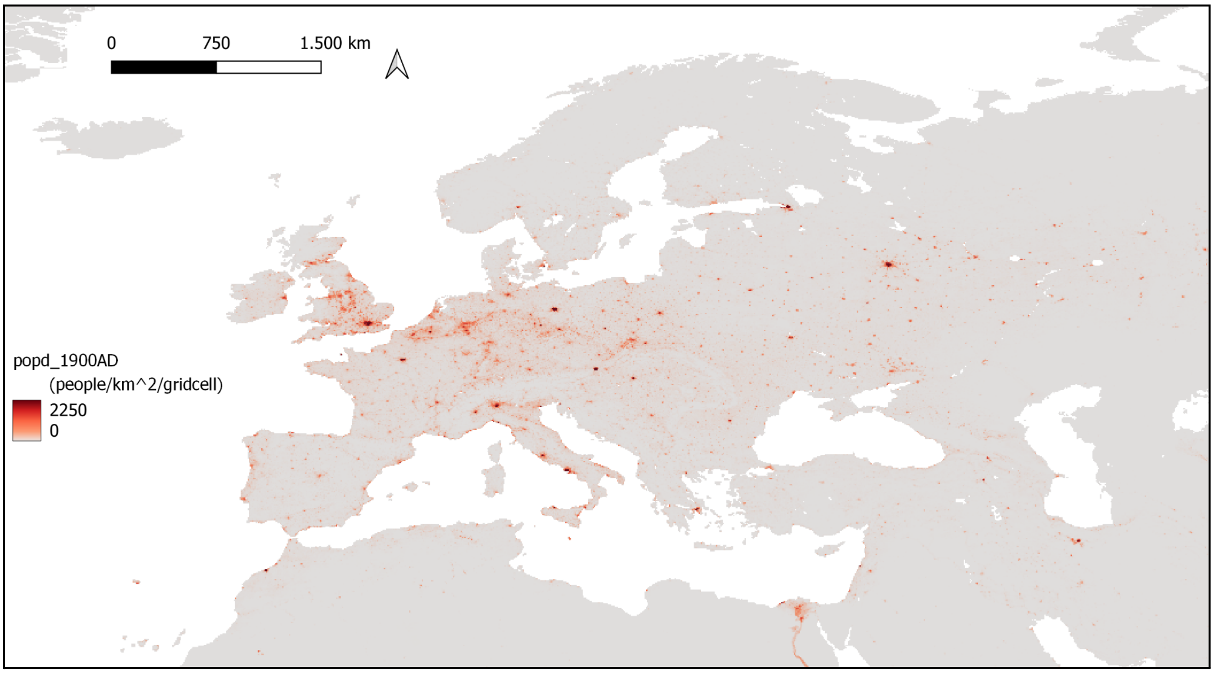


Figure 6: Map of the population density proxy for the year 1900, showing population distribution.

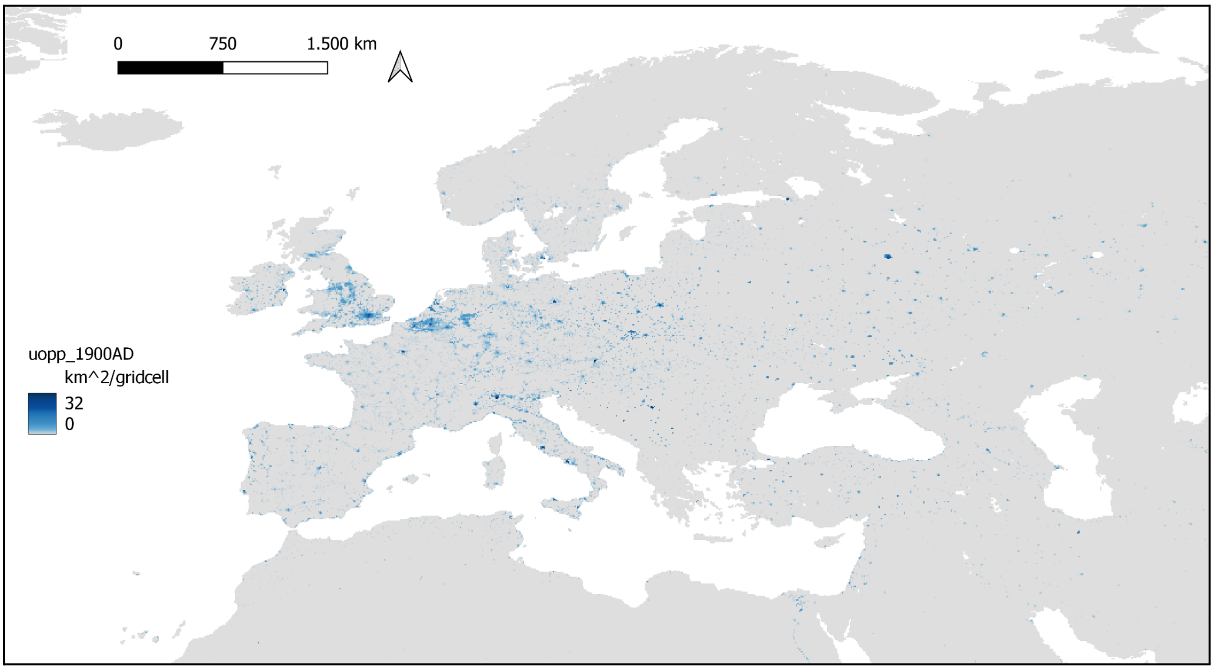


Figure 7: Map of the urban built-up area proxy for the year 1900, highlighting the extent of urbanization.

## 3.3. MODEL DEVELOPMENT

The GIS (Geographic Information System) software QGIS was used to integrate the various datasets. QGIS was selected for this project because of its extensive geospatial processing capabilities and its user-friendly, open-source platform. This choice was also reinforced by the recommendation of my thesis supervisor, Dr. Kees Klein Goldewijk, who has extensive experience in the field.

To generate a comprehensive model, multiple databases were cohesively combined via a series of intricate raster calculations. The selected proxy databases were merged to form a unified, integrated raster layer. Drawing on insights from the literature review, specific parameter values were designated that would theoretically characterize an area as apt for SC; these values are delineated in Table 2. The values chosen for each proxy parameter were determined through a combination of geographic observation, proxy understanding, and hands-on experimenting in QGIS. They were set to reflect in the best possible way the conditions under which SC could have feasibly occurred in Europe. Even though these values may not correspond to a specific source, they are nonetheless informed by a rigorous methodology that takes into account the intricate dynamics of SC and the unique and historical context of Europe.

Table 2: chosen values for each proxy parameter that suit the occurrence of shifting cultivation.

| **Proxy** | **Chosen value** |
|---|---|
| Elevation | >125 meters |
| Biomes | Warm mixed forest<br>Temperate mixed forest<br>Temperate deciduous<br>Boreal forest<br>Temperate coniferous<br>Cool coniferous<br>Closed scrubland |
| Population density | <100 inhabitants per $km^2$ per grid cell |
| Urban built-up area | <1 $km^2$ per grid cell |

The subsequent step involved an intricate raster calculation process where each proxy's chosen values were integrated via a formula (see Appendix for the precise formula) to generate a new raster layer. This layer effectively highlighted areas theoretically suitable for SC according to the developed model for the selected year. For varying years, distinct layers were produced, with the HYDE (History Database of the Global Environment) data serving as the fluctuating parameter. Specifically, population density and urban built-up area data for every 50-year interval, starting from the year 1750, were employed, while the biome and elevation data were assumed to remain constant.

