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The Role of Biochar and Peatlands in Reaching Swiss Net Zero

IN COLLABORATION WITH MYCLIMATE

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Executive summary

This study aimed to build a consistent and robust methodology to obtain the Swiss biochar production capacity from sustainable biomass potential at the communal level on one part, and on the other part a consistent, robust and configurable model to assess current and future peatlands' GHG emissions at the communal, cantonal or national scale, with the emissions savings that a given rewetting scenario would represent compared to a baseline scenario.

With the objective of learning about crucial research topics in the context of climate change, this work sets the general framework where biochar production and peatlands renaturation lie, by exploring the historical, socio-economic context, and scientific phenomena behind these topics.

It was revealed that biochar production from sustainable biomass potential could contribute to the Swiss Long Term Climate strategy by providing 2 Mt CO_2eq of negative emissions per year if properly deployed toward 2050, 40% of the remaining Swiss emissions at this time. In addition, the emission of 125'000 t CO_2eq per year could be avoided from raised bogs, until generating 50'000 t CO_2eq/yr of negative emissions. Those potentials respectively rise to the avoidance of 800'000 t CO_2eq/yr with a possible generation of 200'000 tCO_2eq/yr of negative emissions for Scope 2 (all identified organic soils), and the avoidance of 4 Mt CO_2eq/yr with a possible generation of 1 Mt CO_2eq/yr of negative emissions for scope 3 (all non-localised potential organic soils).

The costs required to achieve these potentials reach several billions, but such an investment is not unprecedented in Swiss history. Reaching those potentials could be game-changing, since it implies societal transitions such as a profound modification of our land use, going with a change of diet and behaviour.

These estimations were obtained by the creation of two databases, of biomass potential and organic soils, and two models to transform these two databases into GHG emissions potentials.

The model OSMOSE developed in this project computes the emissions resulting from the rewetting of organic soils in Switzerland according to a set of configurable parameters. Such a model could be useful for communes, cantons, or even the Federal Office of the Environment, to identify organic soils emissions on their territories and include in their respective Climate Plans an order of magnitude for the emissions reduction potential resulting from their rewetting. It could also be useful to businesses working on the trade of carbon credits from nature-based solutions on the voluntary carbon market to identify the most promising projects of renaturation.

While wetlands are classified as "unproductive vegetation", this thesis invites to redefine the notion of productivity itself with a systemic approach. It emphasizes that the habitability of Earth is due to ecosystems, not to humans, and that ecosystem services are guarantors of human well being in socio-ecological systems. Nature based Solutions tend to restore them with climate, biodiversity and food sovereignty co-benefits that could allow Switzerland to thrive and appear as a leading example for the ecological transition the world needs.

Keywords : Negative emission technologies, nature-based solutions, carbon capture and sequestration, CO_2 monitoring, environmental economics, climate policies, biochar, Organic soils, Peatlands wetlands, ecosystem-based mitigation.

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Acronyms

BC	Biochar
BECCS	Bio-Energy Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CDR	Carbon Dioxide Removal
$CO_2 eq$	Equivalent carbon dioxide
DACCS	Direct Air Carbon Capture and Storage or Direct Air Capture
GHG	GreenHouse Gas
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LUC	Land-Use Change
NDC	Nationally Determined Contributions
NET	Negative Emissions Technologies
NE	Negative Emissions
FOEN	Federal Office of the Environment
PyCCS	Pyrogenic Carbon Capture and Storage
SCS	Soil Carbon Sequestration
SRM	Solar Radiation Management

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"Là où le sol s'est enlaidi, là où toute poésie a disparu du paysage, les imaginations s'éteignent, les esprits s'appauvrissent, la routine et la servilité s'emparent des âmes et les disposent à la torpeur et à la mort. Parmi les causes qui, dans l'histoire de l'humanité ont déjà fait disparaître tant de civilisations successives, il faudrait compter en première ligne la brutale violence avec laquelle la plupart des nations traitaient la terre nourricière. Ils abattaient les forêts, laissaient tarir les sources et déborder les fleuves, détérioraient les climats, entouraient les cités de zones marécageuses et pestilentielles; puis, quand la nature, profanée par eux, leur était devenue hostile, ils la prenaient en haine, et, ne pouvant se retremper comme le sauvage dans la vie des forêts, ils se laissaient de plus en plus abrutir par le despotisme des prêtres et des rois."

Du sentiment de la nature dans les sociétés modernes - **Elisée RECLUS, 1886**

Introduction and Research Questions

Context

The Working Group III contribution to the IPCC Sixth Assessment Report highlights that global GHG Emissions must peak in 2025, before significantly decreasing to have a chance to limit global warming to an average temperature increase of 1.5°C above pre-industrial levels [1]. 8 month earlier, the Working Group I contribution clearly stated that the remaining carbon budget to remain under this objective is around 300 Gt CO_2eq for a likelihood of 83% [2]. Yet current annual GHG emissions are around 55 $GtCO_2eq$ [3] and, among them, the annual CO_2 emissions represent approximately 40 Gt, which implies that this budget can be exceeded in a time frame of 7-8 years, unless we drastically reduce our emissions and start removing carbon of the atmosphere in this very short period.

Already in 2018, the IPCC Special Report for a Global Warming of 1.5°C painted an ambitious picture of what efforts to limit climate change should look like [4]. In addition to the emissions reduction through the development of clean energy, the increase in efficiency in all sectors and processes, and the development of sobriety, sufficiency and change in behaviours, all scenarios to reach Net Zero Emissions converge toward the need to capture carbon and create negative emissions thought Carbon Dioxide Removal, whether the approaches considered are technological or based on ecosystems. However, it is clear that the extremely short time windows to act limits the role of technologies still in the Research and Development phase, as Carbon Capture and Storage [5]. Besides, limiting the climate crisis we are heading towards to the only issue of CO_2 emissions would put aside the biodiversity crisis that questions the very foundations of the life support system on Earth.

Thus, using Nature-Based Solutions as Negative Emissions Technologies offers promising approaches to have a quick and meaningful impact on climate change mitigation and adaptation. It is increasingly recognised that the restoration of ecosystems, in addition to create resilience by protecting ecosystem services crucial for human well-being as one many co-benefits, presents potentials to biologically remove carbon dioxide from the atmosphere. Those climate actions could immediately be implemented as most of the knowledge needed to do so is already known.

Nowadays, Switzerland still emits 50 Mt CO_2eq per year on its territory, but if quick actions, policies and economic measures are undertaken, it could play the role of a leading example in this field. Even with an ambitious plan to decrease the national emissions by more than 90 % until 2050 to fulfil the Paris Agreement [6], it recognized that the emissions of 10-12 Mt CO_2eq are incompressible and considered as difficult to remove. A part of it could be captured before reaching the atmosphere thanks to CCS, but the realistic potential of these technologies could cover only 5 Mt CO_2eq per year if fully developed in time [7][8]. The remaining emissions need to be compensated by negative ones, and Switzerland understood it by giving a important role to Negative Emissions Technologies in its Long-term Climate Strategy, as represented in the following Figure.

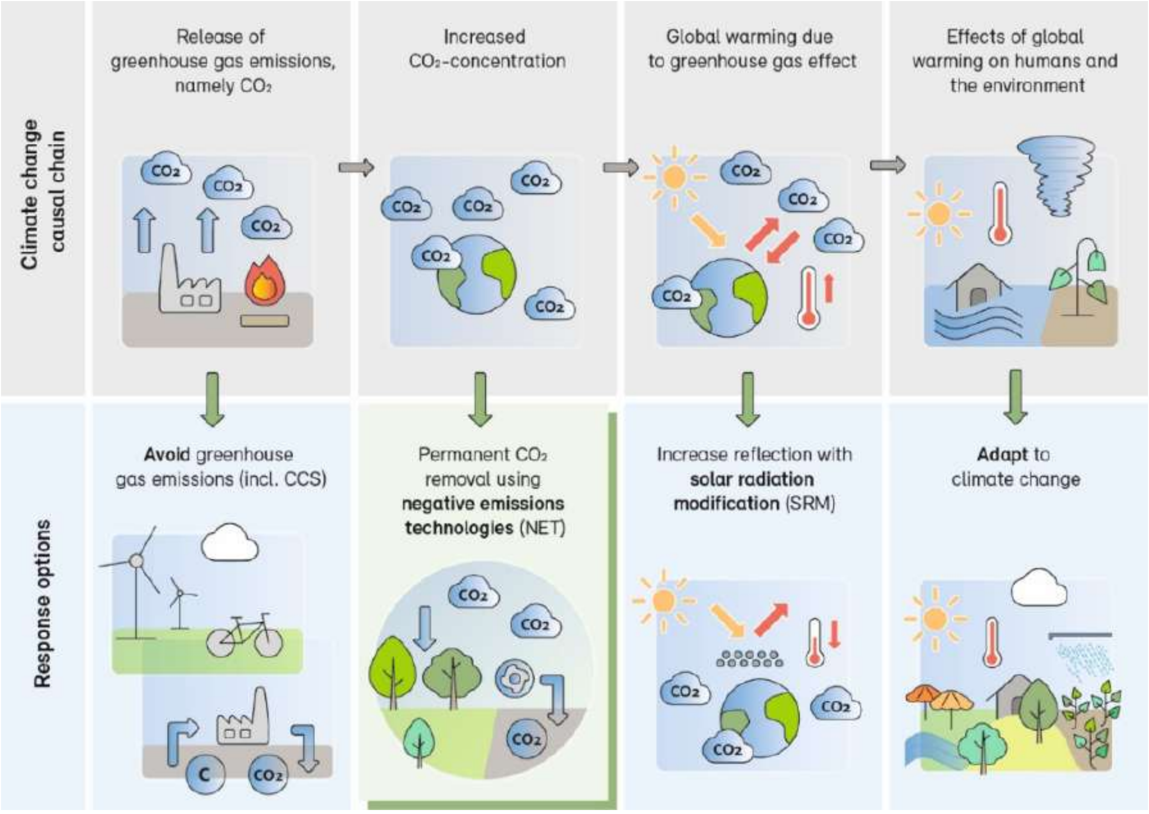


Figure 1: Switzerland possible responses along the climate change causal chain. Source: FOEN illustration based on Jan C. Minx et al., 2018 [9]

However even if the importance of NETs has been recognized by the Swiss Confederation, it is still unclear how they will be implemented. For now, current information on it remains vague and mainly focused in planning emissions off-settings abroad and developing Bio-energy Carbon Capture and Storage (BECCS) by giving a central role to biomass in the energy production, even if the technology readiness level of this approach is still very low and would need further years and research and development.

Research Questions

This thesis explores two nature-based approaches that could play a fundamental role in the Swiss Climate strategy, which are still too little known today.

The first one is the production of biochar through Pyrogenic Carbon Capture and Storage (PyCCS), which is based on the fact that the biomass removes carbon dioxide from the atmosphere to grow as one of its natural biological functions, and could be transformed in a stable and persistent form of charcoal that would prevent carbon to be mineralized and released back into the atmosphere. This approach seems interesting since Switzerland has an important biomass production potential and biochar is a valuable product for agriculture, construction or urban application. This could ensure a rapid deployment since evidence shows that the biochar market is fast growing[10].

The second one concerns the restoration of peatlands in our territory. Peatlands are ecosystems that provide a biodiversity hub, and represent net carbon sinks by permanently storing carbon in the form of organic matter under natural conditions that prevent its decomposition. But this statement is true if and only if they are in good health, which is not the case today. Switzerland lost more than 90% of the peatlands historically present on its territory [11], and more that two thirds of the remaining ones are drained in such a way that transform them into direct and important carbon sources, instead of sinks.

Therefore, the research question posed is as follows: **"How could biochar and peatlands renaturation contribute as effective climate actions to allow Switzerland to reach Net Zero by 2050?"**

This initial question led to the exploration of the topics of biochar and peatlands in the context of Switzerland. After a first exploration phase to identify research gaps, more detailed questions were defined for both research topics.

Regarding biochar, the aims of this thesis were to answer to the interrogations:

- What is the current state of the biochar industry in Switzerland?
- How much biochar could be produced from biomass in a sustainable way on Switzerland's territory?
- What needs to happen for biochar to become scalable in Switzerland?

And the peatlands renaturation topic was declined as the following:

- How much carbon has been lost from organic soils in Swiss Wetlands since the pre-industrial age?
- How and how fast can the current losses be stopped, and the carbon sink potential of peatlands be restored ?
- What needs to happen for peatlands renaturation to become scalable in Switzerland?

Structure of the thesis

After presenting the methodology used throughout this project, this report aims to present the results of the research in 3 different parts

The first one entitled "*Understanding the context*" aims to present in which environment the proposed solutions are rooted, as a way to reveal the relevance of both of them. This part is the result of an exploratory approach based on literature review, semi-structured interviews of experts and a field visit.
A second part will deeply dive into the presentation of the solutions, to precisely understand what they consist of, and how important is the potential they offer in terms of emissions reduction or removal. This section gives official definitions and presents the models developed.
Finally a third part, named "*Implementing the Solutions*", acts as a cost and barrier analysis to understand what it would take in terms of resources for Switzerland to deploy the solutions and concretize the potentials developed in the previous part.

The thesis ends on the critical discussion of the results presented, and recommendations for future researches, as possible continuations to this project, or important gaps identified in the literature.

Methodology

This section outlines the approaches taken to formulate and attempt to answer the research questions previously presented. These approaches range from the construction of the research plan, through the collection and processing of qualitative and quantitative data, to the development of Greenhouse Gases emissions estimation models.

Construction of the research plan

The construction of the research plan for this thesis was carried out in an iterative and inductive manner. The methodology used to refine the research questions was inspired by qualitative social sciences research, allowing for both the collection of qualitative data to gain general knowledge on the topics of nature-based solutions, biochar production and peatlands renaturation, and the identification of relevant research gaps to be explored thanks to interviews of stakeholders working in these fields. Thus, the approach used to define the research questions is very similar to the one described by Giroud and Tremblay, 2009 in their work entitled "Methodology of Humanities 3rd ed" [12], represented by the following figure.

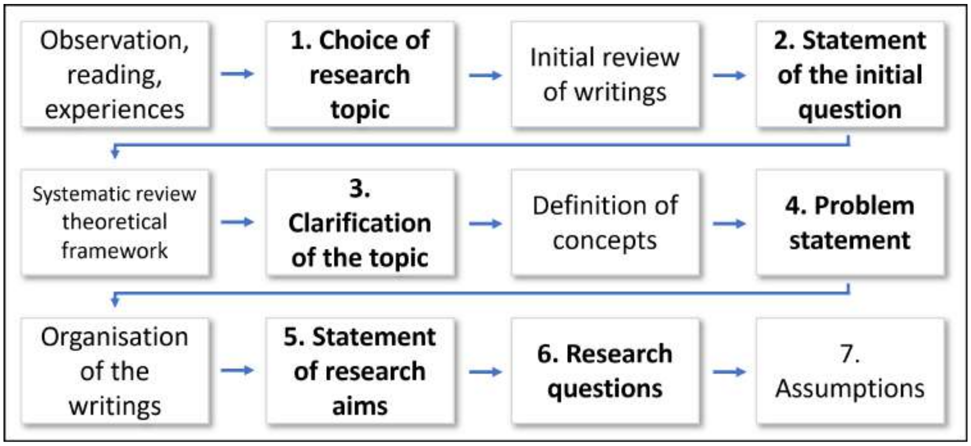


Figure 2: Research plan construction diagram. Adapted from Giroux and Tremblay 2009, Methodology of Humanities 3rd ed. [12]

This approach is close to Grounded Theory Methods -GTM-, which is a systematic method to build a theoretical analysis rooted in the reality of data. It is designated as inductive since it consists of collecting and analysing data simultaneously. Therefore, there is a progressive elaboration of the research object, following an iterative approach, which allows the research subject to be flexible and to adapt to unforeseeable developments in order to gain in relevance.

The choice to focus the research topic on Nature-based Solutions as Negative Emissions Technologies was induced by the following observation : technical approaches explored so far present limitations that allow to reasonably conclude they could not be sufficient to lead Switzerland to achieve Net Zero by 2050 [7]. Previous work on Carbon Capture and Storage technologies both in the Global and Swiss contexts, was also heading in this direction [8].

After having refined the topic to the two NbS most adapted to the Swiss context to achieve carbon removal for the initial question, namely biochar production and peatlands renaturation, a qualitative data collection was needed to clarify the research objectives. Therefore, in parallel to the literature review, a series of semi-structured interviews with experts was conducted.

A semi-structured interview is a data collection method that relies on asking questions within a predetermined thematic framework, in this case, the possible deployment of biochar production and peatlands renaturation in the Swiss context. This process is often qualitative in nature, since it consists of a mix of structured and unstructured interviews. While a few questions are predetermined, the others are not planned, and they are not necessarily set in order or in phrasing. This type of interviews is generally used as an exploratory tool in social sciences, survey methodology, and other research fields. The objectives affiliated to this series of interviews were the following :

- Gain general knowledge on the research topics
- Identify relevant stakeholders for the Swiss context
- Collect relevant sources of data (white papers, peer-review articles, quantitative data)

The sampling of the candidates to be interviewed follows a non-probabilistic approach : the choice of the target is well thought out, the participants are experts in their fields according to the length of their experience and their practical or theoretical knowledge.

The design of the questions and the conduct of the interviews needed to carefully avoid possible biases, such as inducing assumptions in questions or discussions follow-ups, changing environmental conditions, or a too expressive body language. The complete set of questions used as a red thread for the discussion is available in the Annex VIII. Most of the interviews happened remotely through video conferencing software as Zoom or Microsoft Teams, for a duration between 45 minutes and 2 hours, in English or in French. While conducting the interviews, a simultaneous written transcription was carried out to later proceed to a thematic inductive analysis during the cleanse of the text. The information gathered was then translated in English and synthesised in a Spreadsheet.

The two desired final outputs of the interviews are a SWOT analysis to identify the Strengths, Weaknesses, Opportunities and Threats related to the implementation of biochar production and peatlands renaturation, but also a Stakeholders map summarising the whole process.

As a complement of the literature review and the semi-structured interview, a guided field visit in the peatlands of Ponts-De-Martel was organised to have a better understanding of the issues and the reality on the ground.

Data gathering

The analysis performed in this thesis required the collection of the following quantitative data :

- Biomass potential for biochar production
- Conversion factors to compute negative emissions via biochar production from sustainable biomass sourcing (Energy content conversion factors, Pyrolysis Yield, Carbon content, Biochar Persistency rate)
- Organic soils and peatlands geospatial data
- Emissions factors to convert surface areas into avoided and negative emissions potentials.

Biochar Production from Biomass Potentials

The WSL study from 2017 "*Potentials of domestic biomass resources for the energy transition in Switzerland*"[13] and Dr. Vanessa Burg's publication from 2019 "*Analyzing the potential of domestic biomass resources for the energy transition in Switzerland*"[14] offer the following data :

- **At the national level:** the Theoretical Potential, Ecological restrictions, Techno-economics restrictions, Sustainable potential, already-used potential, and additional sustainable potential; for 10 different sources of biomass, in Fresh mass, Dry mass, and Energy Content.
- **At the cantonal level :** the Theoretical Potential and Sustainable potential, for 10 different sources of biomass, in Energy Content.

Dr. Vanessa Burg personally shared the following data set :

- **At the communal level** : the Theoretical Potential and Sustainable potential, for 10 different sources of biomass, in Energy content, in absolute values and normalised per area.

The different terms previously used to describe the different biomass potentials come from the WSL methodology to classify the biomass categories and types of potentials, as explained in the Figure 3. There are 10 different categories of biomass, 4 woody biomass and 7 non-woody, declined in 4 potentials types and various restrictions.

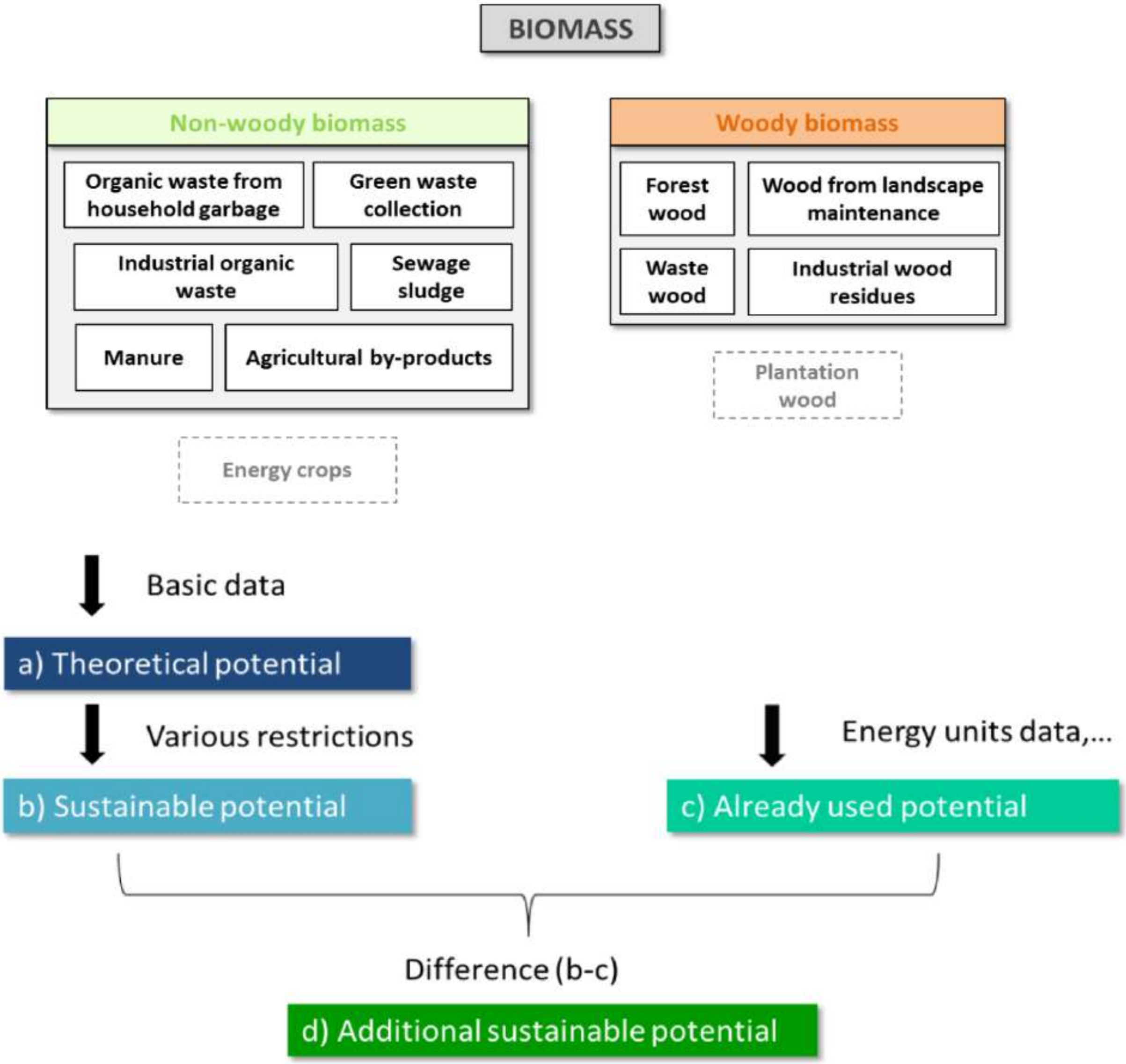


Figure 3: Description of the 10 biomass types and different potentials from WSL 2017 [13]

Peatlands renaturation

The two main types of data involved are geospatial data to express the area, location and current land use of peatlands in Switzerland, and emissions factors to parametrize the model.

Geospatial data were obtained from the following inventories:

- Raised bogs inventory : A wetland inventory gathering 8'025 parcels covering 5'663 ha and representing 551 objects of national importance with their location, area, state and type of vegetation, according to the related ordinance RS 451.32 on the "Haut-marais et marais de transition" [15].
- Fens and marshes inventory : A wetland inventory gathering the 1'335 objects of national importance, peat-forming or not, covering 22'502 ha, with their location and area, according to the related ordinance RS 451.33 on the "Bas-Marais" [16].
- FOEN's "Bas-Marais" partial objects data set : a collection of 11'195 parcels covering 26'305 ha and representing 3'674 objects, fens of national importance or not, peat forming or not, with their location, area and types of vegetation.
- Mire area inventory : A landscape inventory of 89 unique objects of national importance and particular beauty, covering 87'478 ha, with their location and area, according to the related ordinance RS 451.35 on "Zones Marécageuses" [17].
- Organic soils location : Agroscope's identification of Switzerland organic soils, gathering 40'533 parcels, with their location and area, according to the related 2015 report from Dr. Chloé Wüst-Galley [18].

Emissions factors used to parameterize the model come from 3 main sources:

- IPCC AR5 report's drained and rewetted inland organic soils emissions factors for CO_2, DOC, CH_4 and N_2O with the related methodology to obtain them from the IPCC 2013 Wetland supplement chapter 2 [19] and chapter 3 [20], updated by Wilson et al. 2016 [21]. They propose a Tier 1 methodology common to all temperate zones.
- Germany's drained and rewetted inland organic soils emissions factors for CO_2, DOC, CH_4 and N_2O with the related methodology to obtain them from Tiemeyer et al. 2020 [22]. They comes from a Tier 3 methodology.
- Switzerland organics soil emissions factors used in the National GHG inventory, assessed by Paul et al. 2018 [23]. They are based on a Tier 2 methodology but concern only CO_2 emissions. No factor exist for the Methane emissions of organic soils in Switzerland [24], and Nitrous Oxide emissions are considered as out of the scope for Paul et al. 2018.

The Annex IV details the distinctions between Tier 1, Tier 2 and Tier 3 methodologies for emissions factors.

Construction of models to estimate the potentials

For both research topics, the geospatial data previously stated were visualised and analysed thanks to the free and open-source cross-platform desktop Geographic Information System application QGIS. It is a software that supports the edition, analysis and visualisation of geospatial data in addition to composing and exporting graphical maps.

The main operations done consist in geographical treatments as the union or intersection of already existing data sets, followed by the vector layers styling to create intuitive and relevant maps to represent the main results. Data conversion from the geospatial format to a spreadsheet format was also performed to create a more accessible open source database, with an user-friendly exploration and visualisation tool.

Model for biochar production

As the most local scale available for the biomass potentials is the communal level, the geospatial data were clustered to offer the same estimation at different regional scales of Switzerland :

- the Communal scale, composed of 2294 cities as they were organised in 2016;
- the Districts scale, containing 148 administrative groupings (141 districts and 7 cantons) as they were organised in 2016;
- the Cantonal scale, composed of the 26 cantons as they are still currently organised;
- the National scale.