Setting the geographical extent of the study -Europe- in QGIS required a series of precise adjustments to establish the appropriate boundaries. Initially, a custom shapefile mask layer had to be designed to accurately represent Europe's borders. This process necessitated manual modifications, such as partitioning Russia and excluding certain parts of Turkey, to align with the study's geographic scope. The boundaries were drawn from the map portrayed in Figure 3, which can be considered the research area of this project. Subsequently, this newly created mask layer was employed to clip the previously-generated raster layers. These refined raster layers then depicted the SC suitability across different years within the established European boundaries.


Figure 8: Map of Europe showcasing the geographical boundaries used for the research analysis in QGIS [*brittanica.com*].

## 3.4. MODEL VALIDATION

Next up, a mechanism to evaluate the credibility of the developed model was created. This is a fundamental step in any scientific study, to ensure that the outcomes of the model align with real world scenarios and are not just a result of theoretical assumptions or biases. This was done by identifying case studies of historical SC in Europe from existing literature, specifically those that provided a specific location and timeframe (as can be seen in Table 3). For a comprehensive and diverse validation, eight case studies from different European countries were selected. The number of case studies was decided upon considering the balance between depth of analysis and the practical constraints of the research. By juxtaposing these reported occurrences with the SC suitability as suggested by the developed model for the corresponding timeframes, it was possible to evaluate the model's validity. Essentially, if all reported locations of SC for a particular time frame were concurrently shown in the model as suitable for the agricultural practice, this would support the models' validation (or at the very least, it would not invalidate the model).

Table 3: case studies chosen for the model validation, sourced from existing literature.

| **Location** | **Coordinates** | **Timeframe** | **Source** |
|---|---|---|---|
| Udtja, Sweden | 66.8309 N, 20.3992 E | Until 19th century | Hörnberg *et al.*, 2015 |
| Kainuu region, Finland | 64.4865 N, 28.8996 E | Until 20th century | Myllyntaus *et al.*, 2002 |
| Scottish Highlands | 57.1234 N, -4.7117 E | Until 19th century | Otto & Anderson, 1982 |
| Novgorod Oblast, Russia | 58.2581 N, 33.0639 E | Until 19th century | Gerschenkron, 1961 |
| Navarra, Spain | 42.6517 N, -1.5065 E | Not specified | Elósegui & Ollo, 1982 |
| Białowieża Forest, Poland | 52.7082 N, 23.8543 E | Not specified | Hunt, 2020 |
| Siegerland, Germany | 50.7232 N, 8.0704 E | Until 20th century | Sigaut, 1979 |
| Breitenau, Austria | 47.3926 N, 15.4242 E | Until 20th century | Sigaut, 1979 |

## 3.5. ANALYSIS OF RESULTS

The final stage of the methodology involved an in-depth evaluation of the output raster layers generated by the model. This part of the research examined in what ways the suitability of SC evolved over various time periods as projected by the model. The aim was to identify patterns and trends in SC suitability and understand the key drivers behind these changes.

In order to explore the influence of each factor, the proxy parameters within the model were systematically adjusted. The resulting changes in SC suitability of the raster layers allowed for an evaluation of the relative importance of each parameter. This was a critical step in understanding why the observed changes occurred and which parameters contributed the most to these shifts. In essence, the final stage of this methodology entailed much more than just displaying changes in SC suitability over time. It offered a deeper understanding of the dynamics underlying these changes.

This analysis also considered the limitations and uncertainties inherent in historical data and assumptions, aiming to provide a robust interpretation of SC patterns while acknowledging potential uncertainties. This approach enabled the identification of knowledge gaps and areas of further research.

# 4. RESULTS

This section presents the outcome obtained from the model developed in the methodology, following the precise sequence of steps outlined. The research process resulted in a wide array of data and information that offer insights into the evolution of SC practices and its suitability in Europe. In the 'Outcome of Model Validation' subsection, the results derived from testing the developed model against historical case studies are shown and discussed, providing a measure of the model's accuracy and credibility. The following subsection, 'Temporal and Spatial Trends', outlines the shifts and patterns observed in the suitability of SC across different time periods, painting a clearer picture of the evolution of this agricultural practice over time in Europe. The 'Analysis of Proxy Parameters' subsection explores the individual contributions and impacts of each selected proxy to the suitability of SC. Finally, the 'Key Findings and Observation' subsection summarizes the most significant and impactful results that were generated from the analysis.

## 4.1. OUTCOME OF MODEL VALIDATION

As described in the methodology section, a model validation method was implemented to test the SC suitability predictions. After conducting an extensive literature review, eight case studies across Europe, known to have practiced SC in specified years, were selected. These case studies were then plotted on the developed SC suitability maps, which can be observed in Figure 9. By doing so, it could be assessed whether the model correctly identified locations as suitable for SC during the periods reported in the literature. Moreover, by examining these case studies over different time intervals, it was possible to observe if the model's suitability predictions aligned with the actual cessation of the SC practice in these locations.

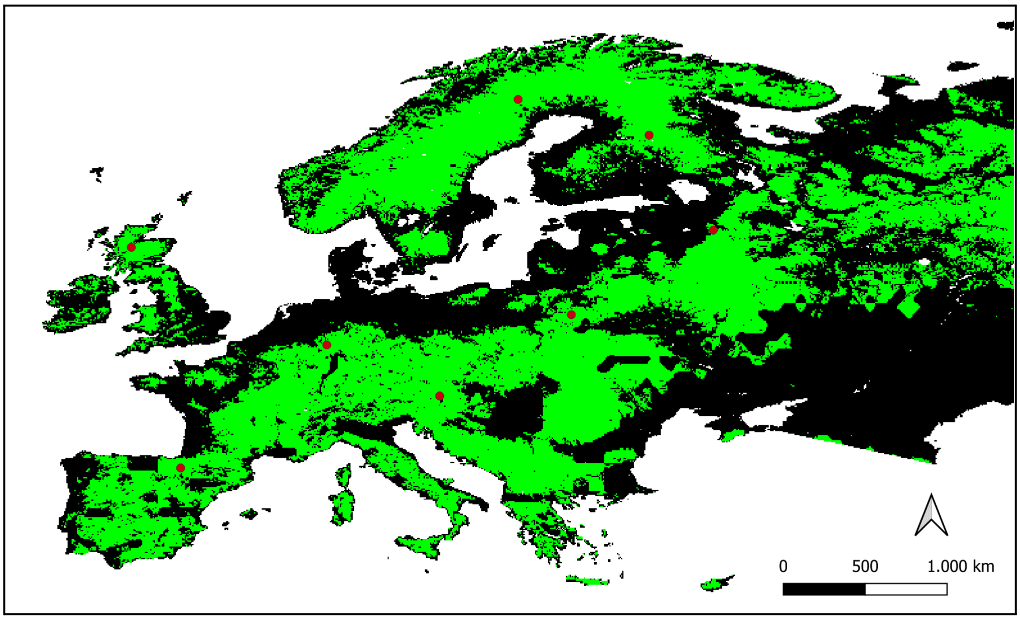


Figure 9: Geographical locations of the eight case study sites for shifting cultivation (red dots), displayed over the 1750 shifting cultivation suitability map of Europe.