The sustainable biomass potentials at the communal scale being only in Energy Content [GJ/yr], 3 conversions were need to go from this potential to the negative emissions potential that biochar production could create :

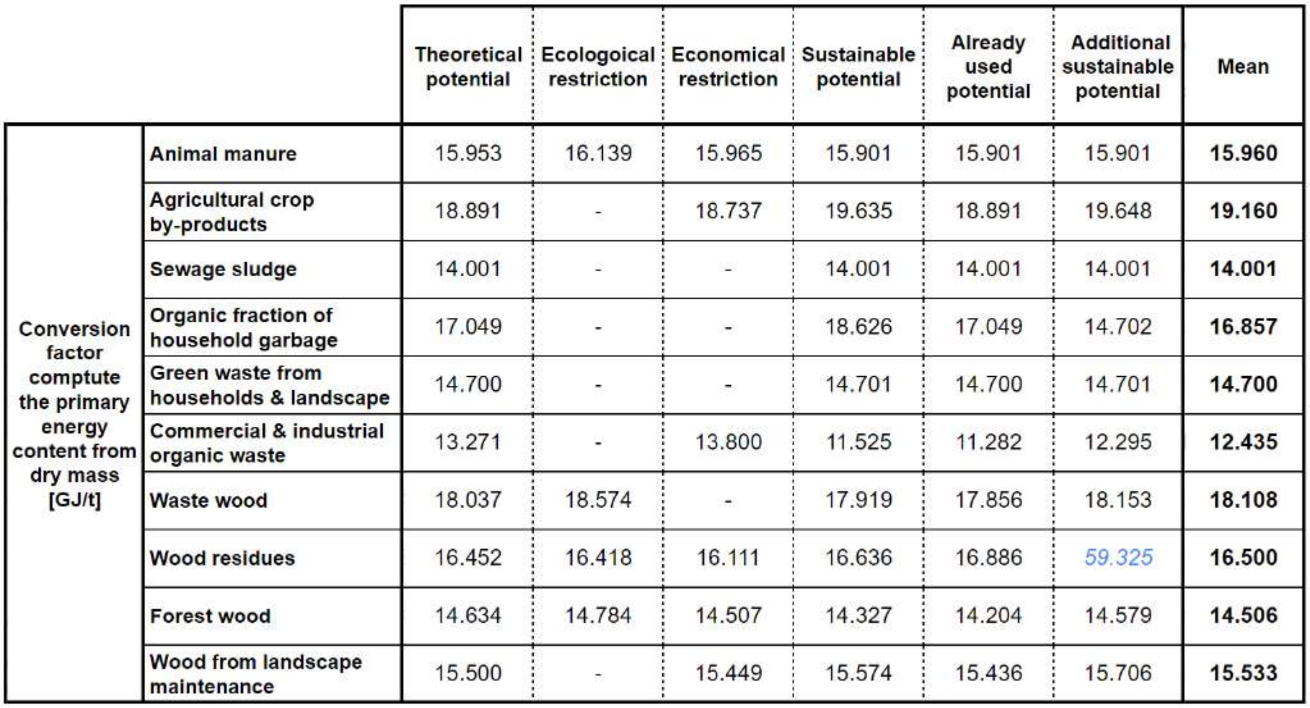
1. Conversion from Energy Content [GJ/yr] to Dry Mass [t/yr]
2. Conversion from Dry mass [t/yr] to Biochar Production capacity [t/yr]
3. Conversion from Biochar Production capacity [t/yr] to Negative Emissions Potential [tCO_2eq/yr]

Conversion from Energy Content Potential [GJ/yr] to Dry Mass Potential [t/yr]

The conversion factors to compute the Energy Content from the Dry Mass are not explicitly given by the WSL 2017 study. Indeed, different factors exist according to the different vegetation types in a same biomass category, and nor these factors, neither the vegetation types distribution among the categories were published.

But the biomass potentials at the national level were given both in Energy Content and Dry Mass, so it was possible to reconstruct the mean conversion factors by dividing both potentials for each category of biomass and type of potentials.

Therefore ratios between the Energy content and the dry mass of biomass for the Theoretical Potential, Ecological restrictions, Techno-economics restrictions, Sustainable potential, already-used potential, and Additional Sustainable potential were calculated for each biomass category to obtain, by doing the mean of these values, plausible conversion factors from the Energy Content to the Dry Mass potentials. Results are presented in Table 1.



		Theoretical potential	Ecologoical restriction	Economical restriction	Sustainable potential	Already used potential	Additional sustainable potential	Mean
Conversion factor comptute the primary energy content from dry mass [GJ/t]	**Animal manure**	15.953	16.139	15.965	15.901	15.901	15.901	**15.960**
	Agricultural crop by-products	18.891	-	18.737	19.635	18.891	19.648	**19.160**
	Sewage sludge	14.001	-	-	14.001	14.001	14.001	**14.001**
	Organic fraction of household garbage	17.049	-	-	18.626	17.049	14.702	**16.857**
	Green waste from households & landscape	14.700	-	-	14.701	14.700	14.701	**14.700**
	Commercial & industrial organic waste	13.271	-	13.800	11.525	11.282	12.295	**12.435**
	Waste wood	18.037	18.574	-	17.919	17.856	18.153	**18.108**
	Wood residues	16.452	16.418	16.111	16.636	16.886	*59.325*	**16.500**
	Forest wood	14.634	14.784	14.507	14.327	14.204	14.579	**14.506**
	Wood from landscape maintenance	15.500	-	15.449	15.574	15.436	15.706	**15.533**

Table 1: Multiplying coefficients [GJ/t] converting dry mass into energy content, source : extrapolated from WSL 2017 [13]

The value in blue was considered as an outlier and not accounted in the mean. Those conversion factors were applied to Biomass Energy content potential in [GJ/yr] of each commune to obtain an estimation of their Dry mass potential in [t/yr] for each biomass category.

Conversion from Dry mass Potential [t/y] to Biochar Production capacity [t/y]

The values obtained for the dry mass of the biomass are then multiplied to a pyrolysis rate of 22,5 % [20-25%] (Schmidt 2021 [25]) to obtain the biochar production capacity in [t/yr] per commune.

Conversion from Biochar Production capacity [t/y] to Negative Emissions Potential [tCO_2eq/y]

The Biochar production capacity is converted to a negative emission potential assuming a carbon content of the biochar of 75.3% (Al-Wabel et al., 2018 [26]), a biochar stability over time of 95% (Keel 2021, unpublished) and a Carbon:CO_2 ratio of 44/12, which gave a ratio of approximately 2.63 tons of negative CO_2eq emissions per ton of biochar.

The three previously mentioned potentials are therefore correlated at 100% since they are obtained by the multiplication of conversion factors. Finally each potential has also a normalised per area value calculated by dividing it by the area of the considered regional scale.

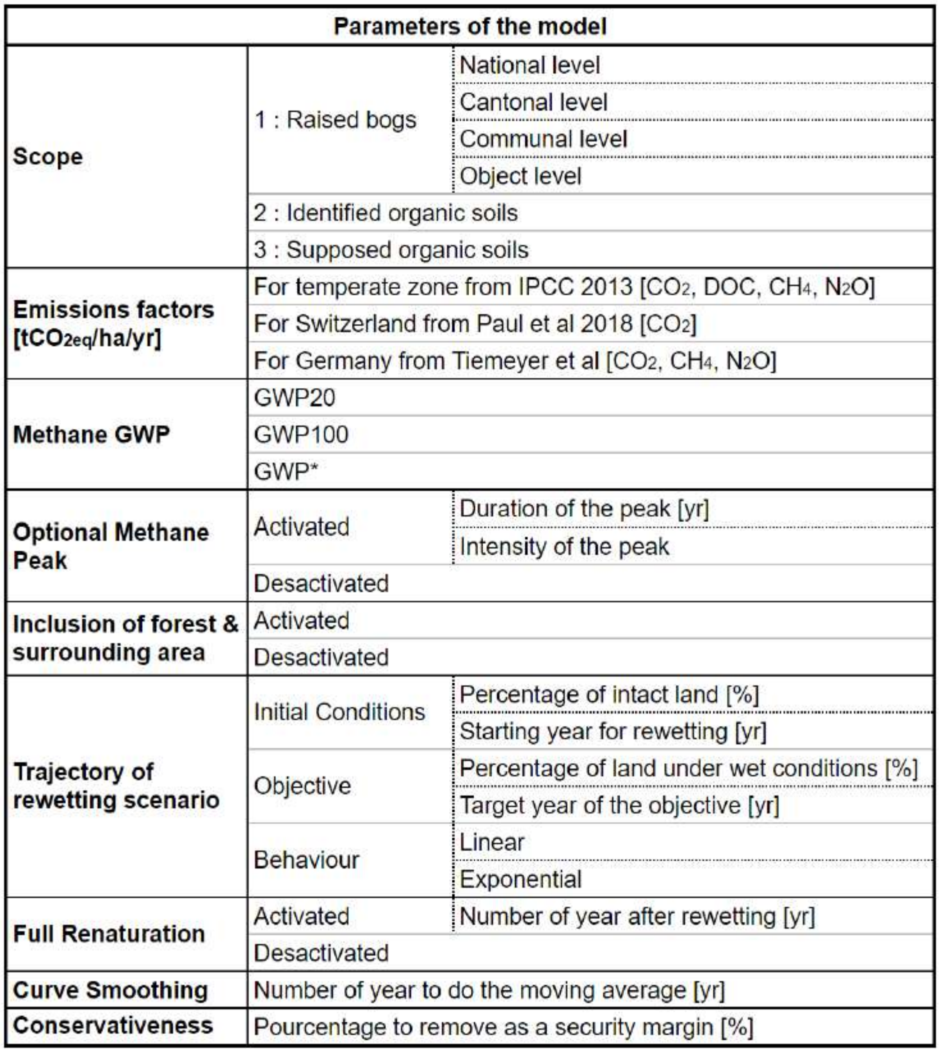
Data visualisation

The different potentials obtained were therefore presented in different ways, through:

- tables per commune, district, canton and at national scale for each biomass category
- communal and cantonal maps per biomass categories
- an exploration and visualisation spreadsheet tool, in the form of a user-friendly interface allowing to display the desired regional scale.

Model for organic soils emissions

Regarding the peatlands, the creation of a more complex model was needed to convert surface areas into potential emissions of GHG. Indeed, contrary to the biochar production for which direct conversion factors were sufficient to obtain a reasonable estimate, the emissions of soils and ecosystems need to take into account more parameters. For example, temporal dynamics or choices between different methodologies to convert GHG emissions. The aim behind this methodology was to build a consistent, robust and configurable model to assess current and future peatland's GHG emissions at the communal, cantonal or national scale, with the emissions savings that a given rewetting scenario would represent compared to a baseline scenario. The model was entitled "OSMOSE" which stands for "an Operable Swiss Model for Organic Soils Emissions". The following table summarises the complete list of parameters implemented in OSMOSE that the user can configure, followed by a more detailed description of each of them.



Parameters of the model		
Scope	1 : Raised bogs	National level
		Cantonal level
		Communal level
		Object level
	2 : Identified organic soils	
	3 : Supposed organic soils	
Emissions factors [tCO_{2eq}/ha/yr]	For temperate zone from IPCC 2013 [CO_2, DOC, CH_4, N_2O]	
	For Switzerland from Paul et al 2018 [CO_2]	
	For Germany from Tiemeyer et al [CO_2, CH_4, N_2O]	
Methane GWP	GWP20	
	GWP100	
	GWP*	
Optional Methane Peak	Activated	Duration of the peak [yr]
		Intensity of the peak
	Desactivated	
Inclusion of forest & surrounding area	Activated	
	Desactivated	
Trajectory of rewetting scenario	Initial Conditions	Percentage of intact land [%]
		Starting year for rewetting [yr]
	Objective	Percentage of land under wet conditions [%]
		Target year of the objective [yr]
	Behaviour	Linear
		Exponential
Full Renaturation	Activated	Number of year after rewetting [yr]
	Desactivated	
Curve Smoothing	Number of year to do the moving average [yr]	
Conservativeness	Pourcentage to remove as a security margin [%]	

Table 2: OSMOSE's Parameters

Scopes

This study presents 3 scopes, detailed in regional scales and land use categories.

The first one focuses on Switzerland's protected raised bogs, 1'568 ha of peatlands and 4'095 ha of surrounding for a total of **5'663 ha**. This scope is particularly interesting since the legislation for its protection already exists and some programs as the one of myclimate already work for their renaturation [27]. For this scope, the model allows to select the regional scale of interest : the national scale, cantonal scale, communal scale and or a precise object. Land use categories refine the data by sorting them in 5 categories : primary peatland, for which no human intervention are visible at the surface, secondary peatland for which anthropogenic disturbance such as drainage ditch are directly visible, surrounding of the peatlands, water bodies and scraped surfaces previously used for peat extraction. For the 3 first categories, vegetation types are also detailed.

Scope 2 represents **27'813 ha** of organic soils in Switzerland identified by Agroscope in their report n°26 from 2015 [18] as the classes I to V according to Figure 4. This scope is interesting since it represents the current area for which the GHG emissions are accounted for in Switzerland's GHG Inventory. However, according to Wüst-Galley et al. 2020 [28], it is recognised that this area is an under-estimation of the total quantity of organic soils in Switzerland, due to the lack of modern data regarding soil mapping and carbon content monitoring.

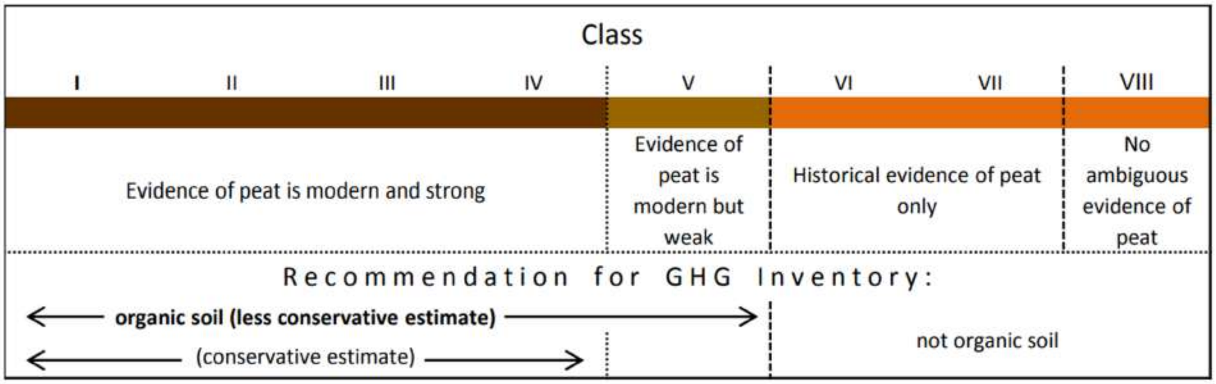


Figure 4: The eight classes into which surfaces were classified and their recommended treatment for the GHGI from Agroscope 2015 [18]

The third scope includes the two previous ones and represents **125'000 ha**. It is an estimation of the non-localized potential total area of organic soils in Switzerland from the minimum and maximum range of 97,659 - 148,561 ha estimated by Wüst-Galley et al. 2020 [28]. This scope represents the 'original' peatland surface estimates that used to be peat-forming bogs before the industrial age according to historical data. Since then, 270 km^2 have been identified as organic soils by Agroscope, as represented in the Scope 2, and another 60 km^2 present historical evidence of peat only, the classes VI to VII, which leaves it in doubt whether they are still organic soils or became mineral. All things being equal, this means that there are potentially still between 670 and 1'170 km^2 of surfaces that have not been located, such that we still don't know if these organic soils still exist, in which state they are or if they were entirely destroyed. Some may have disappeared through extraction or oxidation but it is likely that a significant proportion of these surfaces still contains peat.

Land uses categories

For the Scope 1, the categories used are directly the ones defined by the Raised bog inventory itself. In the Annex III can be found the official legend given to correctly interpret the data of the inventory. There are 5 categories of land uses that are not officially translated in English, the proposed translations for this thesis are :

- Primary peatland, that describes peatlands for which it is not possible to observe visible direct human modification on their surface.
- Secondary peatland, that contains visible human disturbance as drainage ditches
- Surroundings, that are protected similarly to the peatland and act as a buffer zone between them and other land allocations,
- Water bodies, as pond and basin,
- Scraped Area, which reveals a former peat extraction area.

Then, the land uses are detailed into cartographic units that represent the vegetation types as sub-categories, according to the following tables 4 and 5.

Scope 2 and 3 are refined by using the basic 17 categories of the Standard Nomenclature NOAS04 from the Swiss land use statistics (OFS GEOSTAT 2013), available in Annex II. For Scope 2, the distribution of organic soils surface areas among each category were calculated by Dr. Chloé Wüst-Galley using data from Wüst-Galley et al. 2015 [18] and Arealstatistik (OFS GEOSTAT 2013) [29]. Finally Scope 3 is assumed to have proportionally the same distribution as Scope 2, except for the "Unproductive Vegetation" that is supposed to remain the same since it is mainly composed of wetlands that are all already located in inventory presented previously.

Regional Scales

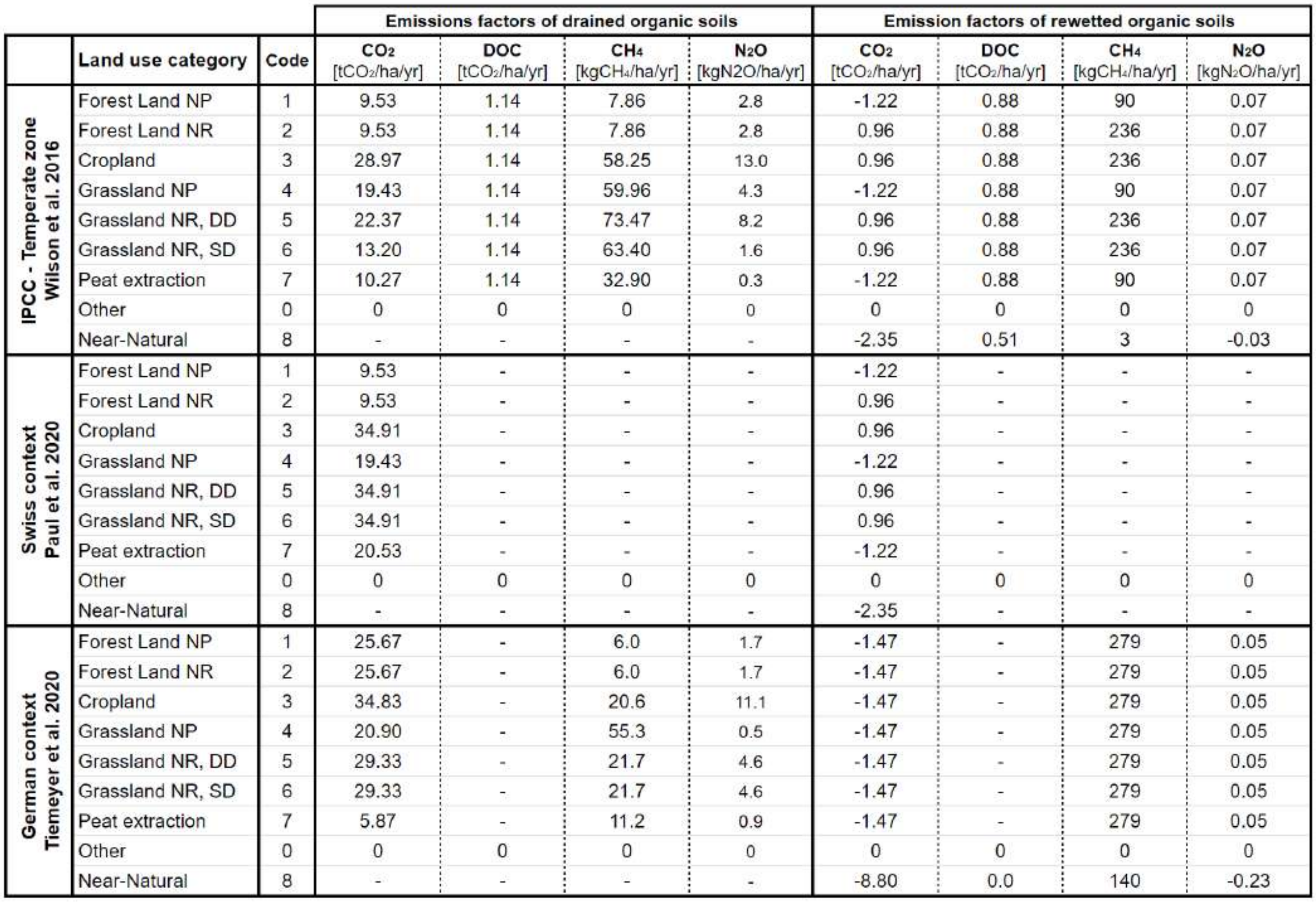
Similarly to the biomass database, an exploratory and visualisation tool was developed for the raised bog inventory. The different potentials obtained were therefore presented in different areas according to the land use categories and vegetation types for the national scale, a precise canton, a precise commune or even a precise raised bog object desired by the user. This tool is linked to the model to allow the user to look at the desired regional scale emissions. This option is not implemented for the Scope 2 and 3.

Emissions factors Attribution

The emissions factors that allow the conversion from surfaces to annual GHG emissions for drained and rewetted organic soils, as represented in Table 3, are based on 3 main sources that can be selected in the Model. Temperate zone from IPCC [21], Switzerland context from Paul et al. 2018 [23] and German context from Tiemeyer et al. 2020 [22]. Each source covers partially or completely the 4 main GHG involved in organic soils rewetting (CO_2, DOC, CH_4 and N_2O) and has its own different land uses classes. To uniformize them, 8 categories were defined : Forest Land nutrient rich [NR] or nutrient poor [NP], Cropland, Grassland [NP], Grassland [NR] deeply drained [DD] (water table level $<$ -30 cm) or shallow drained [SD], Peat extraction and an "other" category setting all Emissions factors to 0.

Finally, the ninth category was created to represent the emissions factors of an intact or near-natural peatland, corresponding to the lowest value of the 95% confidence intervals of the Grassland NP class for each respective source. This methodology was inspired from the 2020 Mike Dettwiler's ETH Master thesis [30]. While the data set from the inventory indicates that the primary peatlands do not suffer from direct human disturbance, they are often surrounded by drained areas. In this case, it is absolutely certain that the water level table of these primary peatlands is affected by the surrounding drainage ditches, and that non-hydrophilic vegetation can develop, deeply modifying the ecosystem and the carbon sink capacity of the peatland.

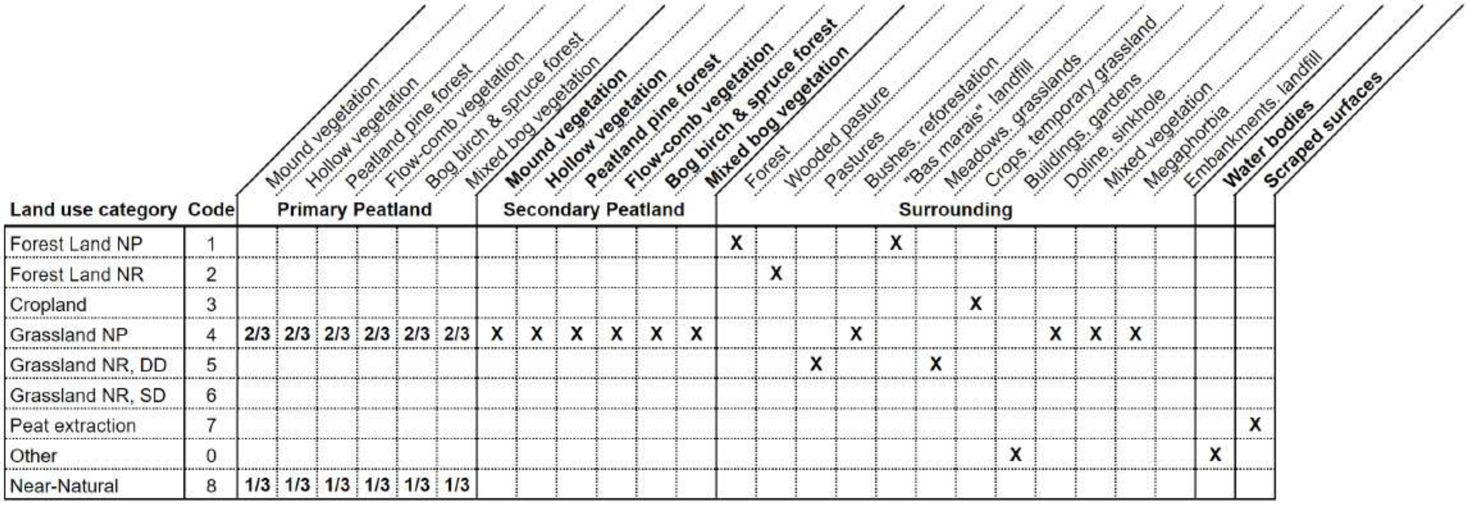
To take this fact into account, OSMOSE allows the user to select the % of primary peatlands that are considered as intact. After discussions with experts on the subject, 33% could be a good estimate of the current situation. This assumption is taken in the following Tables 4 and 5 to detail the emissions factors attribution.



			Emissions factors of drained organic soils				Emission factors of rewetted organic soils			
	Land use category	Code	CO_2 [tCO_2/ha/yr]	DOC [tCO_2/ha/yr]	CH_4 [$kgCH_4$/ha/yr]	N_2O [kgN2O/ha/yr]	CO_2 [tCO_2/ha/yr]	DOC [tCO_2/ha/yr]	CH_4 [$kgCH_4$/ha/yr]	N_2O [kgN_2O/ha/yr]
IPCC - Temperate zone Wilson et al. 2016	Forest Land NP	1	9.53	1.14	7.86	2.8	-1.22	0.88	90	0.07
	Forest Land NR	2	9.53	1.14	7.86	2.8	0.96	0.88	236	0.07
	Cropland	3	28.97	1.14	58.25	13.0	0.96	0.88	236	0.07
	Grassland NP	4	19.43	1.14	59.96	4.3	-1.22	0.88	90	0.07
	Grassland NR, DD	5	22.37	1.14	73.47	8.2	0.96	0.88	236	0.07
	Grassland NR, SD	6	13.20	1.14	63.40	1.6	0.96	0.88	236	0.07
	Peat extraction	7	10.27	1.14	32.90	0.3	-1.22	0.88	90	0.07
	Other	0	0	0	0	0	0	0	0	0
	Near-Natural	8	-	-	-	-	-2.35	0.51	3	-0.03
Swiss context Paul et al. 2020	Forest Land NP	1	9.53	-	-	-	-1.22	-	-	-
	Forest Land NR	2	9.53	-	-	-	0.96	-	-	-
	Cropland	3	34.91	-	-	-	0.96	-	-	-
	Grassland NP	4	19.43	-	-	-	-1.22	-	-	-
	Grassland NR, DD	5	34.91	-	-	-	0.96	-	-	-
	Grassland NR, SD	6	34.91	-	-	-	0.96	-	-	-
	Peat extraction	7	20.53	-	-	-	-1.22	-	-	-
	Other	0	0	0	0	0	0	0	0	0
	Near-Natural	8	-	-	-	-	-2.35	-	-	-
German context Tiemeyer et al. 2020	Forest Land NP	1	25.67	-	6.0	1.7	-1.47	-	279	0.05
	Forest Land NR	2	25.67	-	6.0	1.7	-1.47	-	279	0.05
	Cropland	3	34.83	-	20.6	11.1	-1.47	-	279	0.05
	Grassland NP	4	20.90	-	55.3	0.5	-1.47	-	279	0.05
	Grassland NR, DD	5	29.33	-	21.7	4.6	-1.47	-	279	0.05
	Grassland NR, SD	6	29.33	-	21.7	4.6	-1.47	-	279	0.05
	Peat extraction	7	5.87	-	11.2	0.9	-1.47	-	279	0.05
	Other	0	0	0	0	0	0	0	0	0
	Near-Natural	8	-	-	-	-	-8.80	0.0	140	-0.23

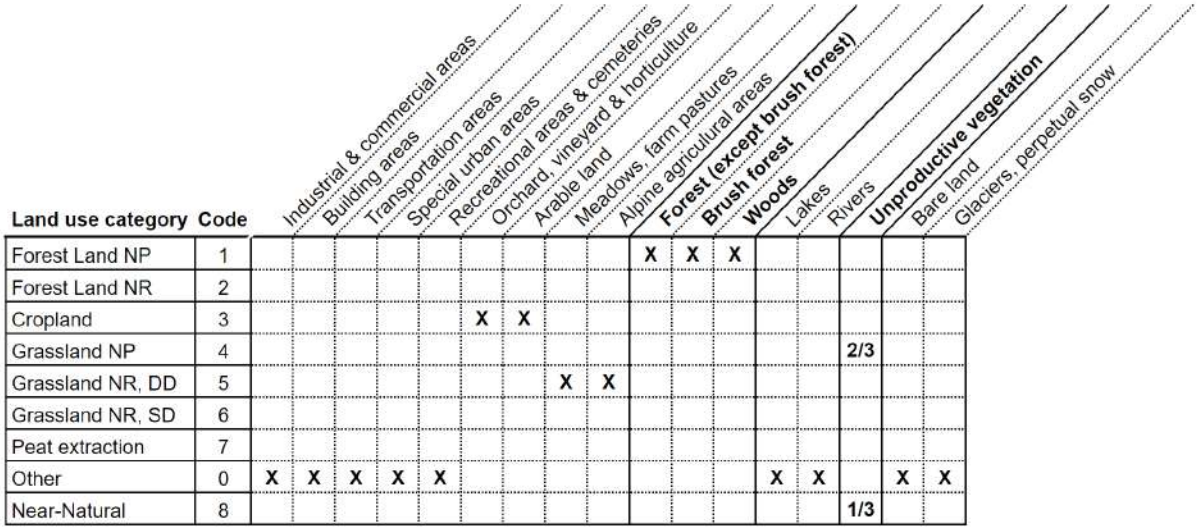
Table 3: Emissions factors from Temperate zone IPCC Wetland Supplement 2013 [21], Paul et al. 2020 [23] and Tiemeyer et al. 2020 [22]

These emissions factors were attributed to land uses categories and vegetation types of the different scopes according to the following correspondence tables.



Land use category	Code	Primary Peatland						Secondary Peatland						Surrounding													
		Mound vegetation	Hollow vegetation	Peatland pine forest	Flow-comb vegetation	Bog birch & spruce forest	Mixed bog vegetation	**Mound vegetation**	**Hollow vegetation**	**Peatland pine forest**	**Flow-comb vegetation**	**Bog birch & spruce forest**	**Mixed bog vegetation**	Forest	Wooded pasture	Pastures	Bushes, reforestation	"Bas marais", landfill	Meadows, grasslands	Crops, temporary grassland	Buildings, gardens	Doline, sinkhole	Mixed vegetation	Megaphorbia	Embankments, landfill	**Water bodies**	**Scraped surfaces**
Forest Land NP	1													X				X									
Forest Land NR	2														X												
Cropland	3																			X							
Grassland NP	4	2/3	2/3	2/3	2/3	2/3	2/3	X	X	X	X	X	X				X					X	X	X			
Grassland NR, DD	5															X			X								
Grassland NR, SD	6																										
Peat extraction	7																										X
Other	0																				X					X	
Near-Natural	8	1/3	1/3	1/3	1/3	1/3	1/3																				

Table 4: Emissions factors correspondence table for Scope 1 (Raised bogs)



Land use category	Code	Industrial & commercial areas	Building areas	Transportation areas	Special urban areas	Recreational areas & cemeteries	Orchard, vineyard & horticulture	Arable land	Meadows, farm pastures	Alpine agricultural areas	**Forest (except brush forest)**	**Brush forest**	**Woods**	Lakes	Rivers	**Unproductive vegetation**	Bare land	Glaciers, perpetual snow
Forest Land NP	1										X	X	X					
Forest Land NR	2																	
Cropland	3						X	X										
Grassland NP	4															2/3		
Grassland NR, DD	5								X	X								
Grassland NR, SD	6																	
Peat extraction	7																	
Other	0	X	X	X	X	X								X	X		X	X
Near-Natural	8															1/3		

Table 5: Emissions factors correspondence table for Scope 2 and 3 (Organic soils)

Global Warming Potential for Methane and Nitrous Oxide

To convert Methane emissions to CO_2eq emissions, 3 options are available :

- Apply a GWP_{20} factor of 86
- Apply a GWP_{100} factor of 34
- Apply a GWP* equation : $CO_2eq = (105 \cdot \Delta_Y E_{CH4}) + (7 \cdot E_{CH4})$

E_{CH4} being the emission of Methane in [tCH_4/yr].
Δ_Y being the difference of emissions over an Y_Δ years period, Y being often set to 20 years.

The GWP* option is particularly interesting as Methane is a near-term climate forcer and common metrics like global warming potential 20 or 100, and its sustained flux variants, fail to account for temporal forcing dynamics[31].

N_2O emissions are converted to CO_2eq emissions by applying a GWP_{100} factor of 296.

Optional Methane Peak

It is known that the transition from drained to rewetted organic soils leads to a phenomena called the "Methane peak" : Methane emissions drastically increase after rewetting due to the return of flooded anoxic conditions that stops the carbon mineralization but favours the methanogenic microorganisms, before stabilising themselves to the Methane emissions of wetlands described in Table 3 for rewetted soils. This phenomena is even more pronounced if the organic soil is rich in nutrients, as chemical fertilisers used in agriculture. However, the current literature remains unclear about the precise behaviour of this Methane peak, and further studies involving emissions monitoring are needed to characterise it properly.

To account for it, the model offers the possibility to simulate a Methane peak by multiplying the rewetted organic soils' standard emissions by a factor of $\mathbf{X}$ for the $\mathbf{Y}_p$ first years after the rewetting.

Inclusion of forest and surrounding area in the rewetting

This option offers the possibility to include the surrounding areas and forest areas into the rewetting scenario. If deactivated, these areas continue to emit as drained organic soils, whereas they would be progressively rewetted as the other surfaces if the option is activated.

The surrounding and forest areas represent :

- 4'064 ha over 5'663 ha for the Scope 1 (72%)
- 4'115 ha over 27'612 ha for the Scope 2 (15%).
- 20'000 ha over 125'000 ha for the Scope 3 (16%).

Trajectory of rewetting scenario

The trajectory of the rewetting scenario in the model is set by the initial conditions defined by the intact surfaces $\mathbf{S}_{in}$ in [ha] at the year $\mathbf{Y}_{in}$ when the rewetting program starts, and objective fixed for the total surfaces rewetted or intact $\mathbf{S}_{obj}$ at the year $\mathbf{Y}_{obj}$.

Then, the model offers the possibility to select a linear or exponential behaviour for the rewetting scenario. As represented in Figure 5, the linear option would rewet every year the same quantity $\mathbf{W}_{lin}$ [ha] of peatlands whereas the exponential one would rewet every year the same percentage $\mathbf{W}_{exp}$ [%] of wet organic soils existing at the previous year. The quantity of organic soils rewetted each year is spread proportionally among all land use categories.

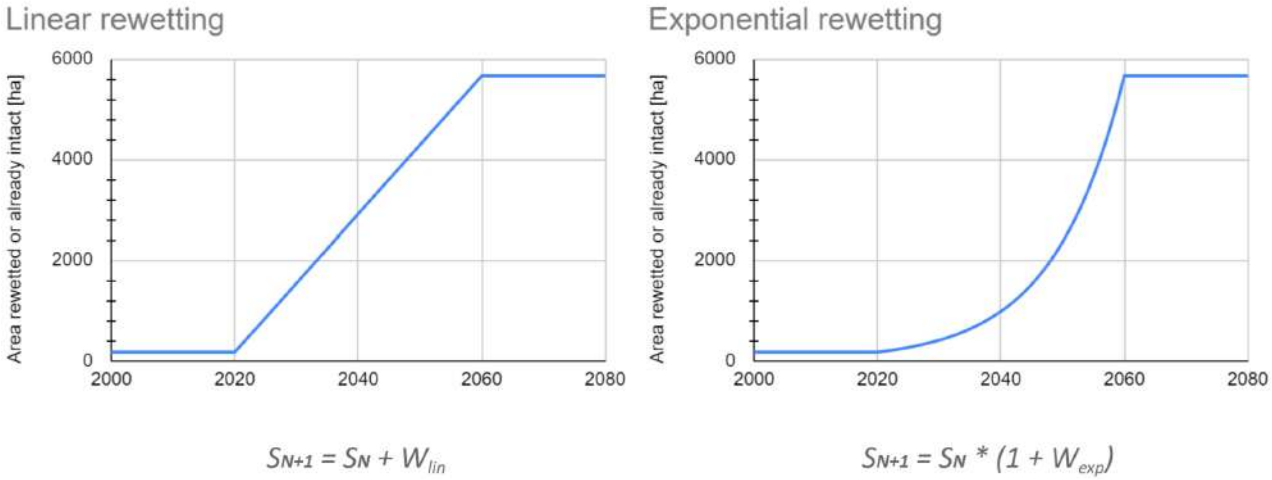


Figure 5: Comparison between linear and exponential rewetting for Scope 1

With $W_{lin} = \frac{S_{obj}-S_{in}}{Y_{obj}-Y_{in}}$ in [ha] and $W_{exp} = 100 \cdot \sqrt[Y_{obj}-Y_{in}]{\frac{S_{obj}}{S_{in}}}$ in [%]

Finally, the rewetting scenario is compared with a baseline scenario that has a different objective, corresponding to the continuation of a past trend or a future plan, and a full renaturation scenario defined in the following paragraph.

Full renaturation of the C-Sink Potential

This option allows the model to compute the organic soil emissions assuming that $\mathbf{Y}_R$ years after the rewetting of a parcel, the ecosystem is fully renaturated and behaves as a near-natural raised bog. So it switches the emissions factors attributed to this rewetted parcel to the ninth category representing the intact peatlands according to the lowest value of the 95% confidence interval of Grassland NP. While it is quite certain that this option is relevant for the Scope 1, the capacity of organic soils under intensive exploitation to be restored as intact peatlands is still to be investigated.

Curve Smoothing This option applies a moving average over $\mathbf{Y}_s$ years (usually 5) to obtain smoother emissions curves.

Conservativeness This option removes **X%** to the emissions reduction to take account for the expected project emissions due to the landscaping work and from a risk buffer regarding the emissions reduction efficiency, carbon sequestration capacity and possible leakages.

Costs and barriers analysis

Costs projections were performed to assess what it would take to implement the proposed interventions in the near future to reach the potentials presented in the result section. For both research topics, the similar methodology was followed :

1. Estimate the capital expenditures to implement the solutions
    (a) Installation of a pyrolysis unit in the case of biochar production
    (b) Renaturation and landscaping work for peatlands renaturation
2. Estimate the operational costs created by the solutions implementation
    (a) Pyrolysis unit running and variable costs as salary, maintenance, consumption etc.
    (b) Peatlands' maintenance and monitoring
3. Human resources needed

As the solutions expand over long periods, a learning curve is implemented to take into account the increase of efficiency in technologies, knowledge and skills that would have the effect of decreasing the cost per unit and workforce needed.

The learning curve is set such that the costs decrease by a factor of $\mathbf{X}_{lc}\%$ at each cumulative doubling in the solution implementation.

- For technological approaches, X is generally supposed to be between 10% - 15% for each cumulative doubling,
- In the case of peatlands, the learning curve concerns more knowledge and understanding of ecosystems, practical skills and public acceptance of the solution. These variables are less quantifiable, so the percentage X is assumed to be lower for a conservative assumption, around 8 % for each cumulative doubling.

PART I - Understanding the context

This section aims to present the understanding of the issues surrounding Nature-based Solutions to climate change in the Swiss context at the time of publication of this thesis. It provides the theoretical framework within which the study is situated. It reveals information gathered from the literature review and results from the semi-structured interviews, and the field visit.

1.1 Switzerland Climate trajectory

Switzerland presented in 2021 its Long-Term Climate Strategy [6] in which the necessary emissions reduction toward 2050 to respect the Paris agreement are revealed. It is an ambitious plan to decrease the national emissions by more than 90 % until 2050, as represented in the Figure 6.

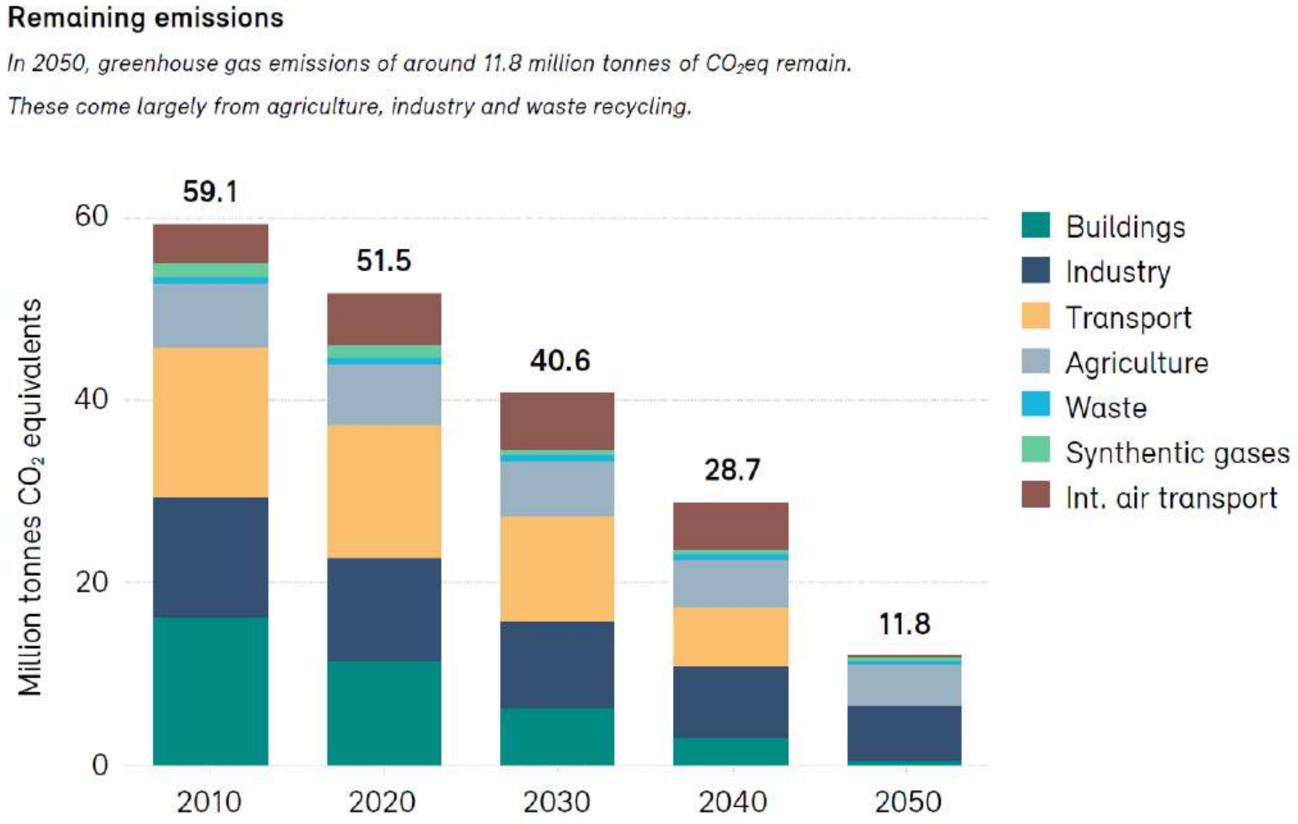


Figure 6: Swiss Emissions reduction as defined in the Swiss Long-term Climate Strategy 2021 [6]

The conclusion of the work done to produce this strategy shows that 12 Mt CO_2eq are incompressible and considered as difficult to remove. This report states that "*there is a growing realisation that the Paris climate goals and the Swiss climate goal for 2050 can no longer be met by emission reductions alone.*". In a report [32] that answers the postulate 18.4211 Thorens Goumaz[33], the Federal Council recognized the importance of NETs and the need to set the framework for research and expansion. The current position of Switzerland to remove those 12 Mt CO_2eq is summarised in the following Figure 7.

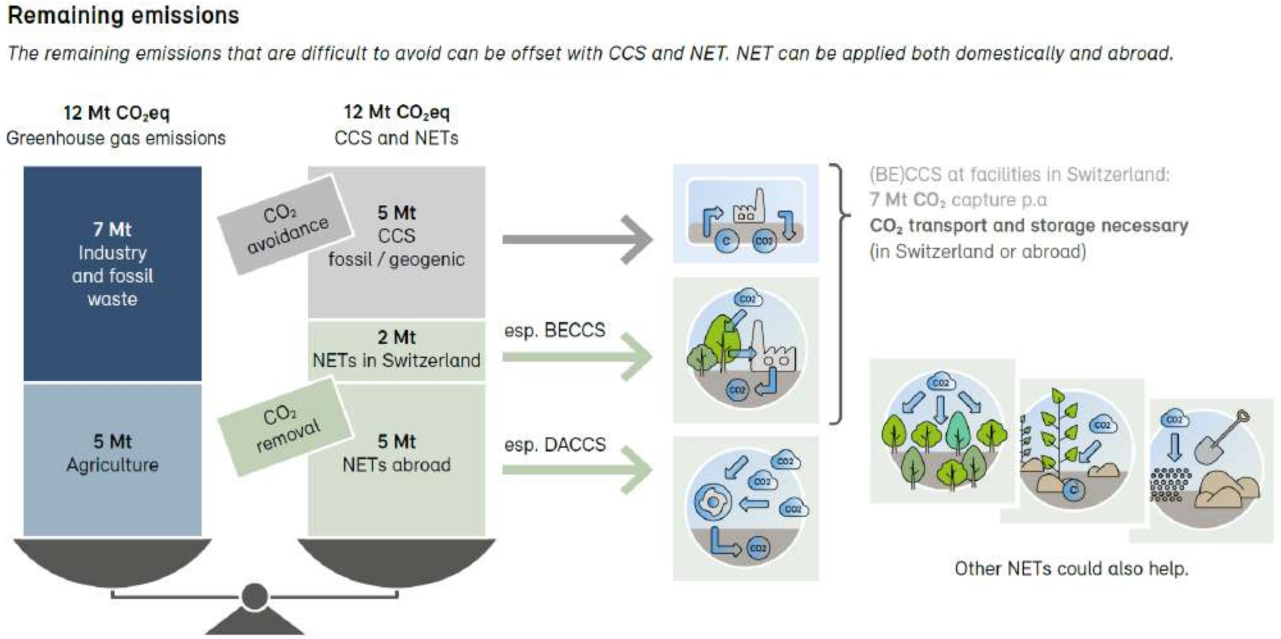
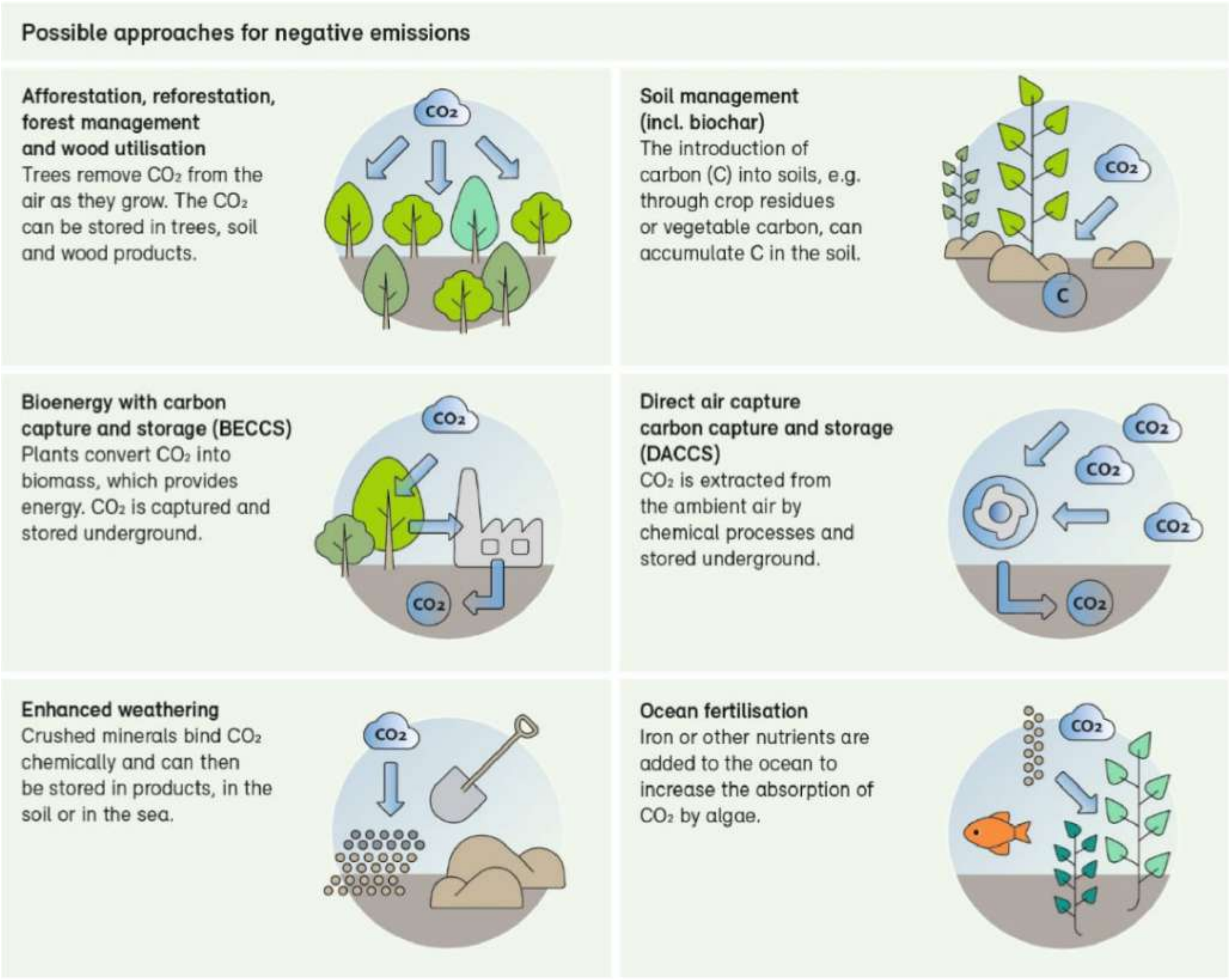


Figure 7: Swiss Strategy for remaining emissions in Long-term Climate Strategy 2021 [6]

As previously mentioned, a part of this remaining emissions could be captured before reaching the atmosphere thanks to CCS, and stored permanently in a geological storage [8]. But the realistic potential of these technologies could only be around 5 M tCO_2eq per year if fully developed in time [7]. Thus, remaining emissions need to be compensated by negative ones, and Switzerland understood it by giving an important role to Negative Emissions Technologies in its Long-term Climate Strategy.

It is still unclear how these negative emissions will be implemented. For now, current information mainly focuses on developing Bio-energy Carbon Capture and Storage (BECCS) and planning emission off-settings abroad, which has a positive impact on the development of climate solutions in the international community, but is also criticised since it could be seen as a way to buy cheap carbon certificate instead of developing a deep decarbonization plan on its own territory. BECCS, which is planned to be developed in Switzerland, would be effective by giving a central role to biomass in the energy production, even if the technology readiness level of this approach is still very low and would need further years of research and development.

Therefore it is relevant to look at the other types of Negative Emissions Technologies that Switzerland could count on. A special report [34] commissioned by the Federal Office of the Environment explores these approaches, which are represented in the following Figure 8.



Possible approaches for negative emissions

Afforestation, reforestation, forest management and wood utilisation
Trees remove CO_2 from the air as they grow. The CO_2 can be stored in trees, soil and wood products.

Soil management (incl. biochar)
The introduction of carbon (C) into soils, e.g. through crop residues or vegetable carbon, can accumulate C in the soil.

Bioenergy with carbon capture and storage (BECCS)
Plants convert CO_2 into biomass, which provides energy. CO_2 is captured and stored underground.

Direct air capture carbon capture and storage (DACCS)
CO_2 is extracted from the ambient air by chemical processes and stored underground.

Enhanced weathering
Crushed minerals bind CO_2 chemically and can then be stored in products, in the soil or in the sea.

Ocean fertilisation
Iron or other nutrients are added to the ocean to increase the absorption of CO_2 by algae.

Figure 8: Negative emissions approaches. Source: Federal Council report in response to Postulate 18.4211 - 2021 [32]

This thesis focused on the two first one, land use management and biochar in soil management, as they are considered as Nature-based Solutions immediately available that could additionally generate substantial co-benefits for Switzerland in terms of ecosystem services.

1.2 Nature Based Solutions

Nature-based Solutions were initially defined by IUCN in 2016 as "*actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g. climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits.*"[35]. During the following years, the concept gained in interest as increased the number of studies showing the possible synergies they offer in terms of climate, biodiversity, and food security. The notion of socio-ecological systems tends to show the complex interactions between human societies and the natural environment, linked by the fact that ecosystem services are crucial for human well-being, as they are the main component of the habitability of our world. As shown in Annex VII, Key et al. (2021) [36] gives a very complete list of the environmental metrics NbS could have a positive impact.

So the notion of NbS has gone beyond the academic world, until touching political institutions such as the European Commission that defines it as the following : "*NbS aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions, e.g. mimicking how non-human organisms and communities cope with environmental extremes. NbS use the features and complex system processes of nature, such as its ability to store carbon and regulate water flow, in order to achieve desired outcomes, like reduced disaster risk, improved human well-being and socially inclusive green growth. Maintaining and enhancing natural capital, therefore, is of crucial importance, as it forms the basis for implementing solutions. These NbS ideally are energy- and resource-efficient, and resilient to change, but to be successful they must be adapted to local conditions.*"

The principles that make NbS relevant can be synthesised as developed in the Annex VI:

- Alignment with natural ecosystem processes
- Benefit biodiversity
- Adaptability
- Locally appropriate actions
- Multi-functional
- Address societal challenges and enhance human well-being

Switzerland has not yet well defined the role of Nature-based Solutions in its Climate Strategy. This thesis suggests that Biochar production and Peatlands renaturation are the two most relevant ones to explore.

1.3 Biochar and Peatlands in Switzerland

To acquire a general knowledge on biochar and peatlands, but also to identify the relevant research questions that guided the aims of this thesis, a series of semi-structured interviews was designed.

After having listed more than 50 experts on both research topics, and received more than 20 recommendations, a total of 40 persons were shortlisted and contacted. Among them, 20 answered positively and the interviews were successfully conducted. Some others declined the interview, shared information by mail, or never answered. Results of the interview series are represented in the Figure 9. The complete list of persons interviewed with their titles and jobs can be found in the Annex IX.