For the earliest time-step map, corresponding to the year 1750, all the case study locations fall within the green zones, which the model recognizes as suitable areas for SC. As the temporal scope advances, however, two of these case study locations (namely the Siegerland site in Germany and the Breitenau site in Austria) transition from being suitable for SC to unsuitable according to the model's predictions. This pattern can be observed in figures 10-13:

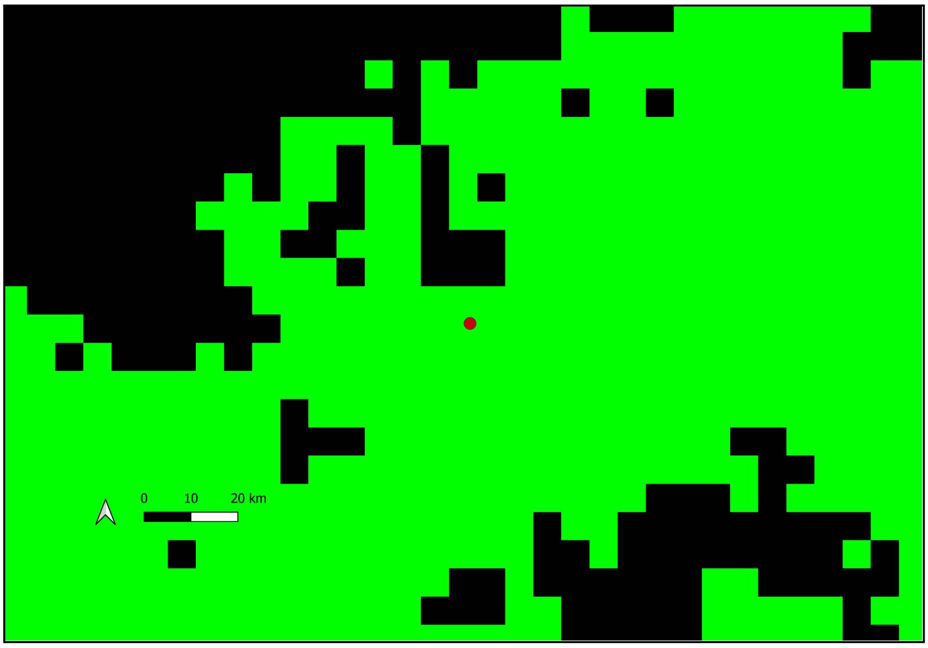


Figure 10: 1750 shifting cultivation suitability map (green = suitable) around the Siegerland case study site (red dot).

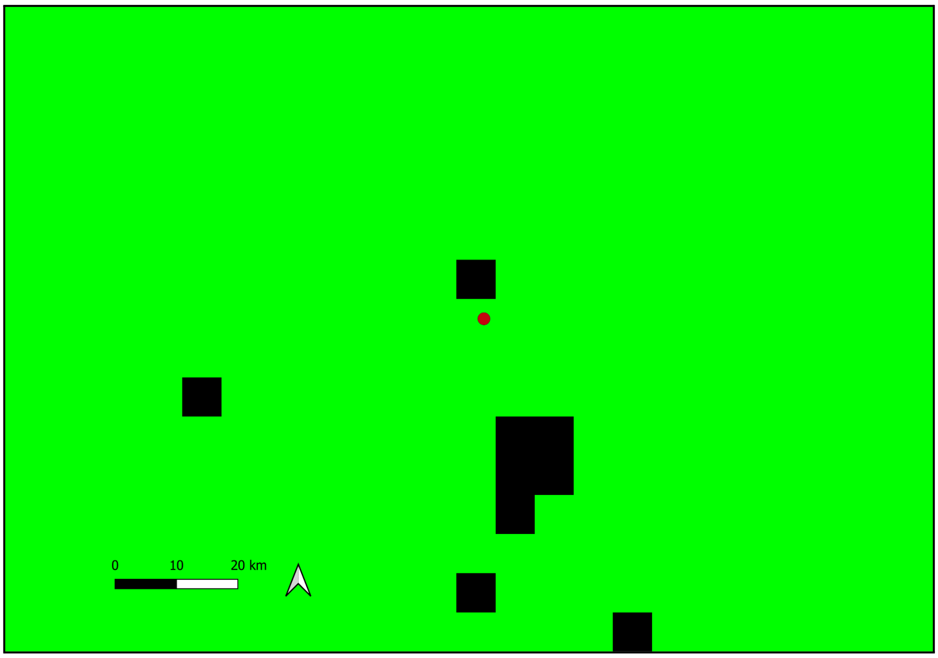


Figure 11: 1750 shifting cultivation suitability map (green = suitable) around the Breitenau case study site (red dot).

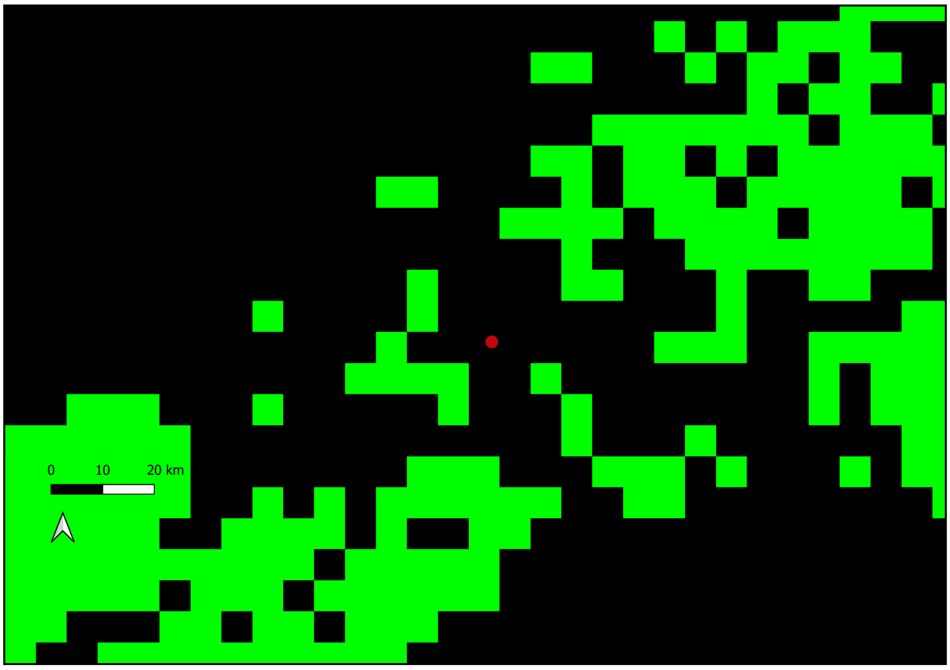


Figure 12: 1900 shifting cultivation suitability map (green = suitable) around the Siegerland case study site (red dot).

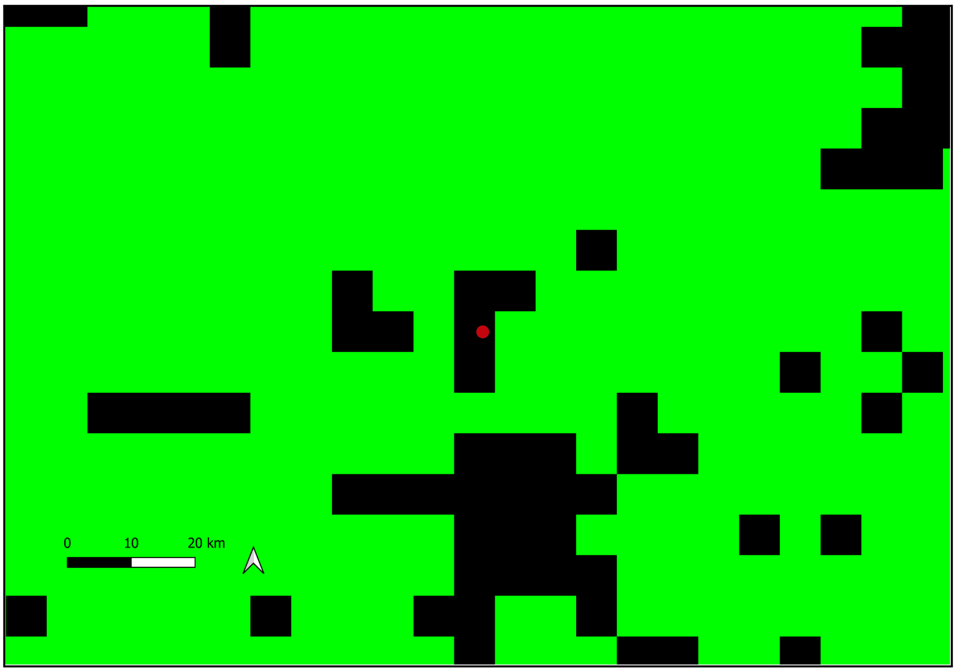


Figure 13: 1900 shifting cultivation suitability map (green = suitable) around the Breitenau case study site (red dot).