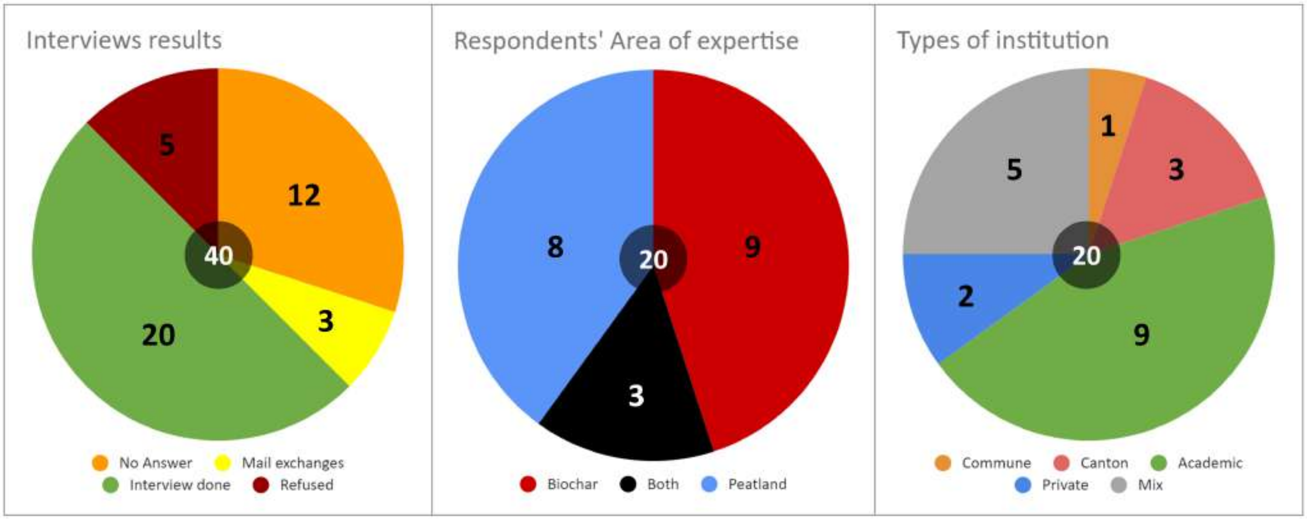


Figure 9: Results of the interviews series

The interviews led to more than a 100 pages of transcription that were translated and synthesised in an Spreadsheet document for personal use, to have an overview of the results and be able to extract common trends or original views between the interview.

The transcriptions are not published due several reasons :
-Some interviews were not recorded, and no transcription software was used to generate the text. Therefore, their transcriptions could be missing some important parts and discussions,
-The English translation of French interviews was not done professionally,
-Some confidential information were shared during the interviews ,
-Some respondents asked their answer not to be published.

All these reasons could lead to a misinterpretation and biased conclusions from an uninformed reader, not aware of the context and details of the interviews. However the complete list of questions, complete list of the persons interviewed with their titles and professions, and an extract of the synthesis spreadsheet document are respectively available in the Annexes VIII, IX and X.

To synthesise the interviews process, another aim of this project was to visually represent the information collected by creating a stakeholder map to position the respondents according to the qualitative data they gave during the interviews, as shown in Figure 10.

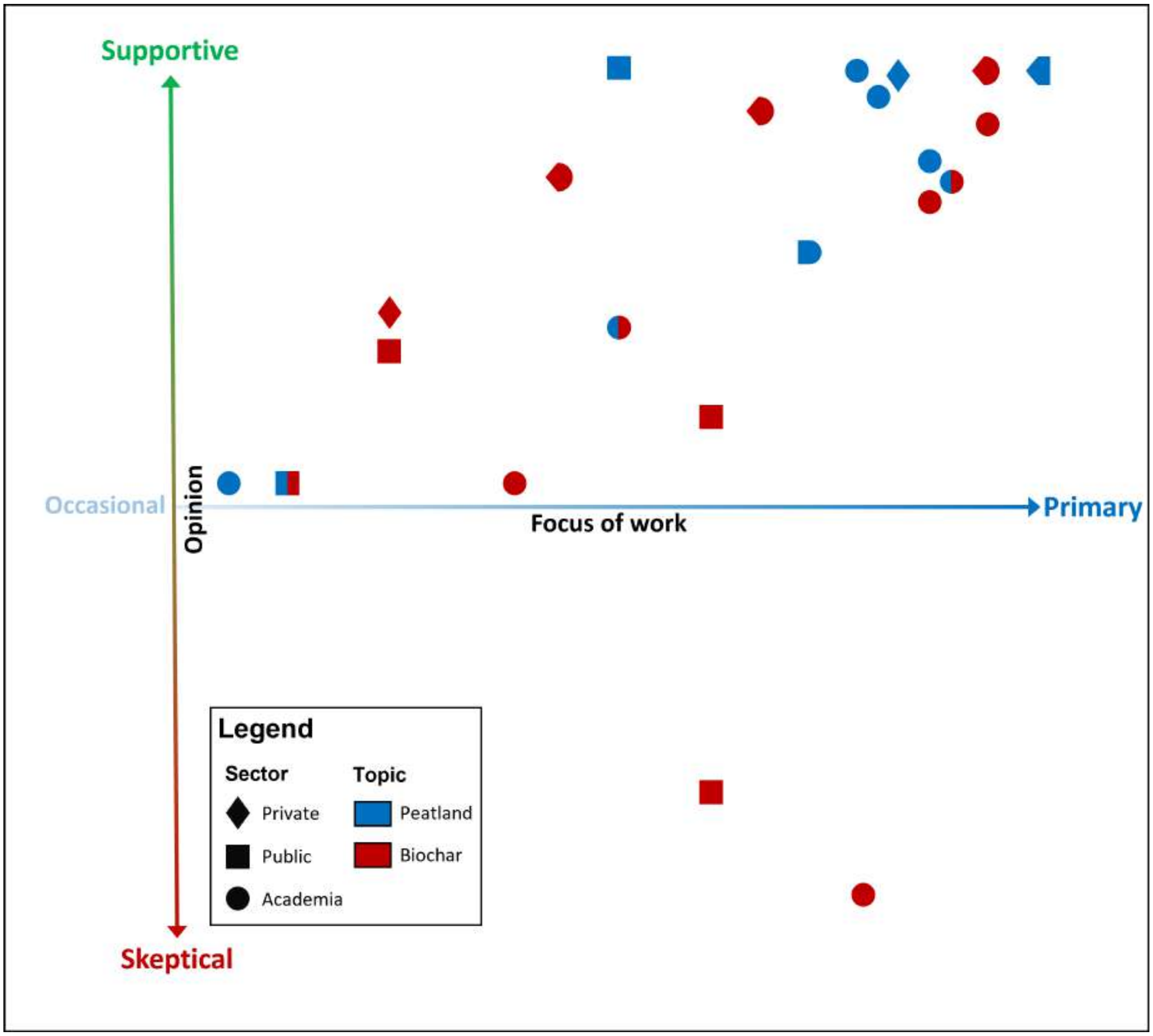
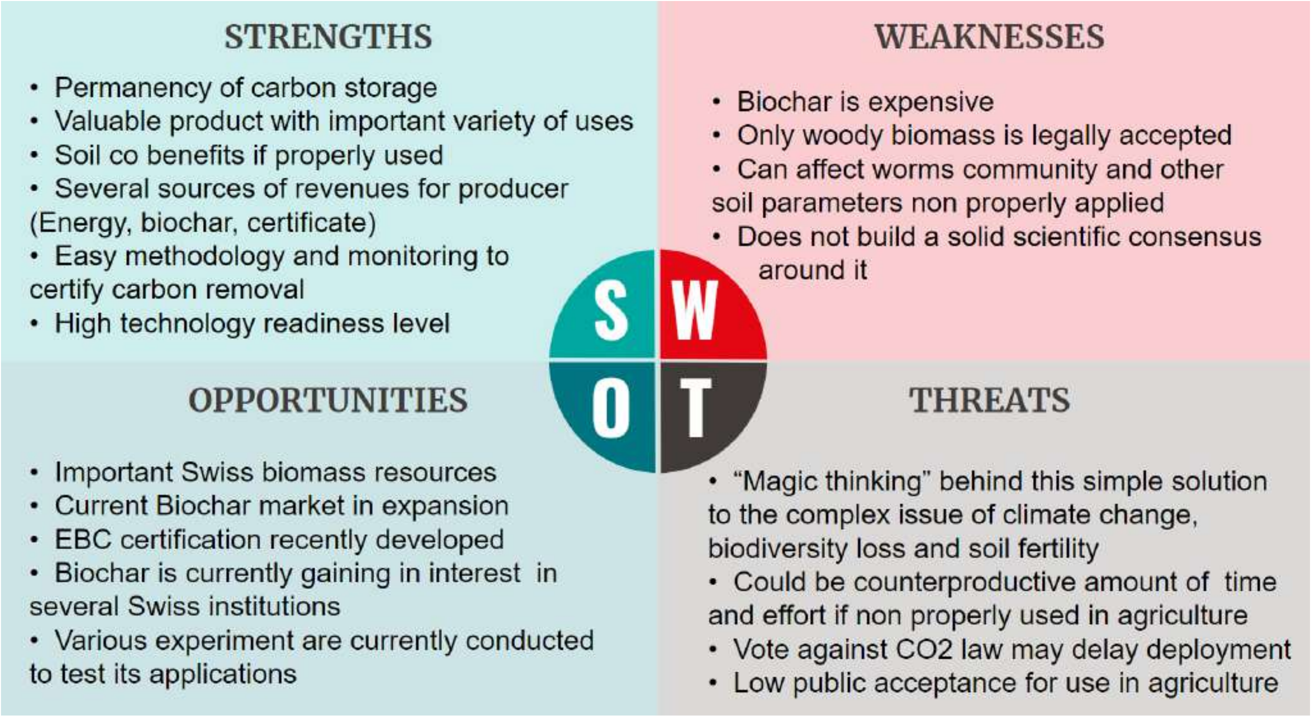


Figure 10: Stakeholder mapping

It is to be noted that this graph does not aim to be representative of the private, public or academia sectors, nor to jump to conclusions regarding biochar and peatlands, as the positions of the participants were attributed after a subjective analysis of the qualitative data shared during the interviews. Moreover the number of samples (n=20) is relatively low and the sampling was not done in a probabilistic way as detailed in the methodology, with all the biases it could create. The only aim of this figure is to summarise the interview process to help me to have a better understanding of the context that surrounds the research topics.

Finally the desired outcome of the interviews was to construct a SWOT analysis for both research topics, and use them to refine the research questions, as presented in Figures 11 and 12.



STRENGTHS

- Permanency of carbon storage
- Valuable product with important variety of uses
- Soil co benefits if properly used
- Several sources of revenues for producer (Energy, biochar, certificate)
- Easy methodology and monitoring to certify carbon removal
- High technology readiness level

WEAKNESSES

- Biochar is expensive
- Only woody biomass is legally accepted
- Can affect worms community and other soil parameters non properly applied
- Does not build a solid scientific consensus around it

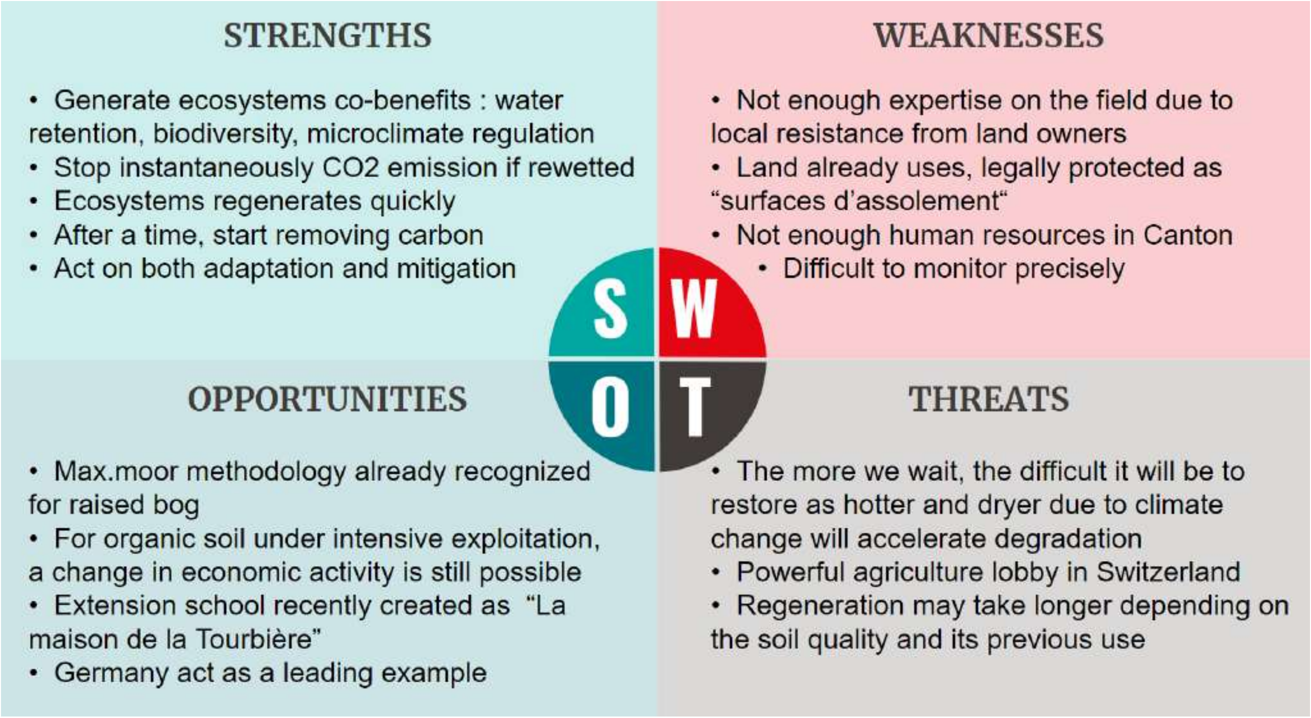
OPPORTUNITIES

- Important Swiss biomass resources
- Current Biochar market in expansion
- EBC certification recently developed
- Biochar is currently gaining in interest in several Swiss institutions
- Various experiment are currently conducted to test its applications

THREATS

- "Magic thinking" behind this simple solution to the complex issue of climate change, biodiversity loss and soil fertility
- Could be counterproductive amount of time and effort if non properly used in agriculture
- Vote against CO2 law may delay deployment
- Low public acceptance for use in agriculture

Figure 11: Biochar SWOT Analysis



STRENGTHS

- Generate ecosystems co-benefits : water retention, biodiversity, microclimate regulation
- Stop instantaneously CO2 emission if rewetted
- Ecosystems regenerates quickly
- After a time, start removing carbon
- Act on both adaptation and mitigation

WEAKNESSES

- Not enough expertise on the field due to local resistance from land owners
- Land already uses, legally protected as "surfaces d'assolement"
- Not enough human resources in Canton
- Difficult to monitor precisely

OPPORTUNITIES

- Max.moor methodology already recognized for raised bog
- For organic soil under intensive exploitation, a change in economic activity is still possible
- Extension school recently created as "La maison de la Tourbière"
- Germany act as a leading example

THREATS

- The more we wait, the difficult it will be to restore as hotter and dryer due to climate change will accelerate degradation
- Powerful agriculture lobby in Switzerland
- Regeneration may take longer depending on the soil quality and its previous use

Figure 12: Peatlands SWOT Analysis

Those results show that in the population of experts interviewed, there is a trend showing that the more respondent's work is focus on peatlands renaturation in a similar approach that the one presented in this thesis, the more they are supportive regarding the solution and convinced of its relevance to tackle climate change and generate various co-benefits for biodiversity and human well being. However the same interpretation cannot be done for biochar production, interviews revealed that using biochar as an effective climate solution does not make the same consensus as for peatlands. The uncertainties does not rely on the capacity of biochar to create negative emissions and store carbon in a stable and persistent way, but more on the relevance to use biochar in agriculture as a soil amendment and as the main strategy to restore the carbon content of Switzerland soils that is drastically decreasing since the last decades, endangering food security [37].

Therefore, it was decided to focus strictly on the biochar potential to produce negative emissions from the available biomass in Switzerland, independently of its uses, even if some of them will still be discussed in the Discussion section. Having an informed discernment about the different biochar uses, especially in agriculture, would need long-term studies and an intense monitoring campaign on the field with laboratory analysis, which this master thesis is not able to provide.

In the literature, negative emissions potential from biochar in Switzerland were only quickly and roughly estimated at the national scale for now, or at a farm level. So this thesis aims to build a consistent and robust methodology to obtain the national biochar production capacity from sustainable biomass potential at the communal, cantonal and national level.

The exploratory phase conducted during the first half of the master thesis allowed the refinement of the research questions, as they are presented in the Annex XI. These research questions constitute an ambitious plan compiling all the unanswered points remaining on Biochar and Peatlands in Switzerland. The approach followed was to explore the most technical parts of them, to create a solid data-based reference for the estimation of the potential, and to send all the unanswered questions to future researches.

PART II - Understanding the solutions

This section aims to present the two possible interventions to tackle climate change addressed in this thesis, Biochar production through Pyrogenic Carbon Capture and Storage, and Peatlands renaturation. Their descriptions start with a general review of the state of the art, definitions and history, before diving into what they would imply for Switzerland in a potentials analysis.

2.1 From Biomass to Biochar

2.1.1 State of the art

Definitions

The European Biochar Certificate, the established quality standard for Biochar according to the European Biochar Industry, defines biochar as the following :

“*Biochar is a porous, carbonaceous material that is produced by pyrolysis of biomass and is applied in such a way that the contained carbon remains stored as a long-term C sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation.*" [38].

Even if biochar has been used for a long time in horticulture as a luxury product to amend soils, it recently gained in interest among the climate discussions because it is the main product behind the process called Pyrogenic carbon capture and storage (PyCCS). This approach is based on the principle that the growth of biomass is considered the most efficient method currently available to extract carbon dioxide from the atmosphere. However, carbon from biomass can be mineralized as it is easily degraded by microorganisms, resulting in the release of greenhouse gases back to the atmosphere. To counter this phenomenon, the process of pyrolysis is presented as a promising way to transform the biomass into a stable and persistent product : biochar.

Werner et al. (2018) defined the process of pyrolysis in the context of carbon capture and storage as "*the thermal treatment of biomass at 350°C–900°C in an oxygen-deficient atmosphere. Three main carbonaceous products are generated during this process, which can be stored subsequently in different ways to produce [negative emissions]: a solid biochar as soil amendment, a pyrolytic liquid (bio-oil) pumped into depleted fossil oil repositories, and permanent-pyrogas (dominated by the combustible gases CO, H2 and* CH_4*) that may be transferred as* CO_2 *to geological storage after combustion.*"[39]. Which makes the process climate positive (creating negative emissions) since biochar is less susceptible to remineralization into CO_2 and CH_4 than non-pyrogenic biomass. The three products described in the previous definition can be tracked in the following energy and matter fluxes diagram presented in Figure 13

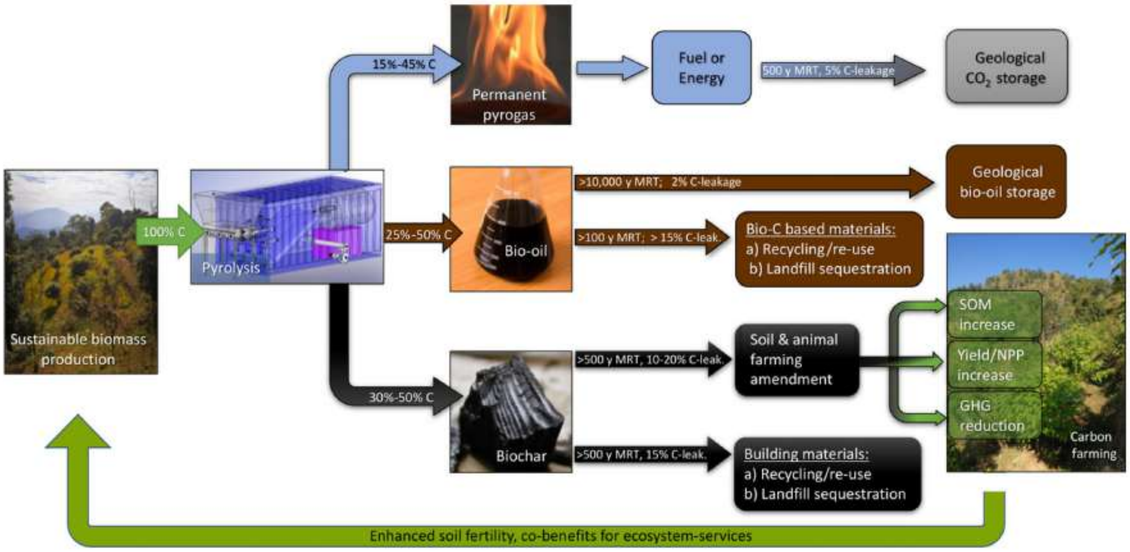


Figure 13: General pyrolytic carbon capture and storage scheme for pyrolytic treatment of biomass, the pathways of solid, liquid, and gaseous products, their use and sequestration scenarios, the respective C-leakage rates, and the circular effect on carbon farming systems and sustainable biomass production, from Schimdt et al. 2019 [40].

Uses

Biochar is defined by its quality characteristics, which are highly variable depending on the biomass type of the raw materials used, its sustainable production with parameters as the heating rate, the pyrolysis temperature or the residence time, and finally its end use. Therefore European Biochar Certificate (EBC) aims to propose different certification processes and guidelines to insures the quality of biochar production and uses, detailed in the Annex XII :

- EBC Agro, EBC AgroOrganic;
- EBC Feed;
- EBC ConsumerMaterials, EBC BasicMaterials;
- EBC Urban;
- EBC Sink (since 2020) that certify the carbon-sink potential of biochar [41].

Today, the main uses of biochar are in agriculture, urban applications and construction materials. It should be noted that not every types of biochar are suitable for every applications, precisely because biochar has different properties depending on the feedstock and process conditions. The Figure 14 offers an overview of the different biochar characteristics to consider, in this case linked to the soil properties for amended agriculture fields.

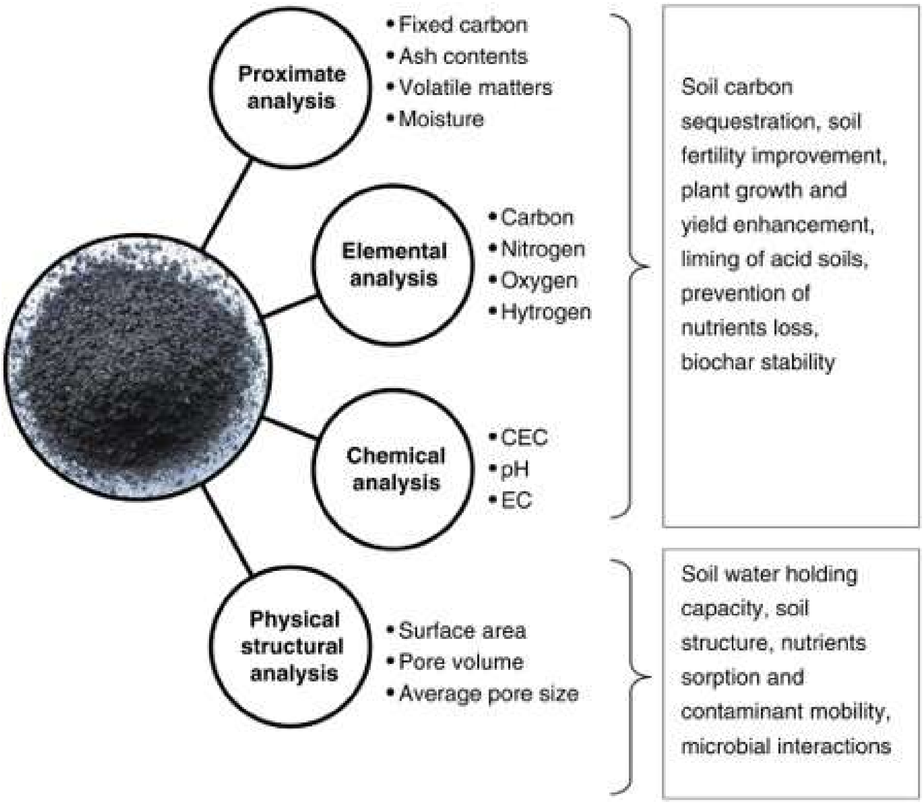


Figure 14: Biochar characteristics and associated soil properties, from Al-wabel et al. 2016 [26].

But as presented in Part 1 of the Results, the beneficial effects of biochar on crop soils are not building a scientific consensus. Considerable uncertainties exist on medium and long terms effects of amending soils with biochar. Some of them can be positive, as presented before, while others can be negative if non properly used, as summarised in the following Figure 15.

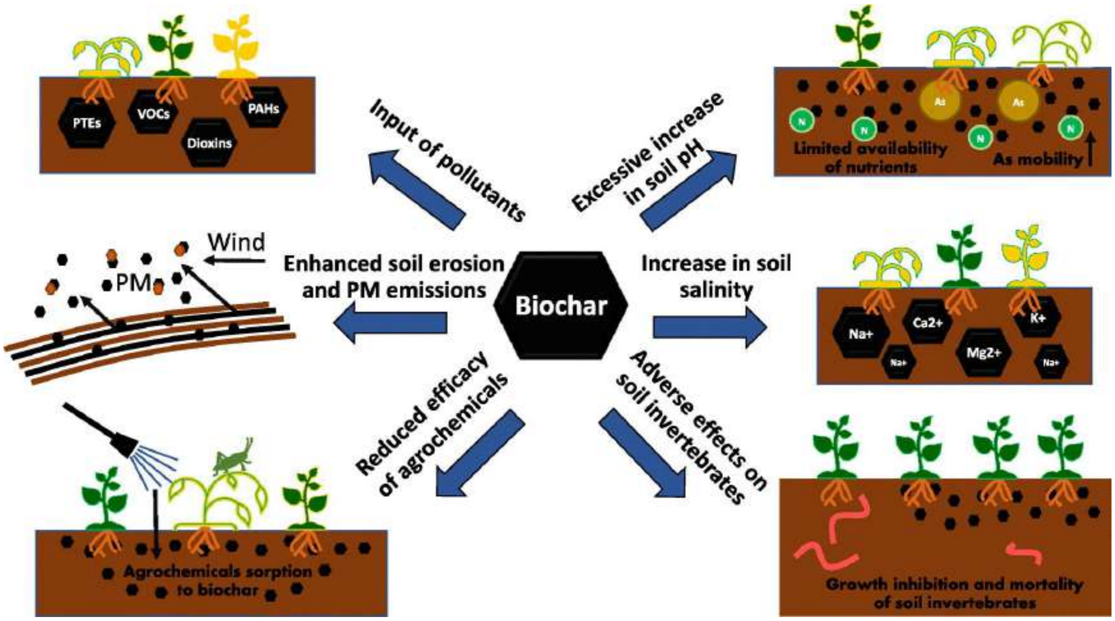


Figure 15: Possible adverse effects of biochar when used in agriculture (Brtnicky et al. 2021) [42]

History

The concept of biochar is considered to be the recovered legacy of an ancient Amazonian practice.

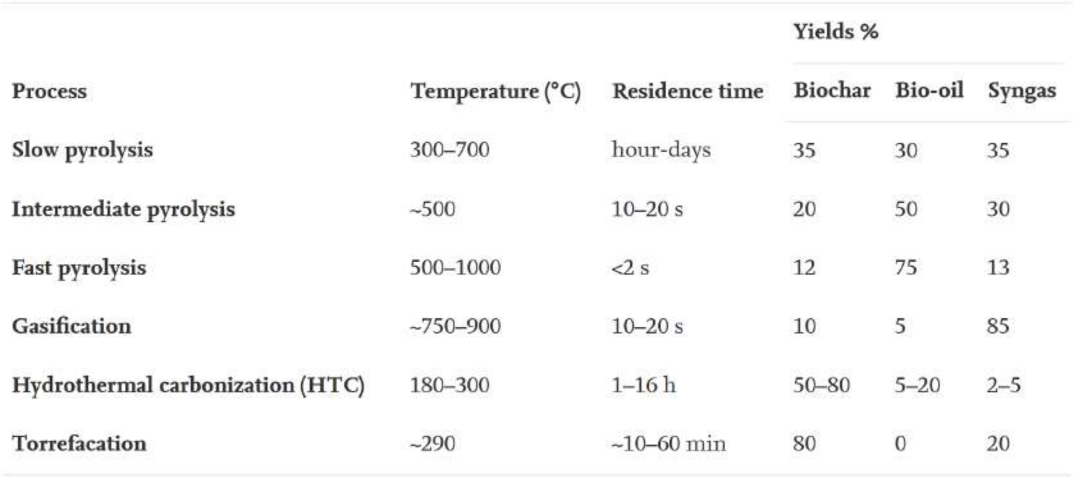
Of course the production of biochar with modern pyrolysis technologies is considered as a recent carbon sequestration strategy, but there is a prevailing belief that the practice of adding carbonised biomass to improve soil quality is not new. This process is thought to be inspired by the 2,000-year-old terra preta (meaning 'dark earth') practice of indigenous peoples in the Amazon basin, which would explain the current observation of areas of rich and fertile soils.

Studies on the subject do not say whether these soils were created intentionally or whether they are simply a by-product of agricultural and culinary practices. But they are mostly based on a common assumption: the fertility of terra preta is much higher than the one of the infertile soils of the Amazon due to past human actions. This would explain why plants grown in terra preta soils grow faster, and are richer in nutrients, than plants grown in nearby soils.

This paradigm persists and is reflected in many of the marketing arguments of companies selling biochar for soil improvement, despite the fact that new studies suggest different hypotheses about the formation of terra preta that are not of human origin (Silva et al. 2020) [43].

2.1.2 Overview of PyCCS technologies

Pyrogenic carbon capture and storage is more generally included under the category of Thermochemical processes which include as well pyrolysis as gasification, hydrothermal carbonization (HTC), and torrefaction to convert biomass into biochar, biofuel, and other bio-based products. The time residence, heating rate and temperature change among these technologies have several effects on the bio-based products yields and quality. The following table summarises the mentioned changes.



			Yields %		
Process	**Temperature (°C)**	**Residence time**	**Biochar**	**Bio-oil**	**Syngas**
Slow pyrolysis	300–700	hour-days	35	30	35
Intermediate pyrolysis	~500	10–20 s	20	50	30
Fast pyrolysis	500–1000	<2 s	12	75	13
Gasification	~750–900	10–20 s	10	5	85
Hydrothermal carbonization (HTC)	180–300	1–16 h	50–80	5–20	2–5
Torrefacation	~290	~10–60 min	80	0	20

Table 6: The reaction conditions and products distribution of various PyCCS technologies, from Quambrani et al. 2017 [44]

This study focuses on the most developed technical approaches that produce a reasonable quantity of biochar with properties optimised for carbon capture and storage. In this regard, conventional pyrolysis appears as the most suitable process, but there is a fundamental distinction to showcase.

As described in Quambrani et al. 2017, Slow pyrolysis is described as a simple, robust and low-cost process, applicable to small-scale and on-farm biochar production. It is a thermal conversion process characterised by long residence times and slow heating rates that produce approximately equal yields of solid, gaseous and liquid products. The heat for slow pyrolysis is provided by partial combustion of biomass, by external heaters or by recirculation of hot gases, and the process is carried out at atmospheric pressure. These conditions improve the yield of biochar by increasing the cracking reactions which reduce the production of liquids or bio-oil.

Fast pyrolysis processes at high temperatures result in increased levels of partially pyrolysed biochar components compared to slow pyrolysis processes. This leads to the formation of polycyclic aromatic hydrocarbons - PAHs, that are organic pollutants that need a careful control of the process and regular analysis. It is also a thermal conversion process characterised by short residence times (<2 s), fast heating rates (>2 °C s-1) and moderate temperatures (500-1000 °C). This process has been the most widely used process until now, as the desired product is mainly bio-oils. It allows high yields of bio-oil (75%) to be obtained from biomass, which is a source of energy and can also be used as a raw material for the production of chemicals.

Different types of reactors have been used for fast pyrolysis, such as vacuum, fluidised bed, transported bed, rotating cone, vortex centrifuge, ablation, screw and screw reactors. Other reaction systems for fast pyrolysis include radiative-convective inflow pyrolysis, microwave pyrolysis, moving and fixed bed pyrolysis, and ceramic ball down-low pyrolysis which are well documented, but not yet commercialised in many countries.

This kind of conventional pyrolysis unit can be represented as the following flow diagram, that includes in this example a part of the pyrolysis gas that is used for Electricity generation and sales as an extra source of revenues. This example will be further analysed in the relevant costs analysis section of this report.

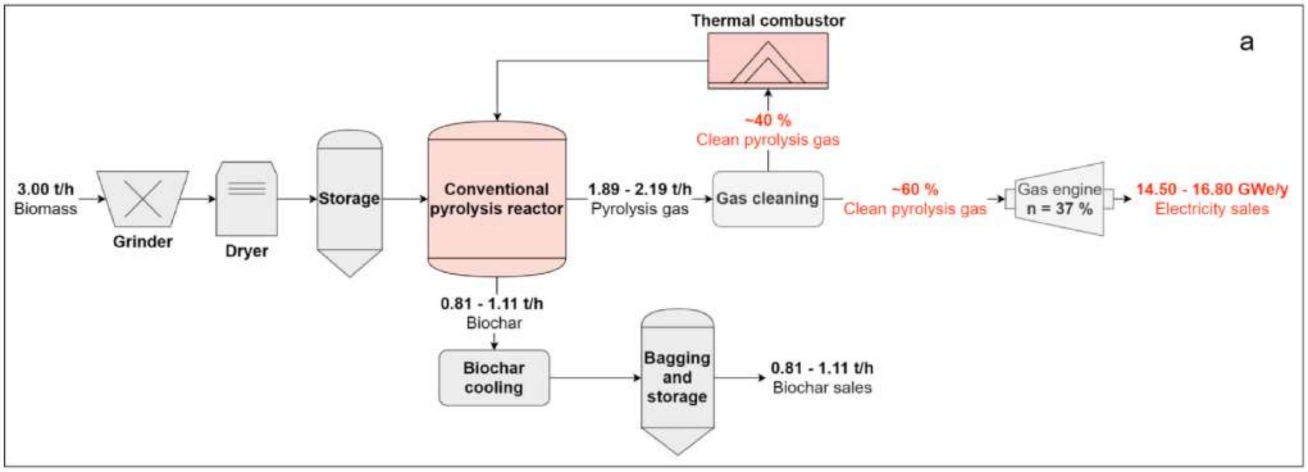


Figure 16: Simplified process flow diagram and mass and energy balance of biochar production with conventional reactors, according to Haeldermans et al. 2020 [45].

2.1.3 Biomass database

The WSL 2017 study [13] presents for the 10 types of biomass the annual biomass theoretical, sustainable, already used, and additional sustainable potentials, in Fresh Mass, Dry mass and Energy Content, as detailed in the Annex XIII. But to create negative emissions, it would not make sense to centralise the biochar production and transport biomass throughout Switzerland, generating by the way more emissions. So the aim was to have access to biomass potential at a local scale to identify local hot spots of production.

To do so, this thesis resulted in the constitution of a Biomass database, compiling the **annual sustainable biomass potential** :

- in term of : energy content [GJ/yr], dry mass [t/yr], biochar production capacity [t/yr], and resulting potential CO_2eq negative emissions [tCO_2eq/yr];
- for the 10 biomass types (Animal manure, Agricultural crop by-products, Sewage sludge, Organic fraction of household garbage, Green waste from households and landscape, Commercial and industrial organic waste, Waste wood, Wood residues, Forest wood, Wood from landscape maintenance), the total for woody biomass, the total for non woody biomass, and the overall total;
- at the communes, districts, cantons and national scales;
- in absolute values and values normalised by the area.

As nowadays the only type of biomass legally accepted to produce biochar are woody biomass, the rest of the results focus on these 4 categories, even though for some figures the potential of Agricultural crop by-products and Green waste from households and landscape are also displayed. Indeed, they represent the 2 most interesting non-woody biomass to include in the biochar production as they are not over-exploited yet and do not have a too large moisture content that would require an important drying process before being pyrolysed.

At the national level, the sustainable woody biomass potential reaches a total of 3.5 millions tons per year that are distributed among the 4 woody biomass types as shown by the figure 17, that would generate 780'000 tons of biochar per year if entirely pyrolysed . The figure 18, for its part, shows this potential classified by canton, with the related maps detailed per biomass types available in the Annex XIII.

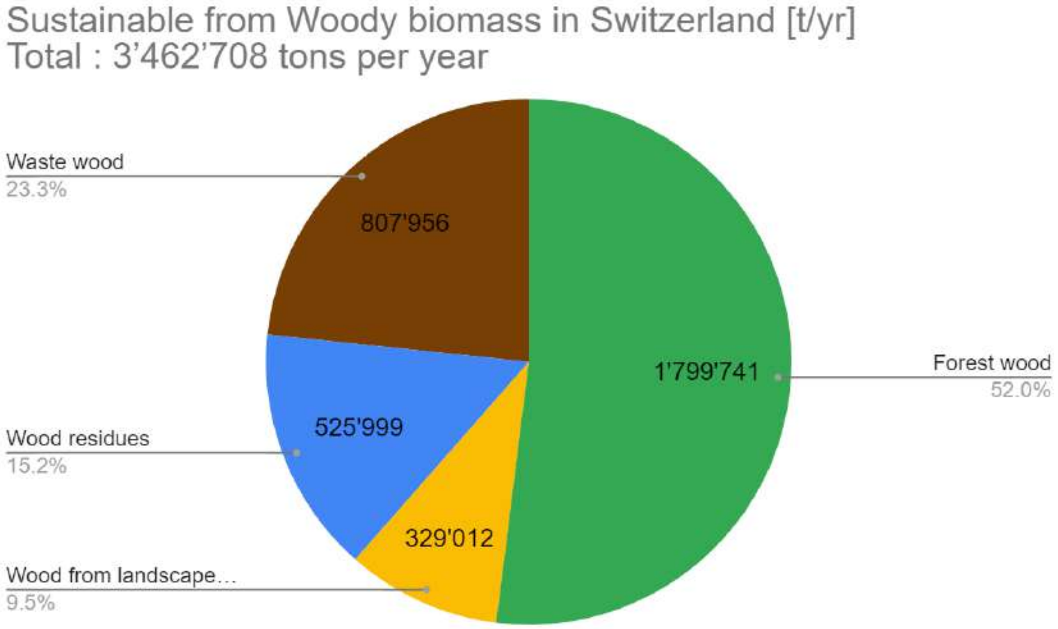


Figure 17: Sustainable biomass potential from total Woody Biomass [t/yr]

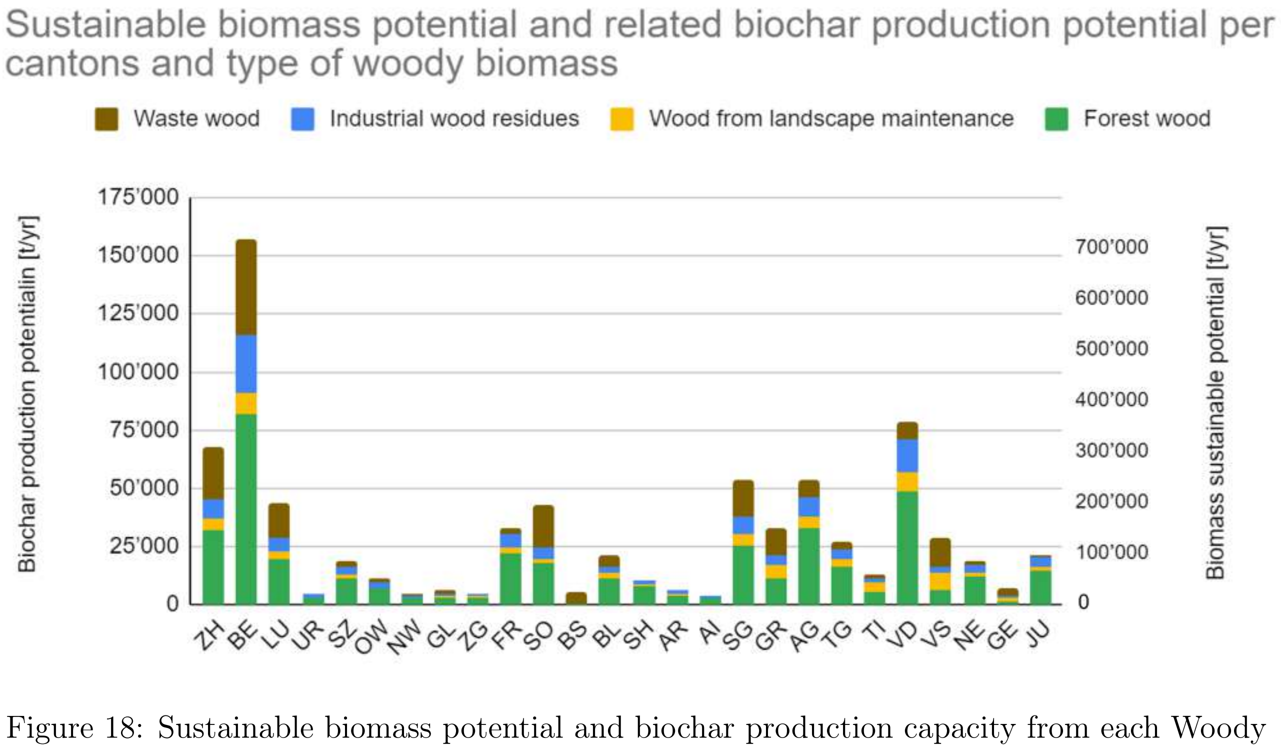
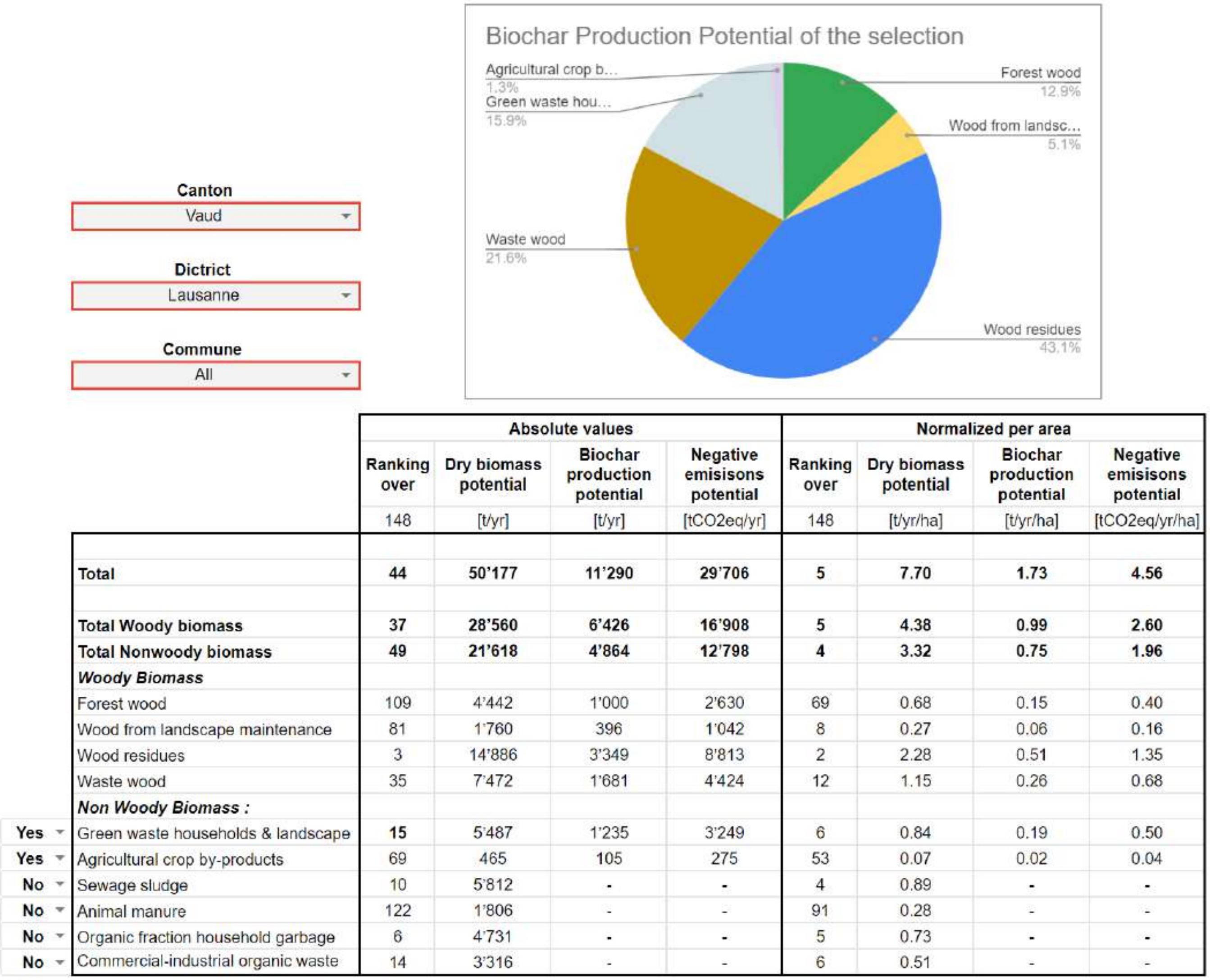


Figure 18: Sustainable biomass potential and biochar production capacity from each Woody Biomass per canton [t/yr]

An exploration and visualisation tool was developed to navigate throughout the database and easily find the desired values, as represented in the Figure 19. It allows the users to select the regional scale of interest, either at the national, cantonal or communal level, and display the biomass, biochar and negative emission potentials according to all types of biomass. It also indicates the ranking of the regional scale regarding its potential for each type of biomass, and automatically produces a graph to represent the respective shares of each type of biomass in the total potential. It is possible to include or not the non-woody biomass types desired in the graph by selecting them with the bottom left buttons.

The values displayed are to be considered as maximum potential regarding the biosphere capacity to produce biomass without being degraded.



Canton: Vaud

Dictrict: Lausanne

Commune: All

		Absolute values				Normalized per area			
		Ranking over 148	Dry biomass potential [t/yr]	Biochar production potential [t/yr]	Negative emisisons potential [tCO2eq/yr]	Ranking over 148	Dry biomass potential [t/yr/ha]	Biochar production potential [t/yr/ha]	Negative emisisons potential [tCO2eq/yr/ha]
	Total	**44**	**50'177**	**11'290**	**29'706**	**5**	**7.70**	**1.73**	**4.56**
	Total Woody biomass	**37**	**28'560**	**6'426**	**16'908**	**5**	**4.38**	**0.99**	**2.60**
	Total Nonwoody biomass	**49**	**21'618**	**4'864**	**12'798**	**4**	**3.32**	**0.75**	**1.96**
	Woody Biomass								
	Forest wood	109	4'442	1'000	2'630	69	0.68	0.15	0.40
	Wood from landscape maintenance	81	1'760	396	1'042	8	0.27	0.06	0.16
	Wood residues	3	14'886	3'349	8'813	2	2.28	0.51	1.35
	Waste wood	35	7'472	1'681	4'424	12	1.15	0.26	0.68
	Non Woody Biomass :								
Yes	Green waste households & landscape	**15**	5'487	1'235	3'249	6	0.84	0.19	0.50
Yes	Agricultural crop by-products	69	465	105	275	53	0.07	0.02	0.04
No	Sewage sludge	10	5'812	-	-	4	0.89	-	-
No	Animal manure	122	1'806	-	-	91	0.28	-	-
No	Organic fraction household garbage	6	4'731	-	-	5	0.73	-	-
No	Commercial-industrial organic waste	14	3'316	-	-	6	0.51	-	-

Figure 19: Exploration and visualisation tool for the biomass database developed in this thesis

2.1.4 Negative emissions potential of biochar production at local scale

At the national scale, the woody biomass has the capacity to produce **779'109 tons of biochar per year**. This could generate **2'050'000 tCO_2eq negative emissions per year**. It is considerable as it represents **40%** of the remaining incompressible emissions of Switzerland if the country makes a success of its energy transition as detailed in PART 1. If we include Agricultural crop by-products and Green waste from households and landscape, the potentials of biochar production and negative emissions respectively reach **1 Millions tons of biochar per year** that could generate **2'630'000 tCO_2eq negative emissions per year**, which would be 50% of remaining emissions.

This biochar production capacity is well distributed among the cantons, as represented in figure 20, but we can note that the 3 main producers could be the canton of Bern, Vaud and Zurich.

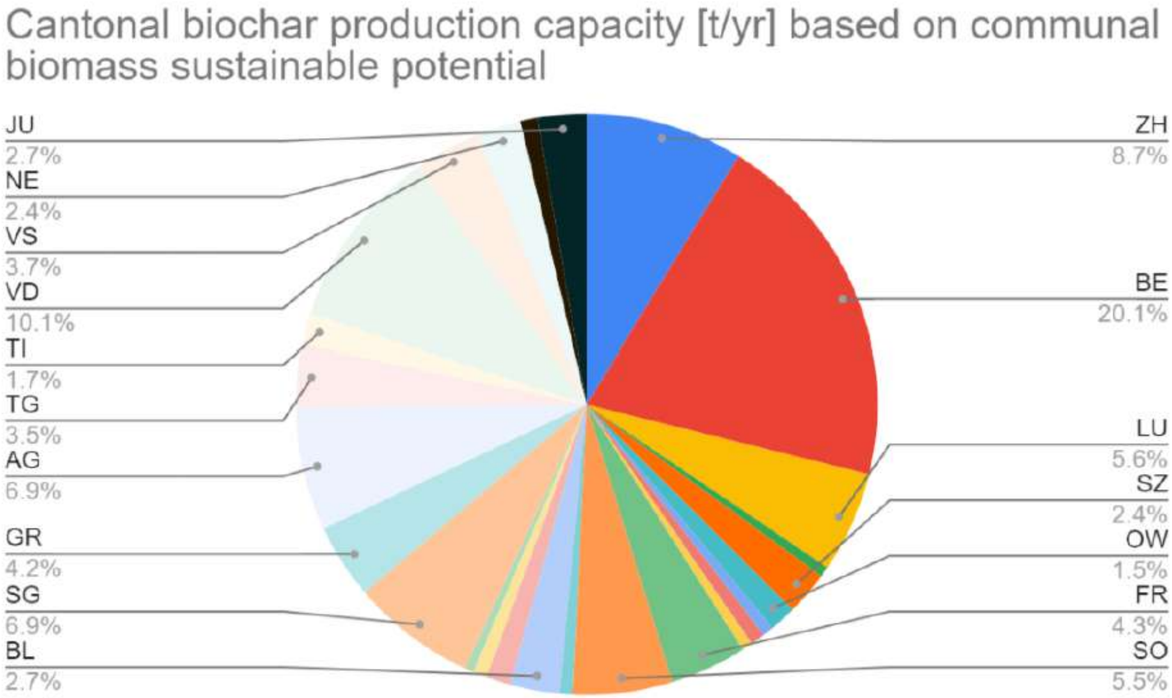


Figure 20: Cantons biochar production capacity distribution

To visually represent the biochar production capacity and negative emissions potential of each canton, maps were created in addition to the tables. It is then interesting to look at the absolute values of the potentials, but also at the normalised values per area, to eliminate the bias that bigger cantons with more important surface areas will naturally have more biomass production on their territory. The following maps in Figure 21 take the example of the total woody biomass, and the legend, in ton of biochar per year, can be converted to Negative emissions potential by applying a multiplicative factor of 2.63.

The complete list of cantonal maps for all biomass types are available in the Annex XIV.

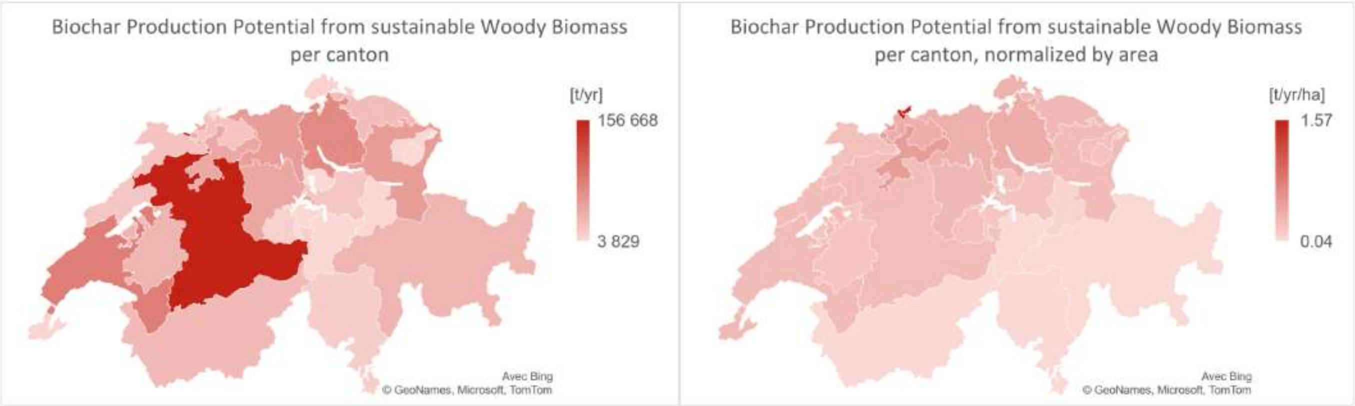


Figure 21: Biochar Production Potential from woody biomass at Cantonal level

It can be observed that the rankings change a lot whether we are looking at the absolute potential or the one normalised per area. It reveals that cantons with a small surface area represent more "intense" spots of biochar production. The same phenomena can be observed between communes of different sizes.

But with a mean value among cantons of 133'181 tons of biomass to process per year, to create 30'000 tons of biochar per year, it is clear that the cantons still represent a too big scale for the implementation of pyrolysis units. It is interesting for the cantons to have those numbers as they could be relevant for their Climate plans and biomass management strategies, but not any pyrolysis unit is capable of producing so much biochar.

Therefore the relevant scale for the biochar production capacity is the communal one. The same maps as for the cantons were edited at the communal level for each biomass type which offers a much finer grid to read the biochar production capacity throughout the Swiss territory. The maps in the following pages represent the potential for the total woody biomass, and the ones for the other specific types of biomass are available in the Annex XV.