These observations present significant findings in terms of validating the model. Not only does the initial model depict all selected case study locations as suitable for SC (as previously mentioned), but it notably tracks the historical trajectory of Siegerland and Breitenau with accuracy. According to reports, these locations saw SC practices phased out by the turn of the 20th century (see Table 3), which is the same time when the model reflects the transition from SC suitability to unsuitability. This alignment between the model predictions and historical data can be considered to confirm the model's accuracy in capturing the evolution of SC suitability in Europe.

However, an aspect that must be considered is that despite the model's accurate predictions for the Siegerland and Breitenau locations, the remaining six case studies continue to be identified as suitable for SC up until 2000. This contradicts the historical records which indicate that SC practices ceased in these areas. This discrepancy most likely reflects external factors not considered in the model that have influenced the cessation of SC in these areas (*e.g.*, economic factors, social factors, or advancements in agricultural methods).

## 4.2. TEMPORAL AND SPATIAL TRENDS

The objective of this section is to examine the mapping of the suitability for SC across Europe. The maps portray the period from 1750 to 2000, with 50 year jumps in between these. This offers a longitudinal (and unique) study on the shifts and fluctuations in suitability, allowing us to understand both the spatial and temporal dynamics. These suitability maps are displayed in the form of a set of raster layers, which have been created by raster calculations from the chosen proxy parameters, using the values displayed in Table 2. For each modeled year, these maps will illustrate how the different geographical regions across Europe vary in terms of their SC suitability.

In this section, two key maps are presented, which were selected to clearly depict the overall shift in suitability, providing a clear before-and-after visualization of the landscape. The first map (Figure 14) shows the initial state of suitability in 1750, around the onset of the Industrial Revolution. The second map (Figure 15) demonstrates the situation in 2000, reflecting the significant shifts that have occurred over this time period. The differences between the two maps underscore the key findings of this study - a noticeable decrease in the areas suitable for SC.

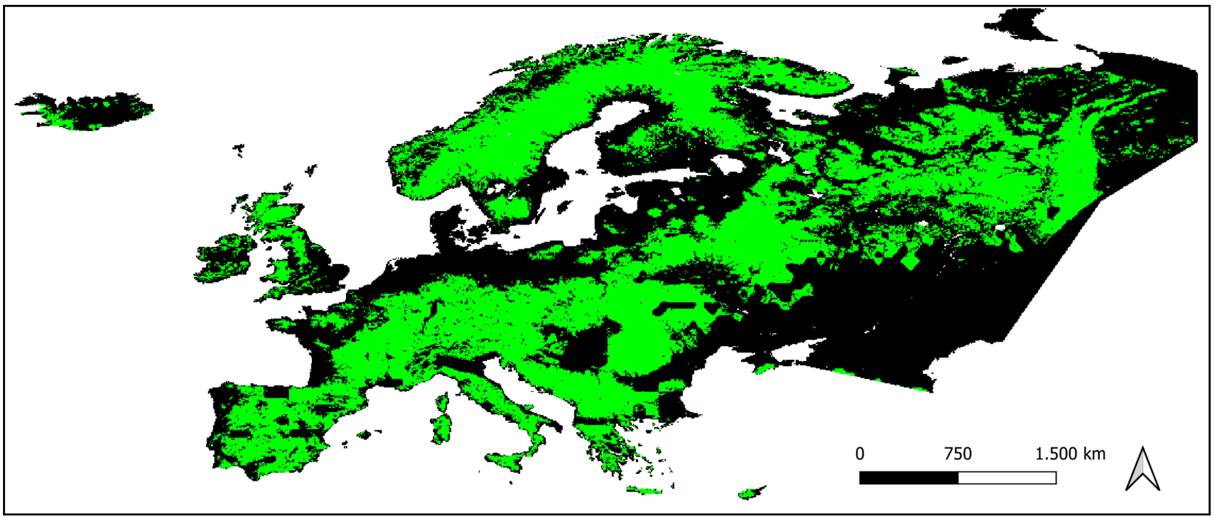


Figure 14: Shifting cultivation suitability map for the year 1750.

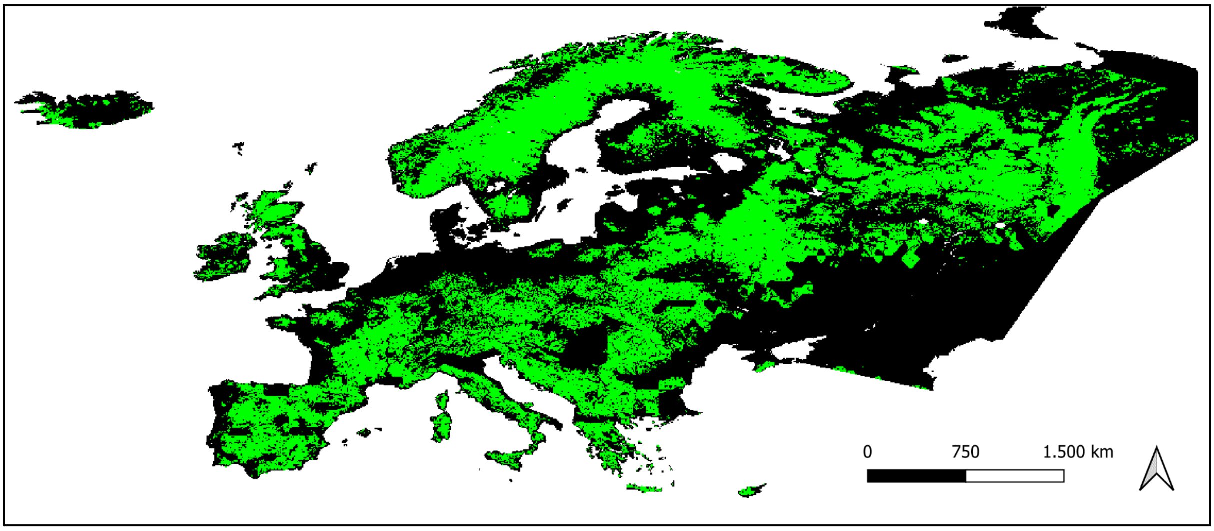


Figure 15: Shifting cultivation suitability map for the year 2000.

It should be noted, however, that the changes did not occur suddenly but unfolded gradually over this period. To grasp these incremental transformations, a series of maps representing the suitability for SC at 50-year intervals is provided in the Appendix. These additional maps offer a more granular view of the changes, although they may not present striking differences when viewed individually.

After visually analyzing this shifting trend, the evolution of predicted SC suitability was then quantified. Applying the *r.report* function within GRASS GIS (Geographic Resources Analysis Support System - an open-source geospatial analysis tool), the decrease in areas suitable for SC in Europe from 1750 up to the year 2000 according to the developed model was calculated. The findings revealed that, in 1750, approximately 44% of the research area was considered suitable for SC. However, by 2000, the percentage of suitable land decreased to approximately 39%. Hence, close to 10% of the area that was suitable for SC ceased to be suitable over a span of 250 years.

This 10% reduction in area deemed suitable for SC was subsequently visualized using a differential mapping technique. By executing a raster calculation in QGIS, the 1750 raster layer was subtracted from the 2000 layer, revealing areas that, according to the model, have lost their suitability for SC over this 250-year period. Figure 16 illustrates this change through a color-coded system. The prevalence of blue dots marks the considerable areas where suitability for SC has ceased, while red dots (although sparse and barely visible) mark a rare increase in suitability during the same timeframe. This contrast serves to effectively visualize the overall trend of suitability reduction for SC in Europe.

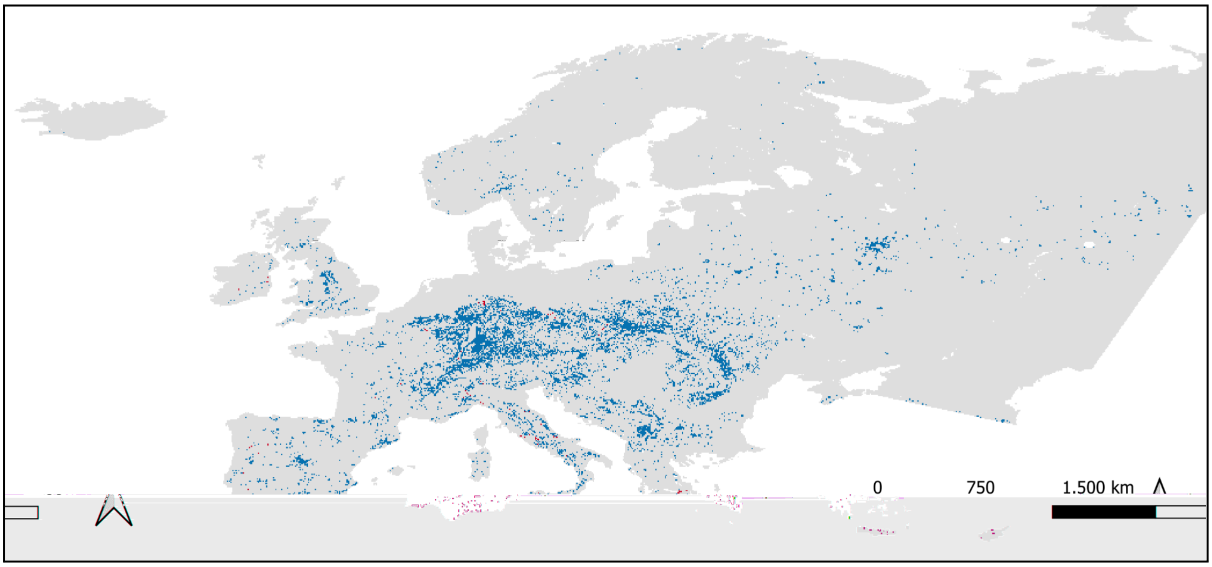


Figure 16: Differential suitability map for shifting cultivation (1750-2000). Blue dots indicate areas where suitability has ceased; sparse red dots represent areas of increased suitability.

## 4.3. ANALYSIS OF PROXY PARAMETERS

An essential aspect of this research is to understand the influence of each chosen proxy (population density, urban built-up area, and elevation) on the SC suitability model. In order to analyze the impact of individual proxies, they were individually adjusted in the model while keeping the other parameters constant. This was done through a series of simple raster calculations on QGIS. This way, the potential influence of changes in a single proxy on the areas identified as suitable for SC could be observed.

The influence of each proxy parameter on SC suitability is unique, which necessitates diverse modifications for their analysis. Specifically, when either population density or urban built-up area exceed a certain threshold, they limit the possibility of SC. Conversely, SC becomes less feasible when the elevation drops below a certain point. Consequently, to address these effects, the population density and urban built-up area parameters were doubled, while the elevation was halved in this analysis.

The fourth proxy, the biome parameter, was handled differently. Given that certain biomes naturally support SC while others do not, it seemed counterintuitive to alter this parameter artificially. Hence, instead of hypothesizing with the biome values, the aim was to understand in what way shifts in the other three parameters influenced SC suitability within the already identified suitable biomes.

The outcomes of these modifications are visualized in Figure 17 to 19. Figure 17 presents the SC suitability map when population density is doubled, referencing the 1750 baseline. Figure 18 showcases the impact of doubling the urban built-up area, while Figure 19 represents the scenario in which the elevation is reduced by half, both compared to the 1750 baseline.

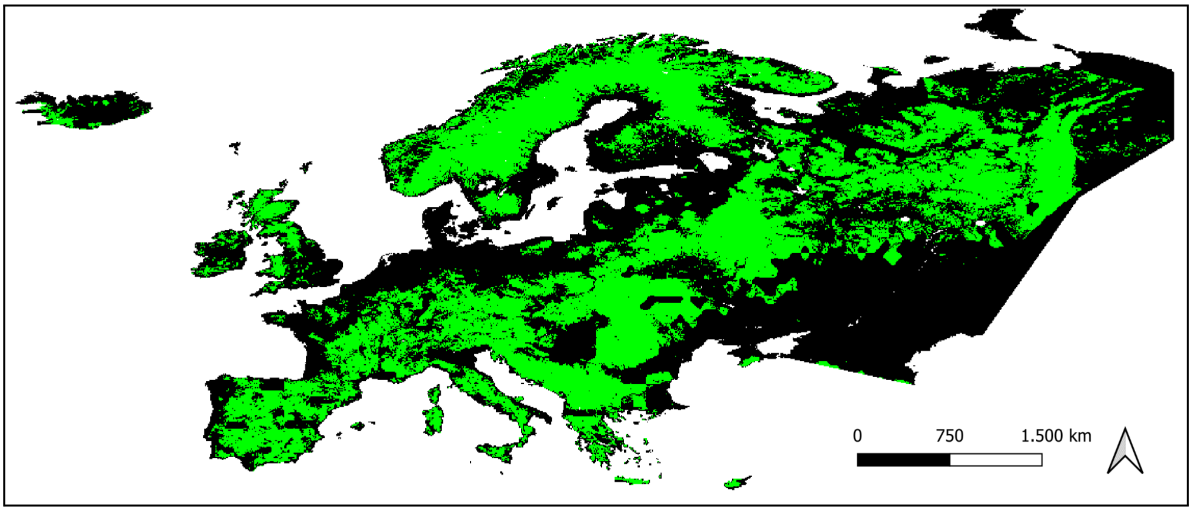


Figure 17: Shifting cultivation suitability map for 1750, with doubled population density values.

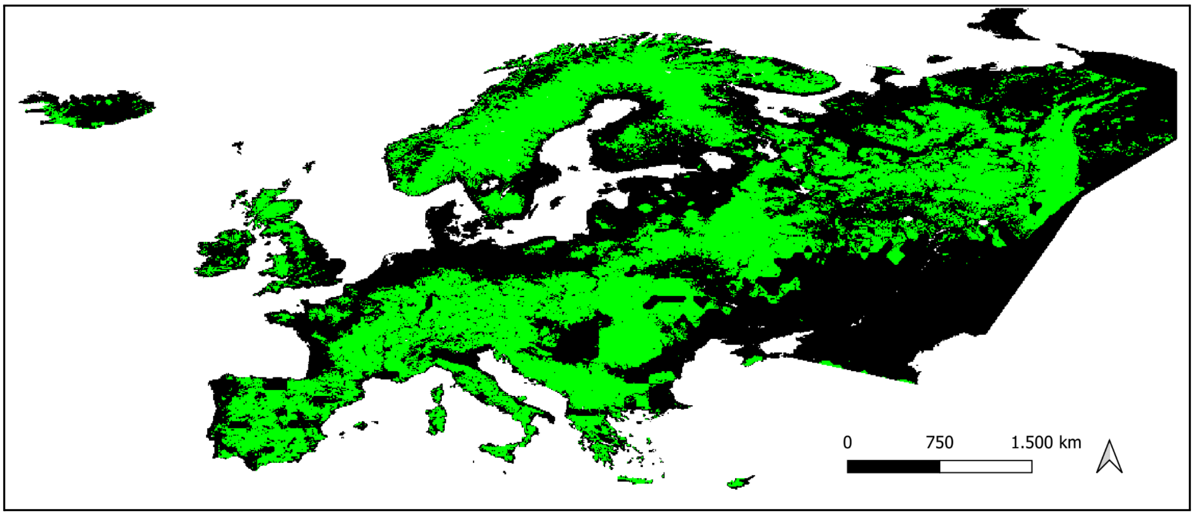


Figure 18: Shifting cultivation suitability map for 1750, with doubled urban built-up area values.