The communes were sorted by classes for the legends to be clear and maps more readable. The classes represent a ranking of commune following an exponential scale, as follows :
Class 1 (the Darker) : TOP 5 communes [1-5]
Class 2 : Following 20 [6-25]
Class 3 : Following 100 [26-125]
Class 4 : Following 500 [126-625]
Class 5 (The Lighter) : All resting communes (1800) [626-2296]

Classifying the communes per rank is the only maps styling methodology able to :

- Have the same number of communes in similar classes between different maps of biomass types and between the absolute and normalised per area ones
- Represent biochar production capacity and negative emissions potentials on the same map, since they are 100% correlated with a factor 2.63.

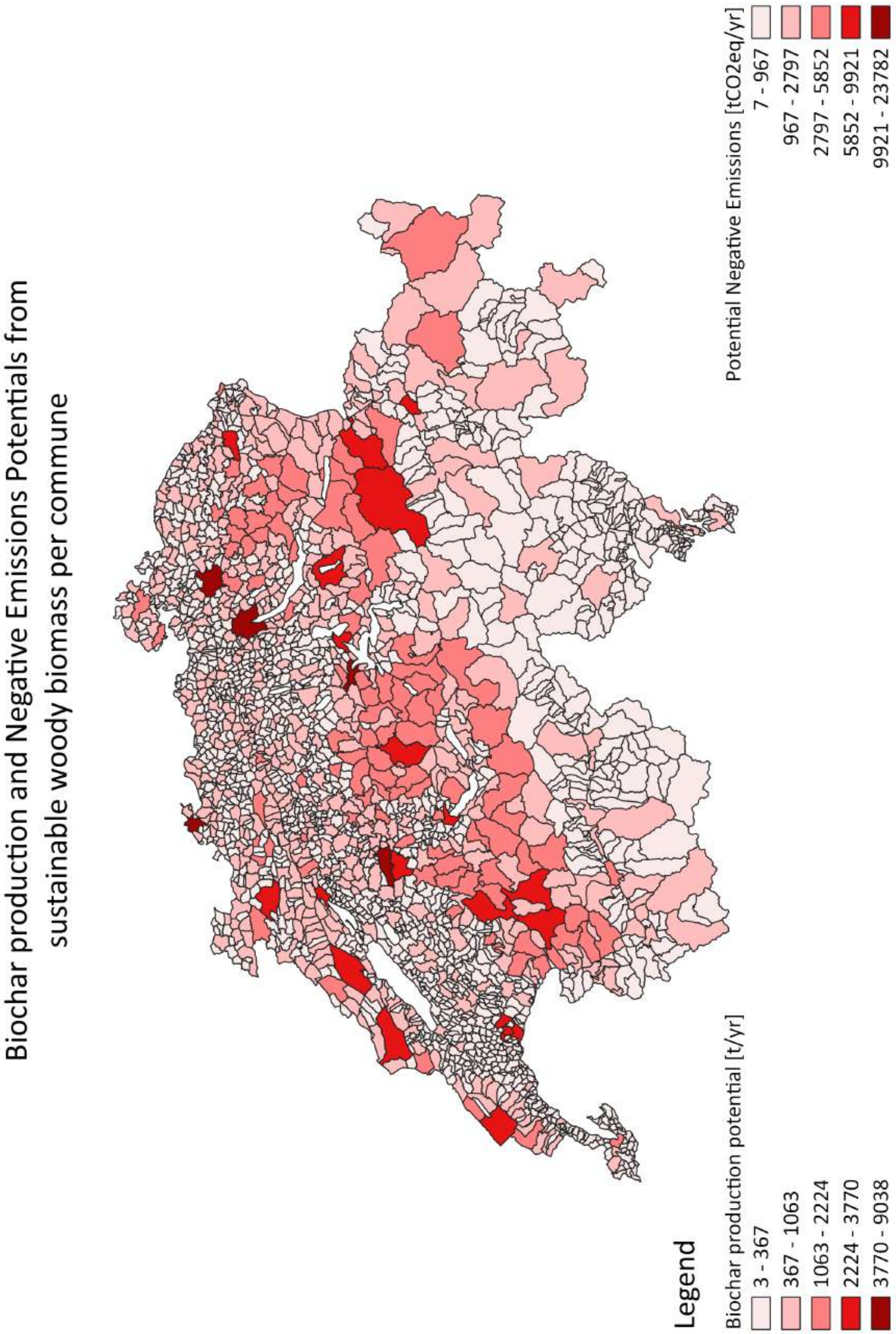


Figure 22: Biochar production and negative emission potentials from sustainable woody biomass at the communal level.

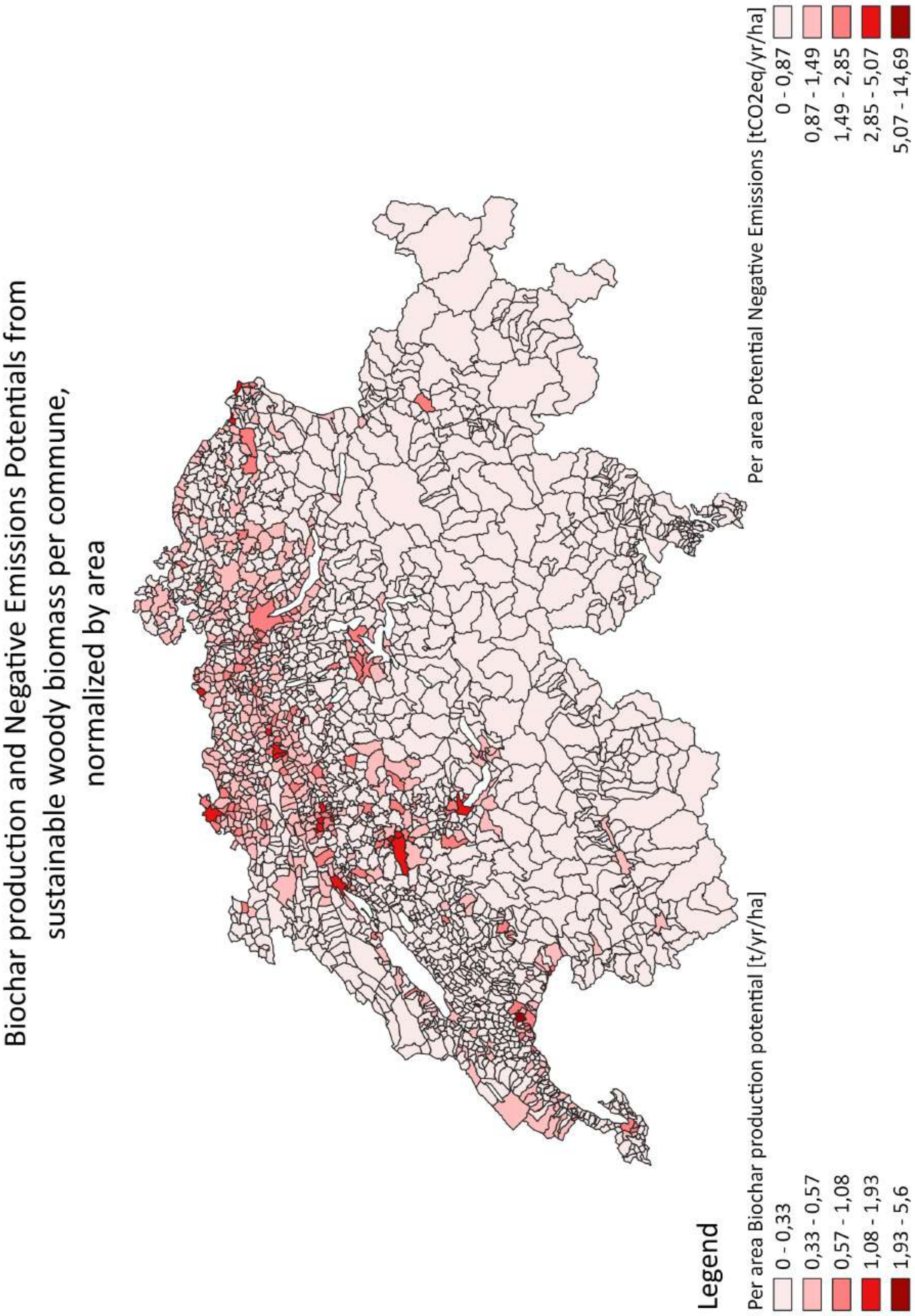


Figure 23: Biochar production and negative emission potentials from sustainable woody biomass at the communal level, normalised per area.

2.2 Regenerating Peatlands' carbon sink capacity

2.2.1 Terminology

The terminology around peatlands, wetlands, and organic soils can be very confusing due to a large variety of definitions that refer to different professions. Some terms were defined by biologists and pedologists to characterise soils according to the biochemical exchanges that regulate the formation and decay of matter in this environment, others were defined by ecologists and environmental scientists to describe the ecosystems according to the vegetation present at this location, or finally other terms exist to allow urban planner to classify these parts of the territory. In addition, there are regional differences in the determination and classification of ecosystems, making it possible that the same biotope could be presented with different names in different countries. Therefore a classification of the terminology seems important.

The following figure is an attempt to clarify the different terminologies encountered during this thesis, based on the subjective interpretation of the official definitions given by The Mediterranean Wetlands Initiative MedWet on their website [46], presented in the Annex I .

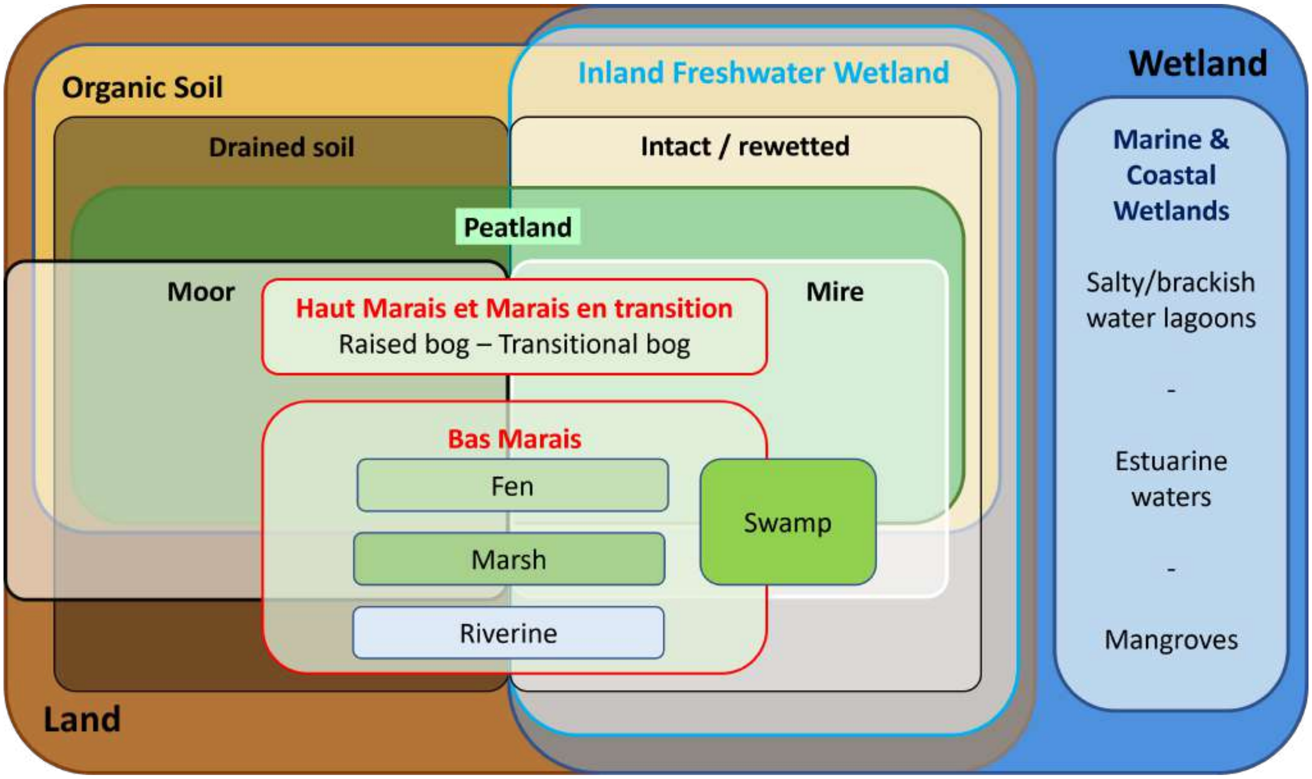


Figure 24: Schematic representation of peatland terminology used in this thesis. In red is the Swiss terminology, in French since there is no official translation in English. In black, the terms used in the international community.

This figure does not represent an official classification, as are, for example, the US Fish and Wildlife Service's "*Classification of Wetlands and Deepwater Habitats of the United States*", published by Cowardin et al. 1979, or the classification adopted by the Ramsar Convention at the Montreux Conference in 1990. It is not intended to be exhaustive of the types, categories and terms used to classify wetlands. The only intended goal is to help the reader clarifying the terms used in the project and the relevance of the scopes choice.

The main learning from this journey into terminology classification is that terms such as wetland, mire, or moor, are very generic terms that includes different ecosystems and have a common meaning that is not necessarily the same as the official definitions.

Two interesting complementary definitions of Wetland are a good way to start with. Keddy, P.A. (2010) defines a wetland as "*an ecosystem that arises when inundation by water produces soils dominated by anaerobic and aerobic processes, which, in turn, forces the biota, particularly rooted plants, to adapt to flooding.*" which covers a broad range of ecosystems, focusing on the processes that occur in those environments. Then, the Ramsar definition completes it with a description of the fundamental components and characteristics that are present in a wetland : "*Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static, flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six metres*". So the term "wetland" includes as well as Coral reefs, Florida estuaries, Borneo peat swamp forests or Swiss raised bogs.

The term "Organic soils" generally refers to any soil or soil horizon consisting chiefly or containing at least 30% of organic matter. But regarding a pedological approach, Agroscope (2015) stated that a soil can be considered as organic in the Swiss GHG inventory if it respects the IPCC 2006 following definition:

"*Organic soils are found in wetlands or have been drained and converted to other land-use types (e.g., Forest Land, Cropland, Grassland, Settlements). Organic soils are identified on the basis of criteria 1 and 2, or 1 and 3 listed below (FAO, 1998):*

1. *Thickness of organic horizon greater than or equal to 10 cm. A horizon of less than 20 cm must have 12 percent or more organic carbon when mixed to a depth of 20 cm.*
2. *Soils that are never saturated with water for more than a few days must contain more than 20 percent organic carbon by weight (i.e., about 35 percent organic matter).*
3. *Soils are subject to water saturation episodes and have either:*
    (a) *At least 12 percent organic carbon by weight (i.e., about 20 percent organic matter) if the soil has no clay; or*
    (b) *At least 18 percent organic carbon by weight (i.e., about 30 percent organic matter) if the soil has 60 % or more clay; or*
    (c) *An intermediate, proportional amount of organic carbon for intermediate amounts of clay."*

Halfway between these two terms stand the Peatlands, particularly adapted for Switzerland since it describes peat-forming ecosystems presented as inland freshwater wetlands colonised by mosses of the genus Sphagnum. The peat itself is described as a dark-brown or black residuum produced by the partial decomposition and disintegration of mosses, sedges, trees, and other plants that grow in bogs and other wet places. For a more rigorous definition in terms of pedology, experts no longer talk about peat but about histosoils, formed by histic horizons. According to the French Association for Soil Studies (AFES, 2009), which is the main authority in the French-speaking

Europe, a histic horizon is a "*holorganic horizon formed in a water-saturated environment for prolonged periods (more than 6 months per year) and composed mainly of hydrophilic or subaqueous plant debris. Its ash content (obtained by calcination at 600°C) must be less than 50%*". In other words, peat contains at least 50% organic matter.

This is why this thesis focuses on peatlands and organic soils in Switzerland, for which it can reasonably be assumed that they were once a peatland, as main GHG emitters if they remain drained.

Regarding the different typologies of actions that can be accomplished on a drained wetland, this thesis follow the definitions of Wilson et al. (2016) that indicated that Wetland restoration (or renaturation) always aims to permanently re-establish the pre-disturbance ecosystem, including the typical hydrological and biogeochemical processes of water saturated soils, as well as the vegetation cover that predated the disturbance (original source : Nelleman Corcoran 2010 [47]). The rewetting is then a voluntary act of adjusting the water table level to raise it, whether it remains at the surface level or fully floods the ecosystem by saturating it in water. Usually, the restoration of drained organic soils is accompanied by rewetting, while the restoration of undrained but otherwise disturbed wetlands may not require rewetting. Rehabilitation, as defined by Poopathy et al. (2005) and Nelleman Corcoran (2010), can involve a large variety of practices on formerly drained organic soils, which may or may not include rewetting. For example, the re-establishment of vegetation on a drained site without rewetting is a form of site rehabilitation.

2.2.2 From carbon sinks to carbon sources - and vice versa?

Global Peatlands, even if they cover only about 3% of the global land area, store more carbon than what is naturally present in the atmosphere [48] and twice as much as global forest biomass [49]. This is due to the fact that year-round water-logged conditions slow plant decomposition to such an extent that dead plants accumulate to form peat. In good health, they store the carbon absorbed by the plants from the atmosphere within peat soils, providing a net-cooling effect and helping to mitigate the climate crisis. According to IUCN, the remaining area of near natural peatlands worldwide is around 3 million km^2 and sequesters 0.37 gigatons of CO_2 a year. Peat soils contain more than 600 gigatons of carbon which represents up to 44% of all soil carbon, and exceeds the carbon stored in all other vegetation types including the world's forests [50].

However, many peatlands are degraded and under pressure from drainage based agriculture and plantation development, which cause the global annual emissions of 2 Gt CO_2 by microbial peat oxidation or peat fire. This represents 5% of all anthropogenic GHG emissions on only 0.3% of the territory[31].

In rain-rich Switzerland, with its diverse surfaces shaped by the ice ages, mires were once widespread before the industrial age. At least 6 % of the country's area (approximately 2'500 km^2) was covered by this ecosystem. 15'000 years ago, the retreating glaciers left behind an impermeable subsoil and depressions in many places where bog formation began. Peatlands also formed during sedimentation of ponds and lakes, at high groundwater levels (e.g. near rivers and lakes), in regions with a lot of precipitation, in the vicinity of springs and on slopes with a constant supply of water.

Peat mosses, as Sphagnum, colonised these environments and its dead plant parts, the base of it, are hermetically sealed by the abundant water and are therefore only slowly decomposed by microorganisms, due to flooded conditions, the absence of oxygen preventing the oxidation of carbon that would cause its mineralization, sending it back to the atmosphere, and acidic conditions that prevent methanogenic microorganisms to develop. Every new layer of plant material formed is then stored as organic matter in a soil that grows steadily, at the average rhythm of 1 mm/yr.

From the 17th century, humans stopped the growth of most peatlands. Peat was an important source of energy (called "underground wood", "black gold"), which was extracted in peat pits, first by hand and later by machine, destroying the whole ecosystem and ending the services it provides to humanity's well-being. If the crime of ecocide was recognized in the international law and the Swiss penal code, peat extraction could have been considered as one.

Most of the peatlands were drained and reclaimed for agricultural and forestry use, due to their high content in carbon that induces a high fertility of the soil, and a high energy content as a source of energy. Since then, ditches and underground drainage systems have diverted the water from the former bogs. The influx of air as a result of drainage and the intensive agricultural use lead to a continuous loss of peat and to a (repeated) lowering of the drainages up to the complete disappearance of the peat soils.

Peat extraction was stopped in 1987 with the Rothenthurm initiative, a Popular initiative "for the protection of the mires". It was officially tabled to protect threatened biotopes, but in fact it was aimed at preventing the expansion of the Rothenthurm parade ground (located on the border between the cantons of Schwyz and Zug). The military department's plan was to build barracks and two training grounds, one of which would have been partially located in a marshy area. The initiative proposed to amend Article 24 of the Federal Constitution by adding a new paragraph specifying that all construction is forbidden on marshes "*of particular beauty and national interest*"; the initiative also provided for the dismantling of all buildings contravening the rule in the Rothenthurm area. Thanks to this initiative, as early as 1977, the Federal Office for the Environment set up a federal landscape inventory which "*identifies landscapes and natural monuments of special value in Switzerland*". Thus, 15 years after the initiative was accepted, 90% of the raised bogs of national importance, 75% of the "*Bas-marais*" and half of the mires area in the country are under protection. However, a 2007 study by Pro Natura, based on photographic comparisons, shows that bogs and marshes are drying out and becoming overgrown as a result of drainage channels that were built before the biotope protection.

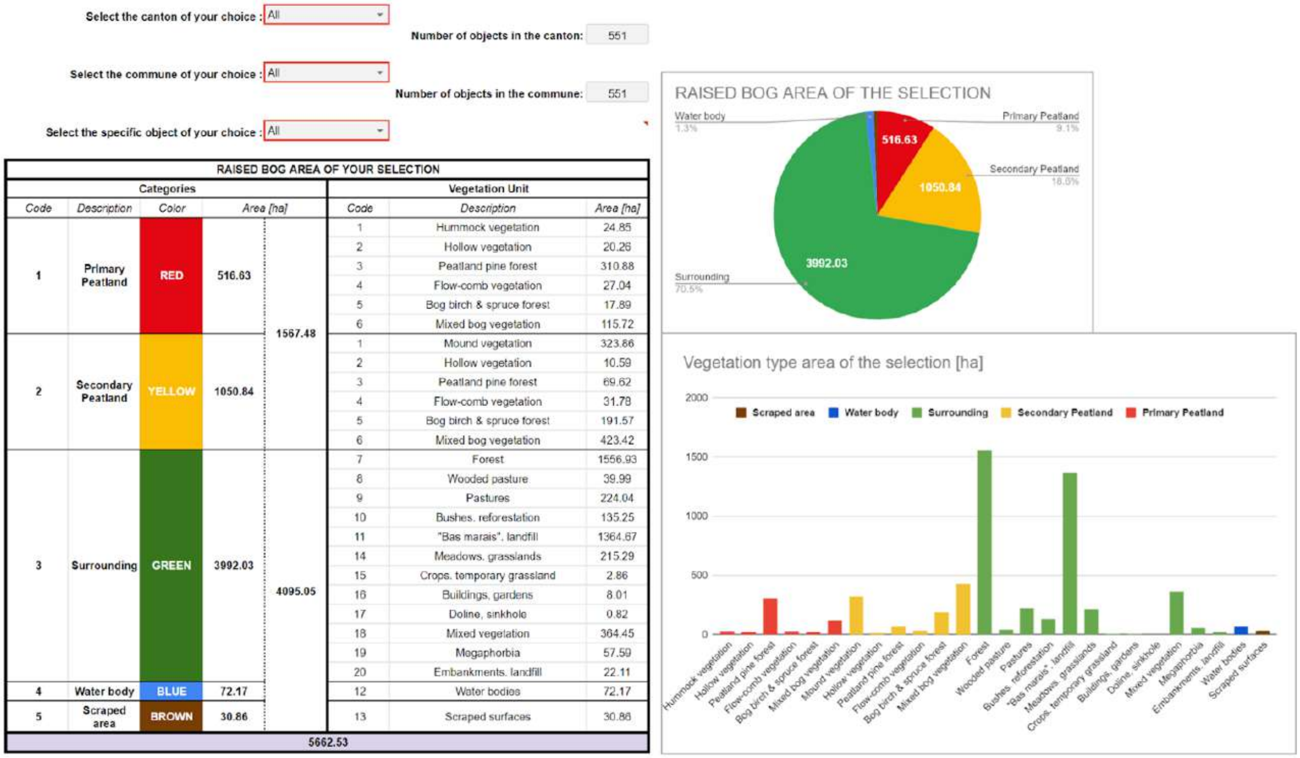
Of these 2'500 km^2 of mires initially present, Dr. Chloé Wüst-Galley identified 1'000-1'500 km^2 of organic soils at the pre-industrial age from historical maps and testimonies that can be considered as peatlands [28]. However, it was possible to locate nowadays only 280-350 km^2 of organic soils (estimates for categories I-V and I-VII of Agroscope 2015 as represented in Figure 4). For now we do not know in which state the remaining soils of the historical estimates are. Among those organic soils, only 15 km^2 (1% of initial pre-industrial estimate) are protected as raised bogs peatlands, but the 2/3 of them present clear signs of drainage ditches at their surface and continue to emit carbon, making only 5 km^2 called as Primary Peatlands (no affected by human activities) and considered in a good state. However, those primary peatlands are surrounded by drained secondary peatlands, and it is clear that their water level table is also affected by the surrounding drainage. According to experts' estimations, the raised bogs actually intact and in their near-natural form would concern only 1/3 of the primary peatlands, approximately 1.5 km^2, or 0.1% of the initial peatlands of Switzerland.

The rest of the former peatlands of Switzerland are organic soils that are currently under intensive or extensive land use and are slowly but surely decomposing, sending back to the atmosphere the carbon accumulated during centuries in a few years. Therefore the challenge is to reverse the current mechanism by restoring peatlands to regenerate their carbon sink capacity.

2.2.3 Organic soils database

For this thesis, data from the respective inventories were taken to build an organic soils database gathering the 3 different scopes presented in the methodology. As the inventory of raised bogs is way more precise that the other ones, it was possible to create an exploration and visualisation tool for the Scope 1 that allows the user to choose the desired regional scale of it choice, either the nation, cantonal, communal scale or a precise raised bog object.

Then, the spreadsheet automatically displays in a table and 2 figures the area of the raised bogs, declined in the 5 land use categories and 20 types of vegetation, as represented in the following Figure 66, for the national scale. A more readable version is accessible in Annex XVI.



Select the canton of your choice : All

Number of objects in the canton: 551

Select the commune of your choice : All

Number of objects in the commune: 551

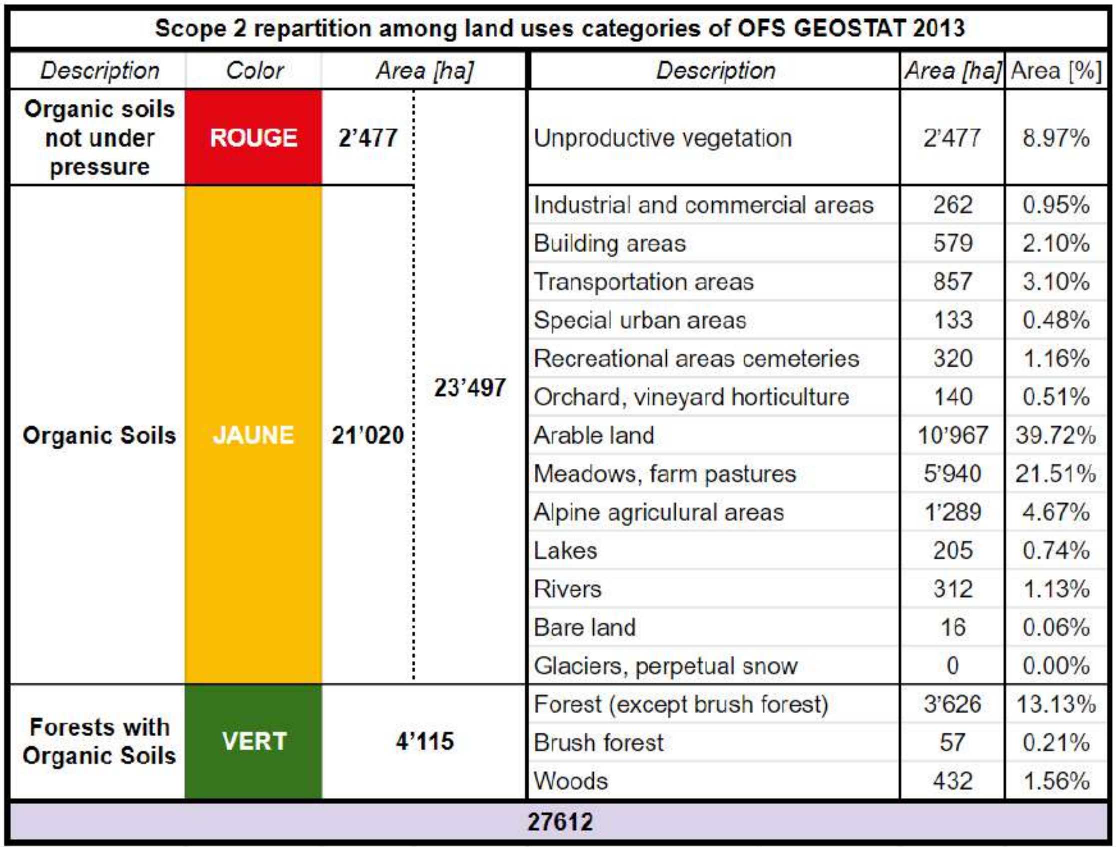
Select the specific object of your choice : All

RAISED BOG AREA OF YOUR SELECTION							
Categories					Vegetation Unit		
Code	Description	Color	Area [ha]		Code	Description	Area [ha]
1	Primary Peatland	RED	516.63	1567.48	1	Hummock vegetation	24.85
					2	Hollow vegetation	20.26
					3	Peatland pine forest	310.88
					4	Flow-comb vegetation	27.04
					5	Bog birch & spruce forest	17.89
					6	Mixed bog vegetation	115.72
2	Secondary Peatland	YELLOW	1050.84		1	Mound vegetation	323.86
					2	Hollow vegetation	10.59
					3	Peatland pine forest	69.62
					4	Flow-comb vegetation	31.78
					5	Bog birch & spruce forest	191.57
					6	Mixed bog vegetation	423.42
3	Surrounding	GREEN	3992.03	4095.05	7	Forest	1556.93
					8	Wooded pasture	39.99
					9	Pastures	224.04
					10	Bushes. reforestation	135.25
					11	"Bas marais". landfill	1364.67
					14	Meadows. grasslands	215.29
					15	Crops. temporary grassland	2.86
					16	Buildings, gardens	8.01
					17	Doline, sinkhole	0.82
					18	Mixed vegetation	364.45
					19	Megaphorbia	57.59
					20	Embankments. landfill	22.11
4	Water body	BLUE	72.17		12	Water bodies	72.17
5	Scraped area	BROWN	30.86		13	Scraped surfaces	30.86
5662.53							

Figure 25: Exploration and visualisation tool for the raised bogs database

This tool is not yet implemented for the Scope 2 as data existed only for the national scale, but could be constructed in a future work, however it is not possible to implement it for Scope 3 as the areas considered in this scope are not located. For the rest of the inventories, tables of areas per object, commune and canton were created on a spreadsheet to access it in an easy way.

Regarding Scope 2, and Scope 3, their distribution among the different land uses categories is detailed in the following Figures 26 and 27.



Scope 2 repartition among land uses categories of OFS GEOSTAT 2013

Description	*Color*	*Area [ha]*		*Description*	*Area [ha]*	Area [%]
Organic soils not under pressure	**ROUGE**	**2'477**	**23'497**	Unproductive vegetation	2'477	8.97%
Organic Soils	**JAUNE**	**21'020**		Industrial and commercial areas	262	0.95%
				Building areas	579	2.10%
				Transportation areas	857	3.10%
				Special urban areas	133	0.48%
				Recreational areas cemeteries	320	1.16%
				Orchard, vineyard horticulture	140	0.51%
				Arable land	10'967	39.72%
				Meadows, farm pastures	5'940	21.51%
				Alpine agricular areas	1'289	4.67%
				Lakes	205	0.74%
				Rivers	312	1.13%
				Bare land	16	0.06%
				Glaciers, perpetual snow	0	0.00%
Forests with Organic Soils	**VERT**	**4'115**		Forest (except brush forest)	3'626	13.13%
				Brush forest	57	0.21%
				Woods	432	1.56%
		27612				

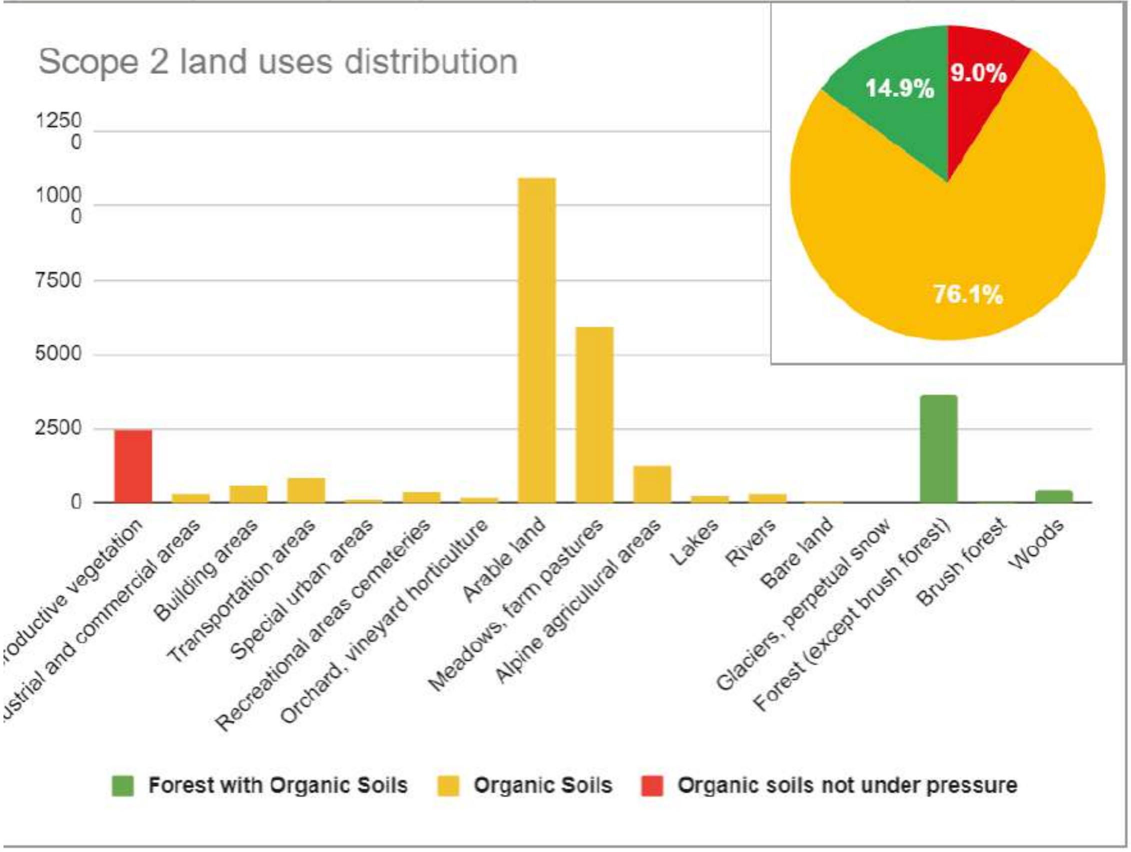
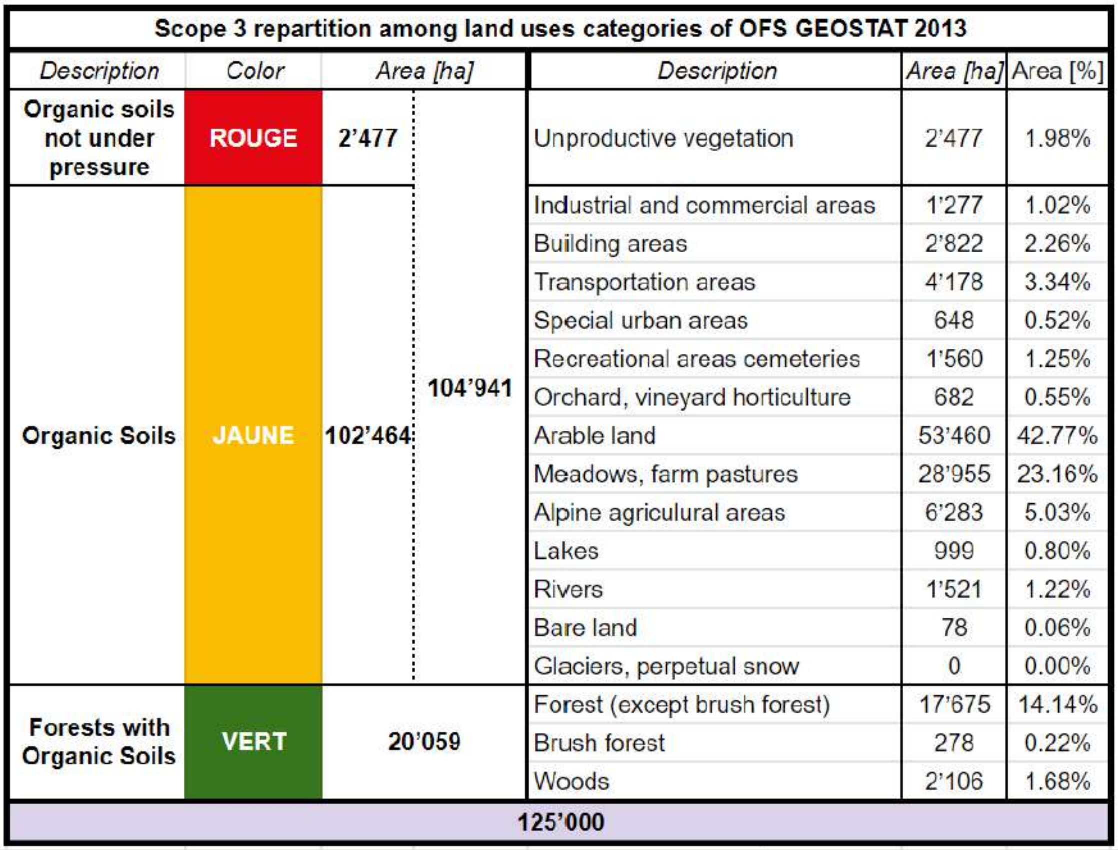


Figure 26: Distribution of Scope 2 among the different land uses categories



Scope 3 repartition among land uses categories of OFS GEOSTAT 2013						
Description	*Color*	*Area [ha]*		*Description*	*Area [ha]*	Area [%]
Organic soils not under pressure	**ROUGE**	**2'477**	**104'941**	Unproductive vegetation	2'477	1.98%
Organic Soils	**JAUNE**	**102'464**		Industrial and commercial areas	1'277	1.02%
				Building areas	2'822	2.26%
				Transportation areas	4'178	3.34%
				Special urban areas	648	0.52%
				Recreational areas cemeteries	1'560	1.25%
				Orchard, vineyard horticulture	682	0.55%
				Arable land	53'460	42.77%
				Meadows, farm pastures	28'955	23.16%
				Alpine agricultural areas	6'283	5.03%
				Lakes	999	0.80%
				Rivers	1'521	1.22%
				Bare land	78	0.06%
				Glaciers, perpetual snow	0	0.00%
Forests with Organic Soils	**VERT**	**20'059**		Forest (except brush forest)	17'675	14.14%
				Brush forest	278	0.22%
				Woods	2'106	1.68%
				125'000		

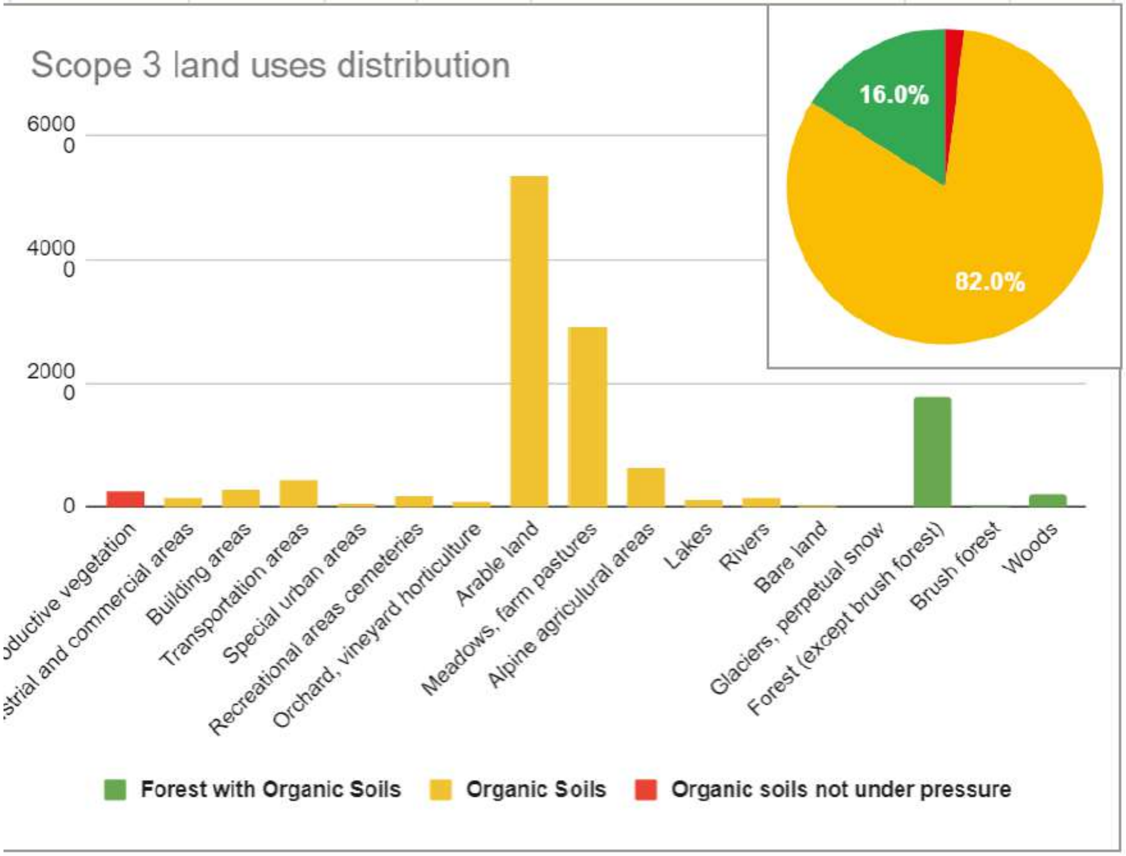
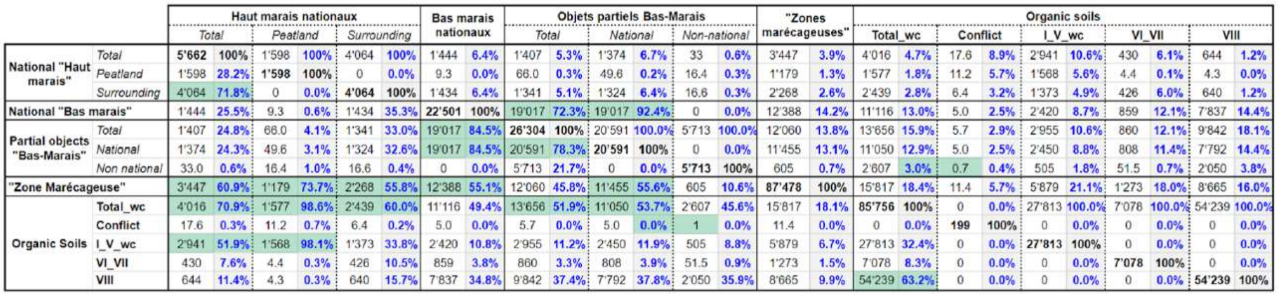


Figure 27: Distribution of Scope 3 among the different land uses categories

It was also interesting to understand how the different inventories overlap together, so the following overlapping table was created. Accessible in a more readable version in Annex XVII



		Haut marais nationaux						Bas marais nationaux		Objets partiels Bas-Marais						"Zones marécageuses"		Organic soils									
		Total		*Peatland*		*Surrounding*				*Total*		*National*		*Non-national*				**Total_wc**		**Conflict**		**I_V_wc**		**VI_VII**		**VIII**	
National "Haut marais"	*Total*	**5'662**	**100%**	1'598	**100%**	4'064	**100%**	1'444	**6.4%**	1'407	**5.3%**	1'374	**6.7%**	33	**0.6%**	3'447	**3.9%**	4'016	**4.7%**	17.6	**8.9%**	2'941	**10.6%**	430	**6.1%**	644	**1.2%**
	Peatland	1'598	**28.2%**	**1'598**	**100%**	0	**0.0%**	9.3	**0.0%**	66.0	**0.3%**	49.6	**0.2%**	16.4	**0.3%**	1'179	**1.3%**	1'577	**1.8%**	11.2	**5.7%**	1'568	**5.6%**	4.4	**0.1%**	4.3	**0.0%**
	Surrounding	4'064	**71.8%**	0	**0.0%**	**4'064**	**100%**	1'434	**6.4%**	1'341	**5.1%**	1'324	**6.4%**	16.6	**0.3%**	2'268	**2.6%**	2'439	**2.8%**	6.4	**3.2%**	1'373	**4.9%**	426	**6.0%**	640	**1.2%**
National "Bas marais"		1'444	**25.5%**	9.3	**0.6%**	1'434	**35.3%**	**22'501**	**100%**	19'017	**72.3%**	19'017	**92.4%**	0	**0.0%**	12'388	**14.2%**	11'116	**13.0%**	5.0	**2.5%**	2'420	**8.7%**	859	**12.1%**	7'837	**14.4%**
Partial objects "Bas-Marais"	*Total*	1'407	**24.8%**	66.0	**4.1%**	1'341	**33.0%**	19'017	**84.5%**	**26'304**	**100%**	20'591	**100.0%**	5'713	**100.0%**	12'060	**13.8%**	13'656	**15.9%**	5.7	**2.9%**	2'955	**10.6%**	860	**12.1%**	9'842	**18.1%**
	National	1'374	**24.3%**	49.6	**3.1%**	1'324	**32.6%**	19'017	**84.5%**	20'591	**78.3%**	**20'591**	**100%**	0	**0.0%**	11'455	**13.1%**	11'050	**12.9%**	5.0	**2.5%**	2'450	**8.8%**	808	**11.4%**	7'792	**14.4%**
	Non national	33.0	**0.6%**	16.4	**1.0%**	16.6	**0.4%**	0	**0.0%**	5'713	**21.7%**	0	**0.0%**	**5'713**	**100%**	605	**0.7%**	2'607	**3.0%**	0.7	**0.4%**	505	**1.8%**	51.5	**0.7%**	2'050	**3.8%**
"Zone Marécageuse"		3'447	**60.9%**	1'179	**73.7%**	2'268	**55.8%**	12'388	**55.1%**	12'060	**45.8%**	11'455	**55.6%**	605	**10.6%**	**87'478**	**100%**	15'817	**18.4%**	11.4	**5.7%**	5'879	**21.1%**	1'273	**18.0%**	8'665	**16.0%**
Organic Soils	**Total_wc**	4'016	**70.9%**	1'577	**98.6%**	2'439	**60.0%**	11'116	**49.4%**	13'656	**51.9%**	11'050	**53.7%**	2'607	**45.6%**	15'817	**18.1%**	**85'756**	**100%**	0	**0.0%**	27'813	**100.0%**	7'078	**100.0%**	54'239	**100.0%**
	Conflict	17.6	**0.3%**	11.2	**0.7%**	6.4	**0.2%**	5.0	**0.0%**	5.7	**0.0%**	5.0	**0.0%**	1	**0.0%**	11.4	**0.0%**	0	**0.0%**	**199**	**100%**	0	**0.0%**	0	**0.0%**	0	**0.0%**
	I_V_wc	2'941	**51.9%**	1'568	**98.1%**	1'373	**33.8%**	2'420	**10.8%**	2'955	**11.2%**	2'450	**11.9%**	505	**8.8%**	5'879	**6.7%**	27'813	**32.4%**	0	**0.0%**	**27'813**	**100%**	0	**0.0%**	0	**0.0%**
	VI_VII	430	**7.6%**	4.4	**0.3%**	426	**10.5%**	859	**3.8%**	860	**3.3%**	808	**3.9%**	51.5	**0.9%**	1'273	**1.5%**	7'078	**8.3%**	0	**0.0%**	0	**0.0%**	**7'078**	**100%**	0	**0.0%**
	VIII	644	**11.4%**	4.3	**0.3%**	640	**15.7%**	7'837	**34.8%**	9'842	**37.4%**	7'792	**37.8%**	2'050	**35.9%**	8'665	**9.9%**	54'239	**63.2%**	0	**0.0%**	0	**0.0%**	0	**0.0%**	**54'239**	**100%**

Table 7: Overlapping table of the different inventories

The most correct way to read the table is as follows : "The intersection between the row and the column account X ha, which represents X% of the column".

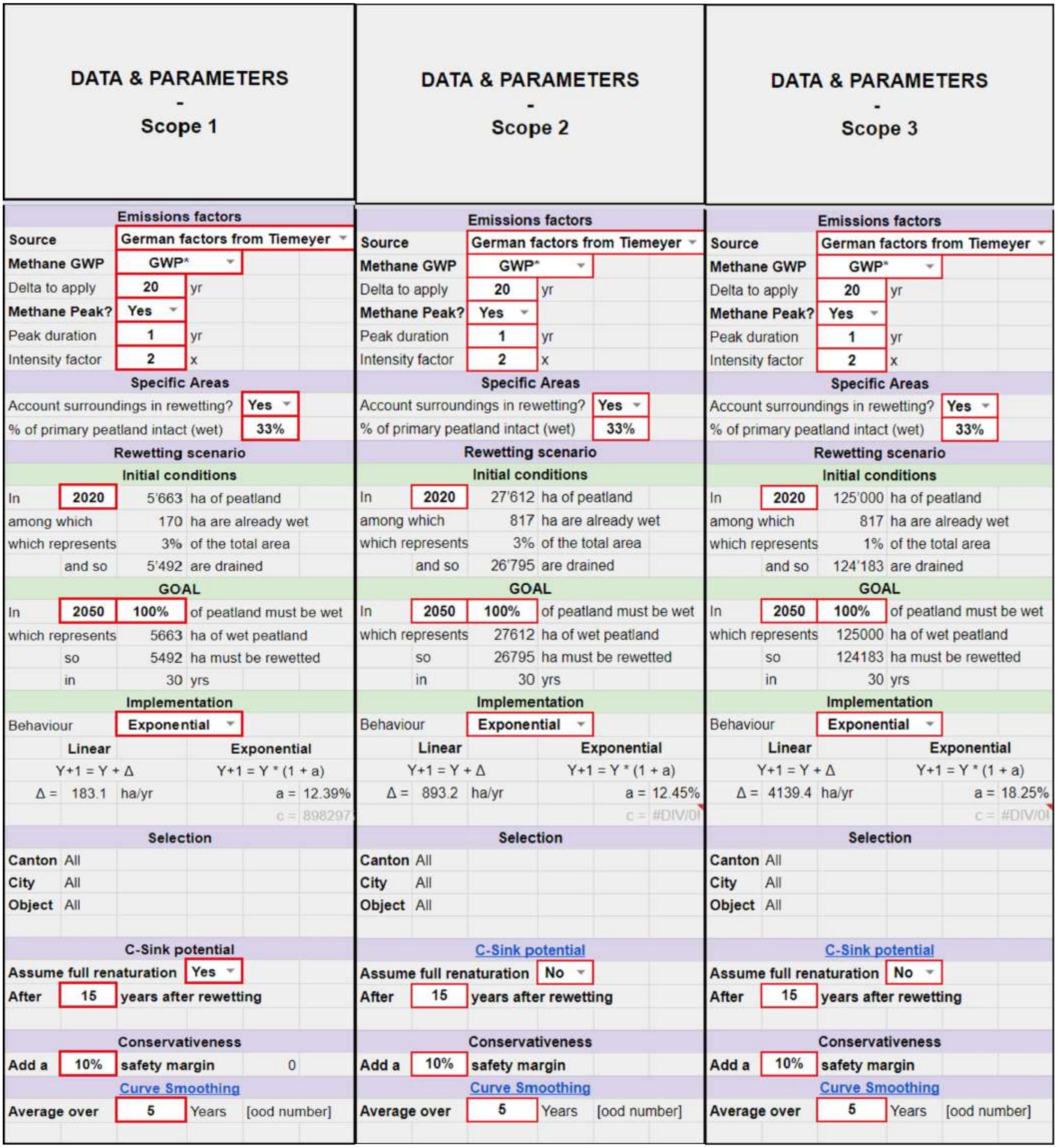
This could be noted that there is well 98% of the peatlands from the raised bog inventory (Scope 1) in the Organic Soils located as categories I-V (Scope 2), the remaining 2 % can be explained by errors and conflict areas removed from the data set.

An important remark to be done is that there is no perfect overlapping or inclusion between the inventories, so if 10% of the "Bas-marais" are present in the organic soils, it does not mean that 90% of the Bas-marais are not organic soils. It only means that the intersection between both inventories represents 10% of the "Bas-marais". The rest of the Bas-marais can be outside of the organic soils already located in the inventory, here it concerns 48.1 %, for which we do not know if they are organic soils or not.

2.2.4 OSMOSE - an Operable Swiss Model for Organic Soils Emissions

Parameters chosen for the model

The following figure describes the parameters selected in the model for the simulation. Some of them are described more in details bellow.