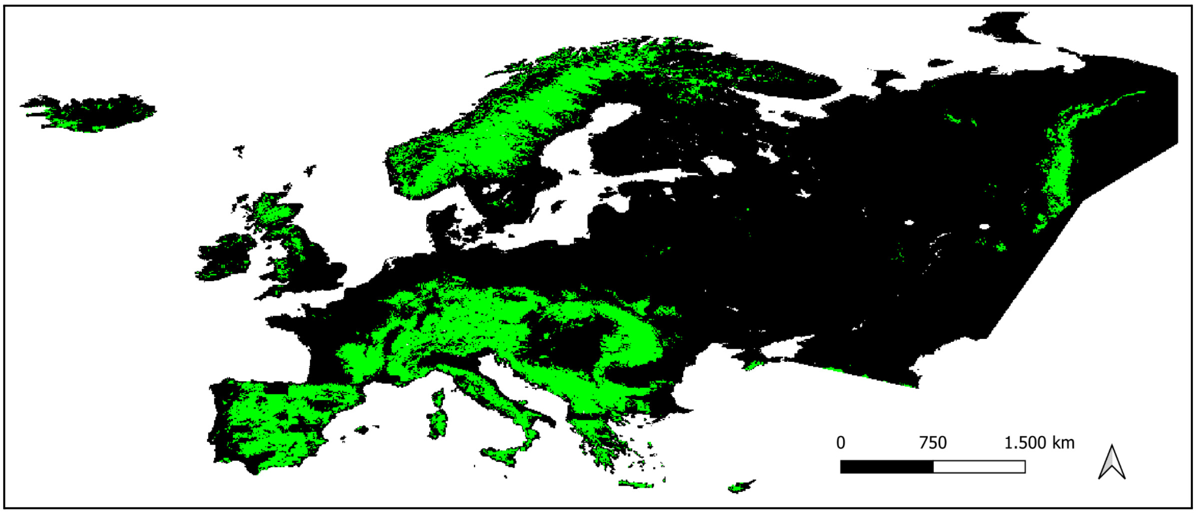


Figure 19: Shifting cultivation suitability map for 1750, with halved elevation values.

Upon adjusting the parameters within the model, distinct variations in SC suitability were observed. Halving the elevation led to the most drastic reduction in suitability, with only 21% of the research area remaining suitable. However, it is crucial to consider that elevation is a fixed parameter that does not change over time, making this exercise more theoretical than practical.

In contrast, when dynamic parameters such as population density and the urban built-up area were doubled, the changes in suitability were more modest. Specifically, the area suitable for SC reduced to 41% when population density was doubled, and 43% when the urban built-up area was doubled. For context, the original 1750 parameters rendered 44% of the area suitable for SC. While these changes are less pronounced than the one observed with the elevation adjustment, they reflect the parameters that are capable of changing over time and thus, can practically influence SC suitability. These adjusted parameter maps can be compared to Figure 14, which portrays the SC suitability in 1750 with unaltered, original parameters.

## 4.4. KEY FINDINGS AND OBSERVATIONS

This subsection presents the key findings and observations derived from the analysis of past SC suitability in Europe. The Analysis revealed a significant decline in suitability over the 250-year study period. Approximately 10% of the areas that were deemed suitable for SC experienced a cessation in suitability, indicating substantial changes in land use conditions and practices across Europe since the Industrial Revolution.

Examining the suitability maps, particularly the differential map showcased in Figure 16, highlighted the spatial distribution of the suitability changes. The most pronounced decrease in SC suitability was observed in central Europe, suggesting a spatially heterogeneous pattern of change. This indicates the influence of specific regional factors and highlights the importance of considering local contexts in understanding SC dynamics.

Furthermore, the influence of the chosen proxy parameters on SC suitability was examined. Elevation emerged as a significant factor, contributing to variations in suitability across different regions. Although elevation cannot be altered in practice, understanding its relevance provides valuable insights into the overall suitability of different areas. Another influential parameter was population density. Changes in this proxy led to noticeable variations in SC suitability, highlighting the role of demographic factors in shaping land use dynamics.

The developed model underwent a robust validation process, which included eight case studies. All locations with reported historical SC occurence classified as suitable for the practice, thus demonstrating the accuracy and reliability of the model. Moreover, for two case study locations, the model correctly identified the cessation of SC, as confirmed by the literature. This validation adds credibility to the model’s results and enhances confidence in its ability to capture SC dynamics in Europe.

# 5. DISCUSSION

## 5.1. INTERPRETATION OF RESULTS

The discussion section aims to delve deeper into the findings of this study, examining the implications, limitations, and broader significance of the results in the context of SC in Europe and beyond. In this research, historical SC in Europe since the Industrial Revolution was modeled using SC suitability maps developed through QGIS. These maps revealed a noteworthy decline in suitable areas for SC over the period from 1750 to 2000, with a decrease of 10% in Europe's overall suitability from 44% to 39% during this 250-year timeframe.

The observed decline in SC suitability across Europe highlights the significant changes that have occurred in the continent over the past couple of centuries. To assess the impact of the selected proxies, each parameter (excluding the biomes) was individually modified to evaluate its influence on the model. The analysis revealed that population density played a crucial role in the observed decrease in suitability, highlighting its significant weight in the model. Elevation was also found to have a considerable effect, although it could not be altered in practice, emphasizing its importance to overall suitability but not specifically to the decrease observed in the study.

Examining the produced SC suitability maps, it becomes evident that the areas experiencing the most pronounced decrease are primarily located in central Europe, where population density is higher. In contrast, regions such as Scandinavia and Russia have shown relatively smaller changes in suitability. This discrepancy can be attributed to the choice of proxies utilized in the model. The increasing population density and urbanization witnessed in Europe since the Industrial Revolution have had a substantial impact on the feasibility of practising SC, as reflected in the model's outcomes.

However, in regions with lower population density and urbanization levels, additional factors have contributed to the decline in SC. For example, studies by Myllyntaus et al. (2002) indicate that SC in Finland largely ceased due to industries privately purchasing forest lands to ensure a steady supply of raw materials. Thus, even if suitable land based on the model's proxies existed, other non-model factors led to the cessation of SC. Historical market integration, as discussed by Vliet et al. (2012), is another example of factors that cannot be computed through QGIS but had a great influence on SC cessation. It is important to note that these factors are however intertwined with the broader industrialization trend observed across Europe during the study period, just like the computed increase in population density and urban built-up area.

## 5.2. LIMITATIONS AND FUTURE RESEARCH

When considering the findings of this study, it is important to acknowledge the limitations and uncertainties associated with the modeling approach and data used. The validation process plays a crucial role in enhancing the reliability and credibility of the model's results by comparing them with real data of reported SC practices. Reflecting on the methodology employed in this study, several strengths can be identified. The use of proxy indicators, such as elevation, biomes, population density, and urban built-up area, along with raster calculations and GIS techniques, has allowed for a comprehensive analysis of SC suitability. These approaches have provided valuable insights into the changes in suitability over time.

However, certain limitations remain. It is crucial to acknowledge that these proxy indicators have inherent limitations and may not capture all the complex factors influencing SC dynamics. For instance, the assumption that each biome is equally suitable for SC may not accurately reflect the varying ecological conditions where specific biomes are more favorable for this agricultural practice. It is hence important to exercise caution when interpreting these results and consider the potential uncertainties associated with the modeling process. Additionally, uncertainties may arise from the quality and resolution of the input data used in the model.

Addressing potential sources of error and uncertainties in the modeling process is essential to ensure the accuracy and reliability of the results. One limitation of the study lies in the availability of proxy indicators that can be computed and incorporated into QGIS. The selected proxies were chosen based on their computability and relevance to SC suitability. However, it is important to mention that other factors, such as market integration or cultural practices, which have been reported to influence SC, could not be directly computed into the QGIS model. Therefore, the model in a way fails to capture all factors that influence SC dynamics, and the results should be interpreted with this limitation in mind.

In terms of future research and methodological improvements, there are several areas to explore. Incorporating additional factors, such as historical climate data, soil characteristics, and cultural factors, can enhance the understanding of SC dynamics and help to better predict its past trends. Moreover, integrating remote sensing data and advanced machine learning techniques can provide more accurate and detailed predictions of SC occurence. Collaborative efforts between researchers, land managers, and local communities can facilitate the collection of reliable data and contribute to the development of more robust models.

## 5.3. IMPLICATIONS

The findings of this study have important implications for land management, conservation, and policy-making. The modeling outcome highlights the need for sustainable land use practices and policies that carefully consider the impacts of population density, urbanization, and industrialization on land resources. It is crucial to acknowledge that SC, when practiced sustainably, allows for the necessary fallow period to restore the land's health and productivity. However, the intensification of population density, urbanization, and industrialization presents challenges in maintaining appropriate fallow periods, leading either to unsustainable SC or to other more intensified forms of agriculture. By understanding the implications of these factors on SC suitability, policymakers and land managers can develop strategies that balance agricultural needs with environmental conservation goals.

The research findings also highlight the broader applicability of this study beyond Europe. Developing tropical countries still remain highly reliant on SC, with Heinimann *et al.* (2017) estimating that SC landscapes currently cover around 280 million hectares worldwide. Hence, these can benefit from the insights and methodology presented in this research. By understanding the potential changes in SC suitability in these regions, efforts can be directed towards sustainable land management practices and the development of policies that promote a harmonious relation between agricultural practices and environmental conservation. Ultimately, the aim is to achieve sustainable development and ensure the preservation of vital land resources for future generations. By integrating the findings of this research into land management practices and decision-making processes, we can strive towards more sustainable and resilient land use systems worldwide.

# 6. CONCLUSIONS

This study aimed at answering the following two questions: How can we model the potential locations and extent of shifting cultivation in Europe from the Industrial Revolution to the present using proxy indicators? How and why have the potential locations and extent of shifting cultivation in Europe changed over this period according to the developed model? By analyzing the findings of this research and addressing the research questions, several key conclusions can be drawn.

Firstly, the developed model successfully utilized proxy indicators within the QGIS framework to assess the potential locations and extent of SC in Europe. By integrating variables such as population density, elevation, biomes, and urban built-up area, the model provided valuable insights into the suitability of different regions for SC. This modeling approach, facilitated by QGIS, allowed for a comprehensive assessment of SC dynamics over time, capturing the interplay between various factors influencing the suitability of land for this agricultural practice.

The findings of this study reveal a significant decline in the potential extent of SC in Europe over the studied period. The model demonstrates a decrease in suitability by approximately 10%, indicating the impact of various socio-economic changes on land use patterns. Notably, alterations in population density emerged as a highly influential factor driving these changes. The increasing population density, along with urbanization and industrialization in general, have resulted in a decreased feasibility of practicing SC in Europe.

Elevation was identified as another important factor influencing SC suitability, although it obviously remained static over time. The model demonstrates that certain regions, particularly those in central Europe with higher population density, experienced the most pronounced decline in SC suitability. In contrast, areas such as Scandinavia and Russia exhibited relatively smaller changes in suitability, highlighting the influence of additional factors beyond population density and urban built-up area. These factors, such as market integration and private industrial land acquisitions, have been reported to contribute to the decline in SC in these regions.

It is essential to highlight that the model captures the potential suitability of areas for SC rather than providing precise locations. This limitation emphasizes the need for further research to consider non-computable factors (*e.g.*, cultural factors) which are known to influence SC dynamics. Remote sensing data and advanced machine learning techniques could further advance this research as well, contributing to a more comprehensive understanding of SC dynamics in Europe.

The research findings are significant in the fields of land conservation, management, and policy-making. By modeling the decline in SC across Europe, this study sheds light on the complex dynamics existing between human activities and the environment, particularly the impact of industrialization and associated changes on land resources. Moreover, the results emphasize the urgency of adopting sustainable land use practices and policies that account for future trends, including population density and urbanization growth. These findings underscore the importance of aligning land management strategies with the imperative of sustainable development.

Lastly, the relevance of this study extends beyond Europe. As SC remains prevalent in developing countries, the findings emphasize the global significance of this topic in the context of land management and sustainability. It is plausible to predict a parallel decrease in SC in developing nations, mirroring the European trajectory observed in this research. By understanding the potential changes in SC suitability in these areas, policymakers and land managers can develop strategies that promote sustainable land use practices, balancing agricultural needs with environmental conservation goals.

In conclusion, this study successfully models the potential locations and extent of SC in Europe using proxy indicators. The findings highlight the decline in SC suitability, driven primarily by population density, urbanization, and industrialization. The study provides valuable insights into the interplay between human activities and land use dynamics, emphasizing the need for sustainable land management practices and policies. Furthermore, the broader applicability of this research highlights its relevance in addressing land management challenges and promoting sustainability globally.

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# 8. APPENDIX

## 8.1. RASTER CALCULATIONS

The raster calculation formula, referred to in section 3.3, was as follows (for the year 1750):

```
("elevation3x3_modified@1" > 125) * ("popd_1750AD@1" < 100) * ("uopp_1750AD@1" <
1) * (("biome_cr_final@1" = 3) + ("biome_cr_final@1" = 4) + ("biome_cr_final@1" = 5) +
("biome_cr_final@1" = 6) + ("biome_cr_final@1" = 7) + ("biome_cr_final@1" = 8) +
("biome_cr_final@1" = 11))
```

In this formula, "elevation3x3_modified@1" is the georeferenced EUDEM elevation dataset, "popd_1750AD@1" and "uopp_1750AD@1" are HYDE's population density and urban built-up area datasets, respectively, and "biome_cr_final@1" is the biome dataset by Prentice *et al.*. The HYDE files used variate per year. For instance, when calculating the raster layer for shifting cultivation suitability for the year 1800, the used HYDE files were "popd_1800AD@1" and "uopp_1800AD@1".

## 8.2. INTERMEDIATE SUITABILITY MAPS

The following maps (Figures 1-4) display the SC suitability for the years 1800, 1850, 1900, and 1950. They offer a closer look at the gradual changes that occurred throughout this 150-year span. Although these transitions might not be strongly evident in these individual maps, they contribute to the overall trend observed from 1750 to 2000, as discussed in section 4.2.

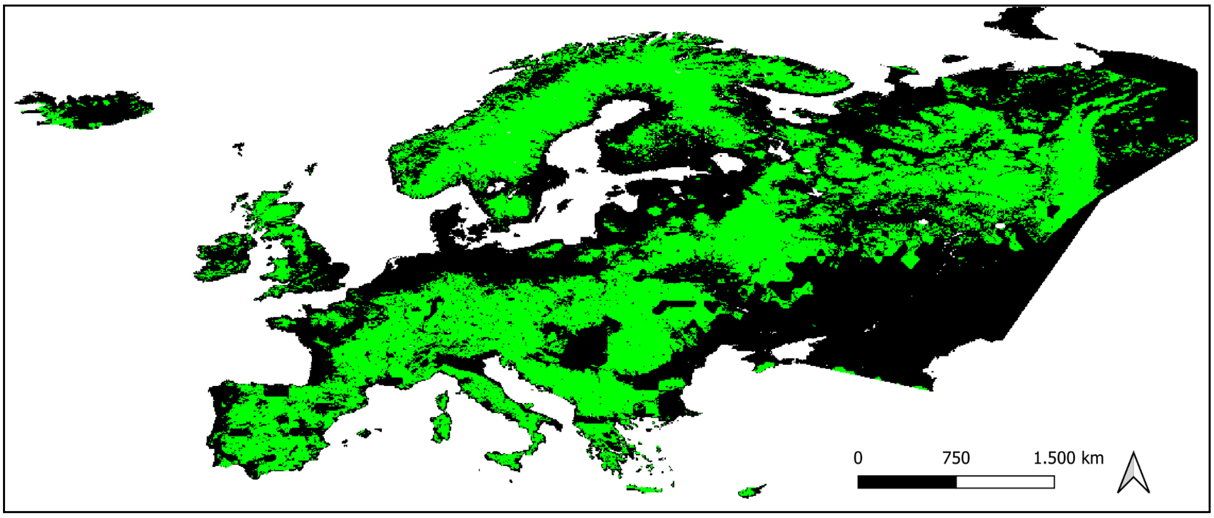


Figure 1: Shifting cultivation suitability map for the year 1800.

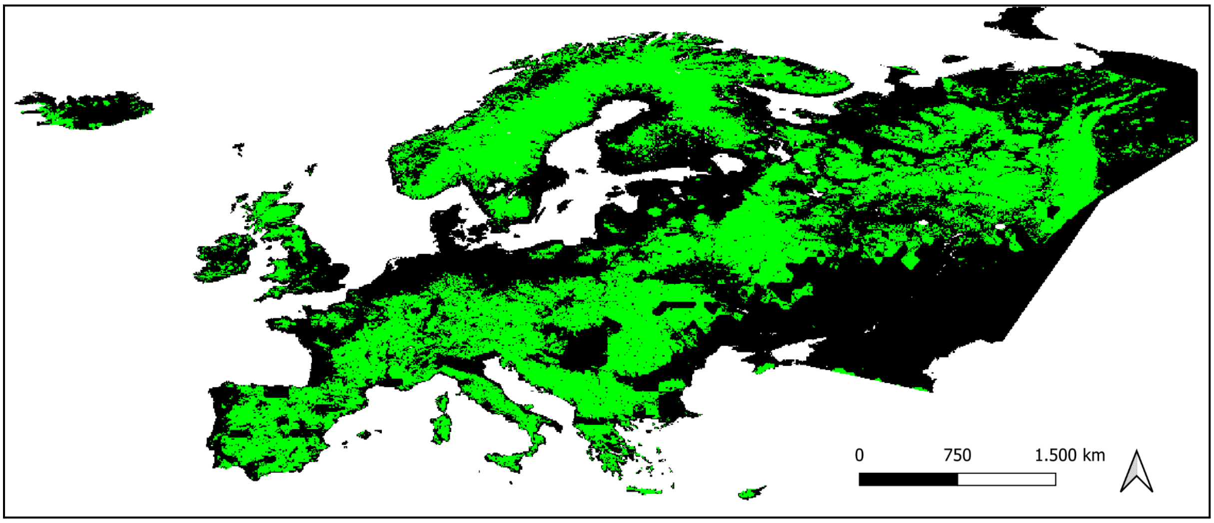


Figure 2: Shifting cultivation suitability map for the year 1850.

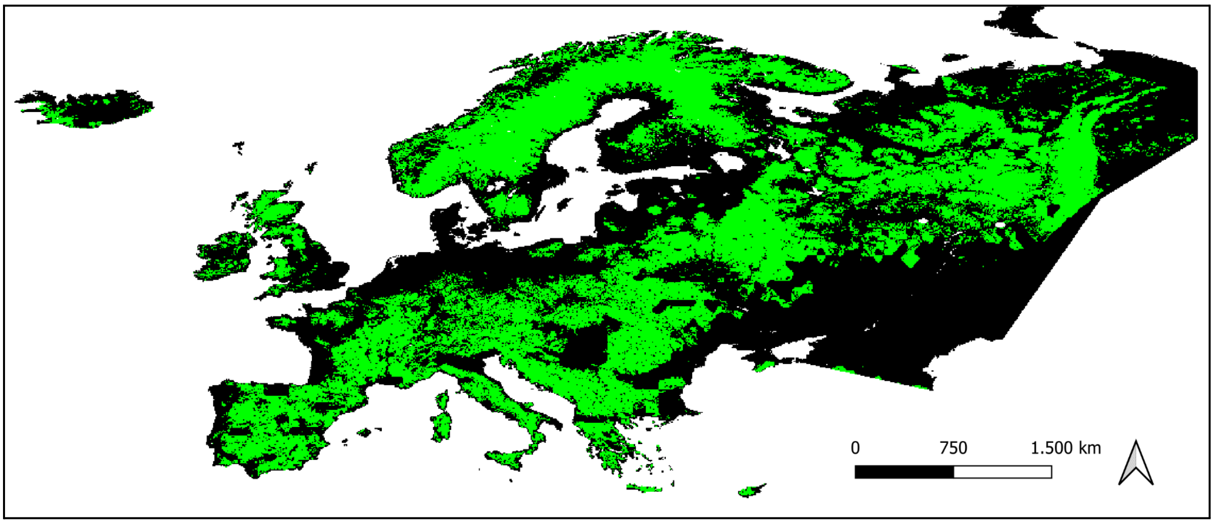


Figure 3: Shifting cultivation suitability map for the year 1900.

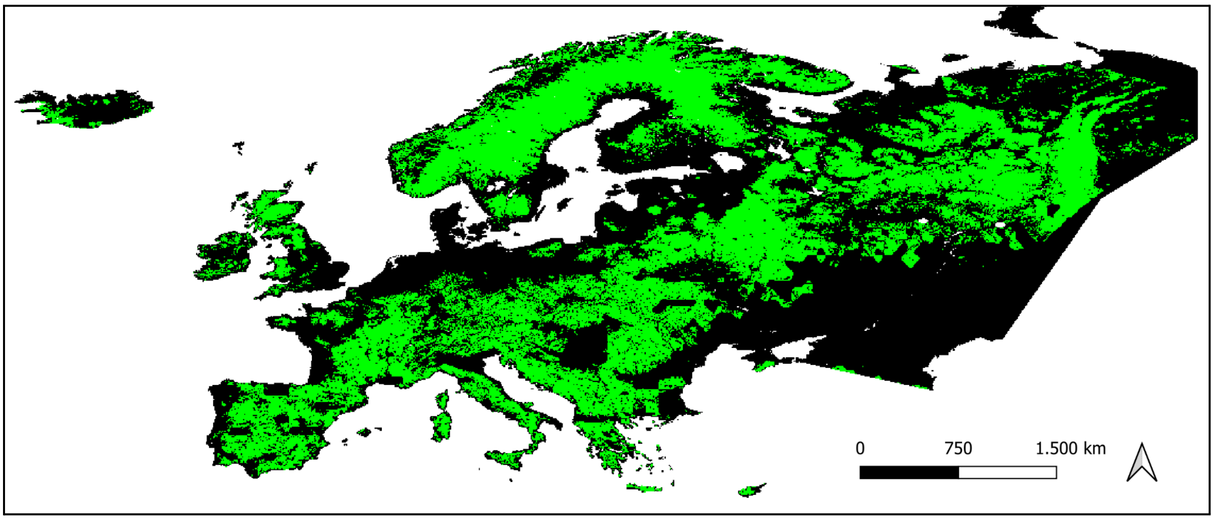


Figure 4: Shifting cultivation suitability map for the year 1950.