DATA & PARAMETERS - Scope 1

Emissions factors				
Source	**German factors from Tiemeyer**			
Methane GWP	**GWP***			
Delta to apply	**20**	yr		
Methane Peak?	**Yes**			
Peak duration	**1**	yr		
Intensity factor	**2**	x		
Specific Areas				
Account surroundings in rewetting?	**Yes**			
% of primary peatland intact (wet)	**33%**			
Rewetting scenario				
Initial conditions				
In	**2020**	5’663	ha of peatland	
among which		170	ha are already wet	
which represents		3%	of the total area	
and so		5’492	are drained	
GOAL				
In	**2050**	**100%**	of peatland must be wet	
which represents		5663	ha of wet peatland	
so		5492	ha must be rewetted	
in		30	yrs	
Implementation				
Behaviour	**Exponential**			
Linear		**Exponential**		
Y+1 = Y + Δ		Y+1 = Y * (1 + a)		
Δ =	183.1	ha/yr	a =	12.39%
			c =	898297
Selection				
Canton	All			
City	All			
Object	All			
C-Sink potential				
Assume full renaturation	**Yes**			
After	**15**	**years after rewetting**		
Conservativeness				
Add a	**10%**	**safety margin**		0
Curve Smoothing				
Average over	**5**	Years	[ood number]	

DATA & PARAMETERS - Scope 2

Emissions factors				
Source	**German factors from Tiemeyer**			
Methane GWP	**GWP***			
Delta to apply	**20**	yr		
Methane Peak?	**Yes**			
Peak duration	**1**	yr		
Intensity factor	**2**	x		
Specific Areas				
Account surroundings in rewetting?	**Yes**			
% of primary peatland intact (wet)	**33%**			
Rewetting scenario				
Initial conditions				
In	**2020**	27’612	ha of peatland	
among which		817	ha are already wet	
which represents		3%	of the total area	
and so		26’795	are drained	
GOAL				
In	**2050**	**100%**	of peatland must be wet	
which represents		27612	ha of wet peatland	
so		26795	ha must be rewetted	
in		30	yrs	
Implementation				
Behaviour	**Exponential**			
Linear		**Exponential**		
Y+1 = Y + Δ		Y+1 = Y * (1 + a)		
Δ =	893.2	ha/yr	a =	12.45%
			c =	#DIV/0!
Selection				
Canton	All			
City	All			
Object	All			
C-Sink potential				
Assume full renaturation	**No**			
After	**15**	**years after rewetting**		
Conservativeness				
Add a	**10%**	**safety margin**		
Curve Smoothing				
Average over	**5**	Years	[ood number]	

DATA & PARAMETERS - Scope 3

Emissions factors				
Source	**German factors from Tiemeyer**			
Methane GWP	**GWP***			
Delta to apply	**20**	yr		
Methane Peak?	**Yes**			
Peak duration	**1**	yr		
Intensity factor	**2**	x		
Specific Areas				
Account surroundings in rewetting?	**Yes**			
% of primary peatland intact (wet)	**33%**			
Rewetting scenario				
Initial conditions				
In	**2020**	125’000	ha of peatland	
among which		817	ha are already wet	
which represents		1%	of the total area	
and so		124’183	are drained	
GOAL				
In	**2050**	**100%**	of peatland must be wet	
which represents		125000	ha of wet peatland	
so		124183	ha must be rewetted	
in		30	yrs	
Implementation				
Behaviour	**Exponential**			
Linear		**Exponential**		
Y+1 = Y + Δ		Y+1 = Y * (1 + a)		
Δ =	4139.4	ha/yr	a =	18.25%
			c =	#DIV/0!
Selection				
Canton	All			
City	All			
Object	All			
C-Sink potential				
Assume full renaturation	**No**			
After	**15**	**years after rewetting**		
Conservativeness				
Add a	**10%**	**safety margin**		
Curve Smoothing				
Average over	**5**	Years	[ood number]	

Figure 28: Parameters chosen for the simulation of the scopes 1, 2 and 3

It seems relevant to use in priority the emissions factors determined by Tiemeyer et al. 2020 [22], since they were assessed using a Tier 3 methodology and are applicable to a country bordering Switzerland and having common ecosystems. The IPCC ones are complete, they represent a Tier 1 methodology valid for the temperate zone, but they are less accurate for Switzerland, as they are estimated with values from all European countries in the temperate zone, however they remain good to do a sensibility analysis of the model. Finally the Swiss emissions factors take only CO_2 into account, which would make all the model characteristics for Methane useless. It would represent an important loss of information, and makes the estimation away from reality as it would not include Methane emissions or peaks. Finally we assume that the time needed for the ecosystem to be fully restored is approximately 15 years. This assumption is valid for the Scope 1, but way more uncertain for scopes 2 and 3.

Regarding the baseline scenarios, they were defined as the continuation of past trends or the realisation of present plans for the future. For Scope 1 the baseline scenario assumes that the current plan of myclimate to renaturate 3 projects of 5 ha per year is successfully reached, making a linear evolution of 15 ha rewetted per year from 2020 to 2080. For the Scopes 2 and 3, as no organic soils under intensive or extensive were renaturated in the past, an that there is not any programs that plan to do so, the baseline was set as no rewetting of organics soil, except for the raised bogs part that is protected, but it represents a very small portion of Scope 2 and 3.

Results of the model

The following pages present the results for the 3 scopes with the 4 main figures of the model:

1. A graph showing the rewetting scenario in hectares rewetted
2. A graph showing the GHG emissions evolution of the scope in the case of a simple rewetting, or a full renaturation, compared to its baseline scenario.
3. A graph with the GHG emissions saved per year compared to the baseline scenario
4. A graph of the cumulative GHG emissions saved compared to the baseline scenario

Results for Scope 1

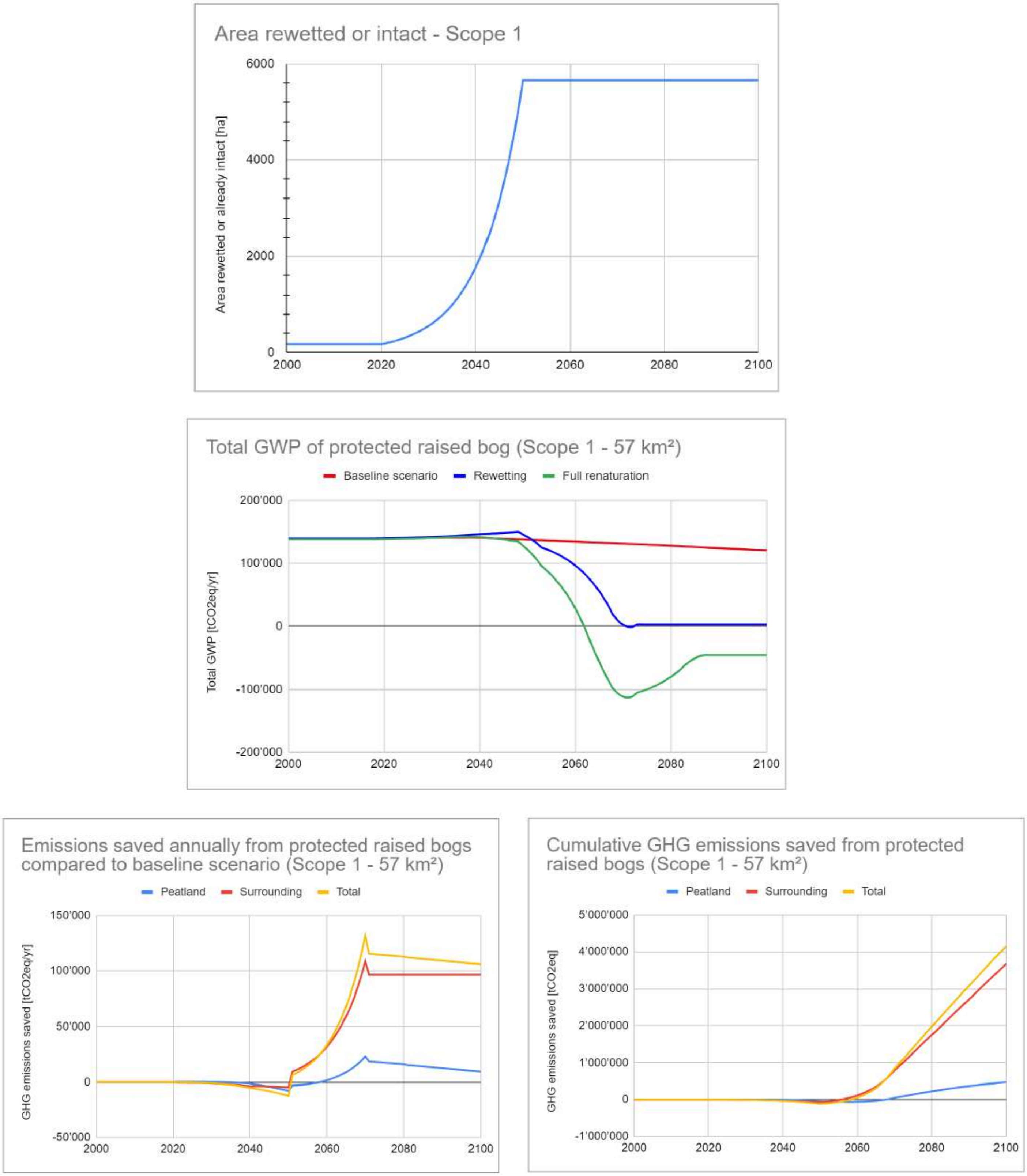


Figure 29: OSMOSE's Results for Scope 1

Results for Scope 2

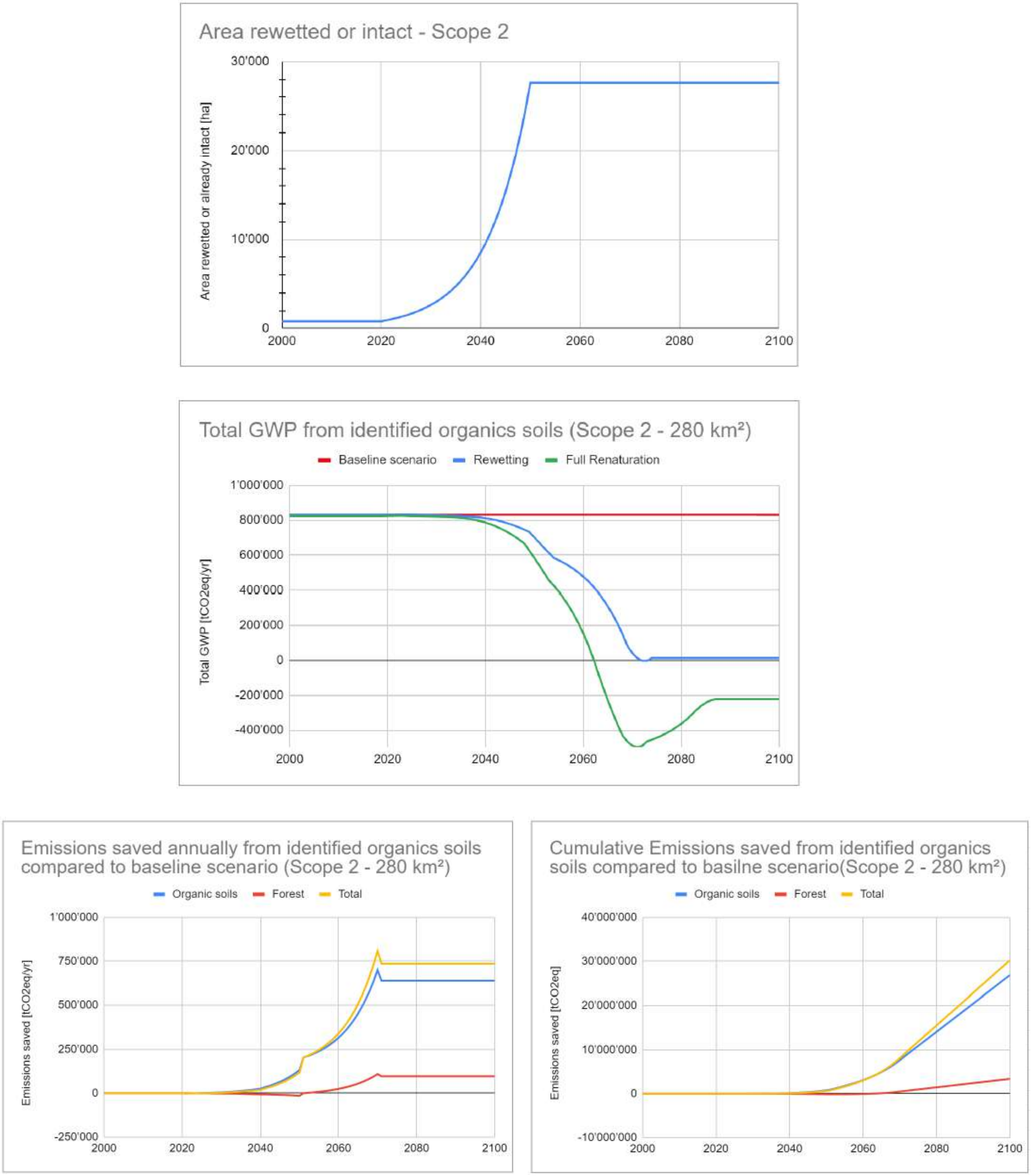


Figure 30: OSMOSE's Results for Scope 2

Results for Scope 3

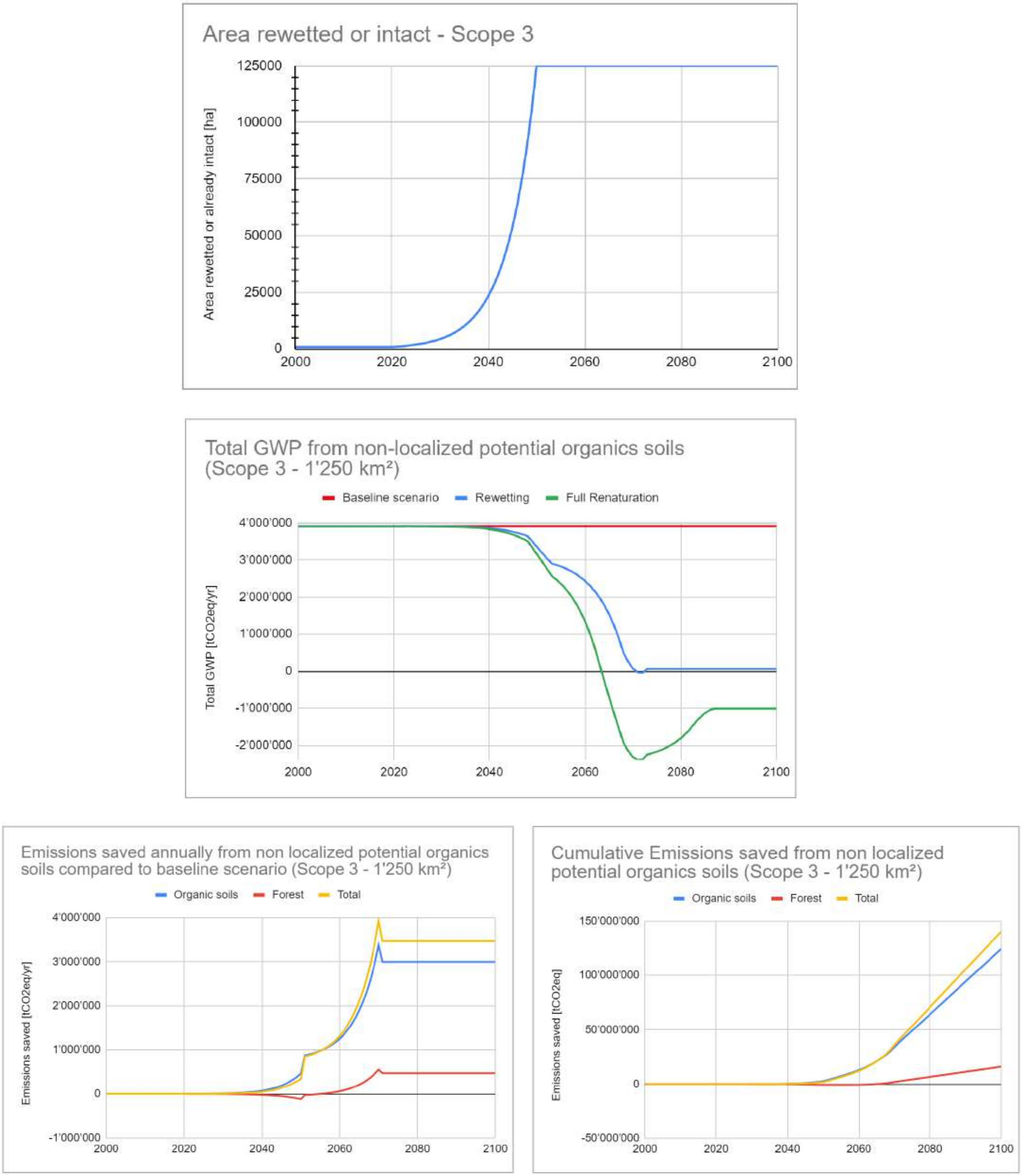


Figure 31: OSMOSE's Results for Scope 3

We observe a delay of approximately 20 years between the restoration and the emissions peak that can be explained by Methane peak option coupled with the GWP* parameter computing the difference of delta emissions over a period of 20 years. Regarding the peak in negative emissions around 2070 before the new increase until 2085 before reaching stabilisation, it could be explained by the fact that the full renaturation option is activated 15 years after the rewetting, coupled with the GWP* delta of 20 years.

According to the model and the parameters selected, the current emissions of the Scope 1 are approximately around 140'000 $tCO_2eq/$yr. With an annual growth rate of 12,4% for the rewetting, after having reached the 100% of the scope rewetted (57 km^2) in 2050, we can see the emissions decrease until reaching the emission of 3'000 $tCO_2/$yr around 2070 if no carbon sink from the full renaturation hypothesis is assumed, which means a reduction in emissions of 98%. It is nearly net zero, but still positive due to the Methane and Nitrous Oxide emissions counter-balancing the small carbon removal capacity. But if the full renaturation hypothesis assumption is taken and that the ecosystem regains its entire near-natural capacity to store carbon, emissions peak and reach net 0 in 2062, before reaching a peak in negative emissions around 100'000 $tCO_2eq/$yr in 2070, and stabilising themselves around 50'000 $tCO_2eq/$yr of negative emissions in 2087.

At its maximum, the rewetting scenario presents an annual difference in emissions with the baseline scenario of approximately 120'000 $tCO_2eq/$yr. Cumulatively, this scenario would have saved the emission of 4 Mt $CO_2eq/$yr until 2100 compared with the baseline scenario, without counting negative emissions. This potential reaches 7 Mt $CO_2eq/$y if negative emissions are accounted for.

The forests and surroundings represent respectively only 15% and 16% of the surface of Scopes 2 and 3, rewetting them or not would only have a minor influence on the emissions (a reduction 85.5% of the emissions instead of 98.5%). But for scope 1, as the forests and surrounding areas represent 72% of the total area, it is way different.

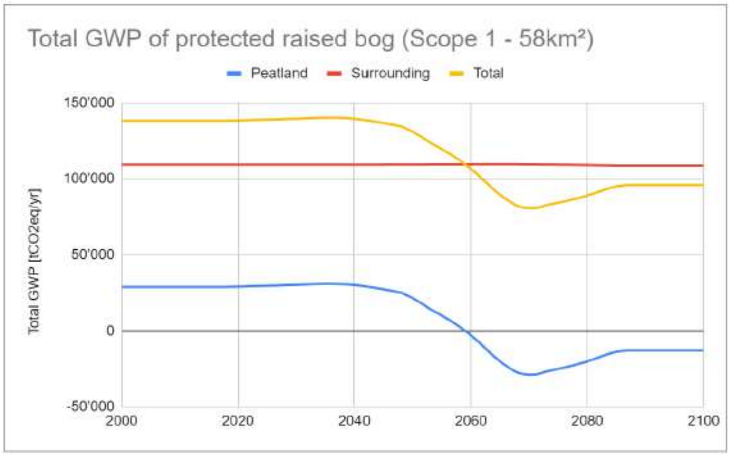


Figure 32: Simulation of Scope 1 without including forest and surroundings in the rewetting

The emissions of the surrounding areas represent more than triple of the emissions of the peatlands areas, so even if they decrease well until producing negative emissions, the total effect is compensated by the surrounding emissions and Scope 1 remains an important emitter for Switzerland. The reduction observed is only about 31%. This proves the importance of rewetting also the surrounding and forest areas for the protected raised bogs of national importance.

PART III - Implementing the solutions

This section explores what the implementation of the solutions previously described would imply in terms of financial and human resources, skills development and incentives needed.

3.1 Biochar production

Current Biochar market

According to the European Biochar Industry (EBI), the biochar market is expanding fast.

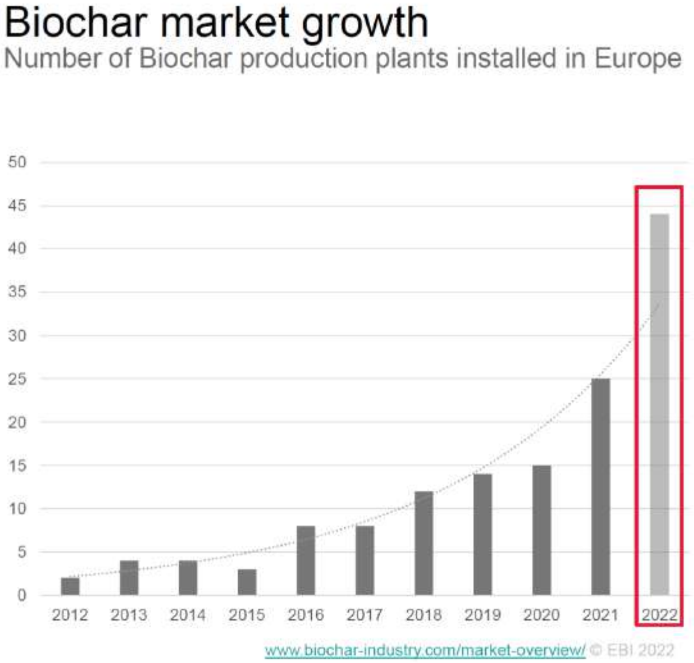


Figure 33: EBI Market report 2021-2022 - Biochar Market Growth [10]

The EBI Market report 2021-2022 [10] shows that 25 Biochar production plants were installed in 2021. Apparently, in February 2021, EBI had 32 projects on the radar screen for a completion this year, but 12 of them were delayed due to Covid, permitting or material shortage. However 5 projects completed in 2021 were previously not on the radar screen.

The cumulative number of installed Biochar production plants has grown to more than 100 installations, almost 80 of them with a production capacity $\geq$ 200 t/yr. There are 44 projects under construction or under contract for 2022 commissioning. Many further projects are in an advanced planning and permitting process and could be commissioned by 2023. Moreover, there are certainly a few projects that are not on the radar screen yet.

As shown in Figure 34, EBI assumes an important annual growth rate of 85% to be reached in 2022 and maintained for the following years.

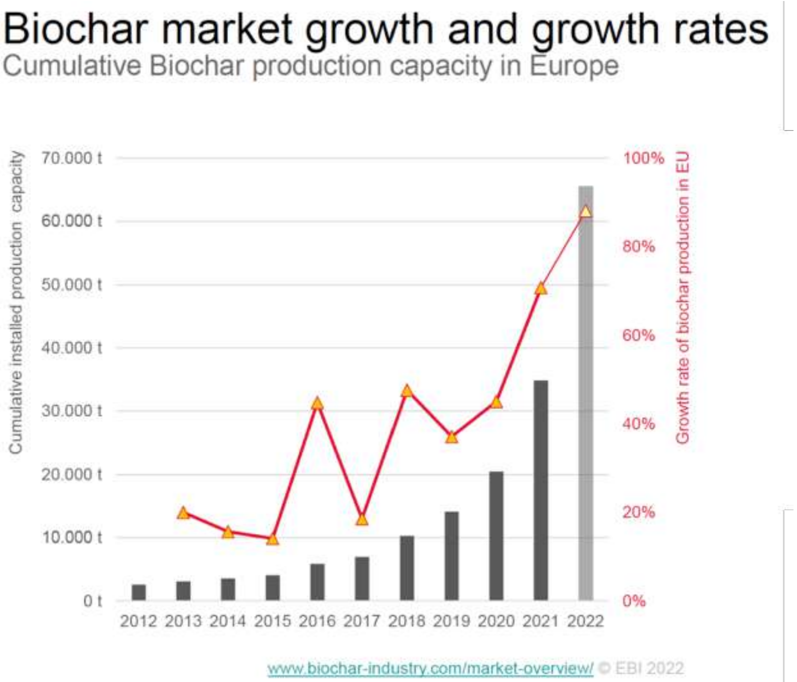


Figure 34: EBI Market report 2021-2022 - Market growth rates [10]

Making the cumulative biochar production in Europe reaching 0.8 M tCO_2eq removed by 2022, 10 MtCO_2eq by 2030 and 100 Mt CO_2eq by 2034, but they do not include any feasibility analysis regarding the sustainable biomass availability.

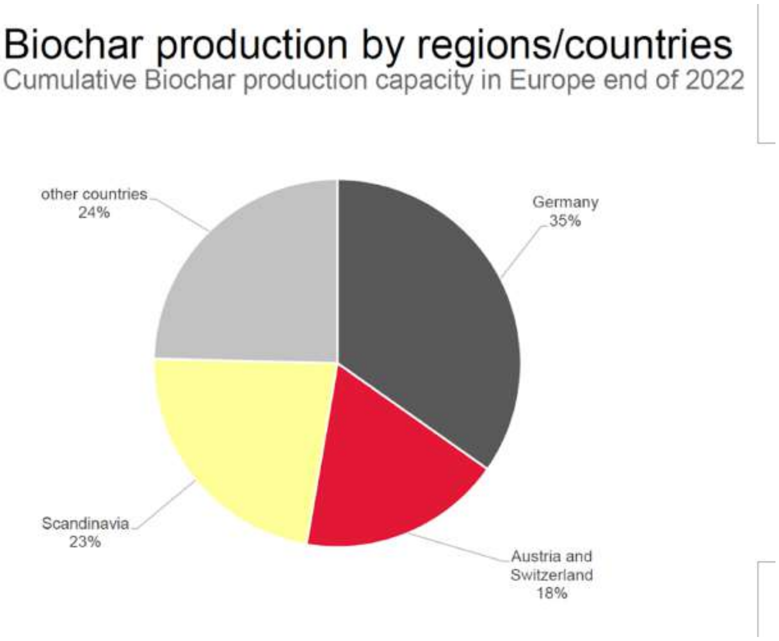


Figure 35: EBI Market report 2021-2022 - Countries distribution [10]

According to Figure 35, Austria and Switzerland represent 18% of this market. So if this proportion does not change, it would mean that 18 Mt CO_2eq would have been removed in those countries by 2034. This estimate seems very high.

For now, the Swiss market is composed of the following companies selling EBC certified biochar

Biochar producer	Production Capacity [t/y]	Price [CHF/t]	Location	Since
VERORA	450	1260	Edlibach (ZG)	2012
Swiss Biochar	-	810	Belmont-sur-Lausanne (VD)	2010
AgroCO2ncept	300-350	-	Flaach (ZH)	2019
INEGA	500	1100-1215	Maienfeld (GR)	2019
Pyrocycle Sarl	-	NA	Démoret (VD)	2021
IWB	-	1100	Basel (BS)	?
HolzenergieGut	160-200	1000	Buch-am-Irchel (ZH)	2021

Table 8: Swiss EBC biochar producers complete list up to 2022

Production capacity data were difficult to find. But it is known from the Ithaka Institute that today's Swiss biochar production is around 2'000 tons of biochar per year, and is expected to be at 5'000 t/yr by 2023 thanks to the opening of a big unit from Bioenergie Frauenfeld AG.

So far, the Swiss market is still clearly focused on agriculture, e.g. for the production of high-quality composts, slurry additives, biochar-based fertilisers, and in animal husbandry as feed additive and stable bedding. But the market with the largest growth in Switzerland is currently the use of biochar in substrates for urban trees. According to Schmidt et al. 2021 [25] maintaining and promoting them is an important measure for adapting cities to climate change, as trees help to cool cities, reduce dust pollution and drain rainwater during extreme weather events. At the same time, the more frequent and pronounced heat summers in particular pose major challenges for urban trees, which can be effectively mitigated using biochar-based root substrates. Here, the city of Stockholm is a pioneer in the use of substrates made from defined quarry, compost and biochar, which, when properly installed, can enable tree survival even under extreme conditions. In such a project the biochar is stored once and can remain without being changed before 50-100 years, depending on the pollution of the city.

In this context, a number of successful urban tree projects using co-composted biochar have also been implemented in Switzerland, for example at Sechseläuten-Platz in Zurich, on the Plaine de Plain-palais in Geneva, in Basel and even in new eco-districts of Lausanne.

The “Stockholm system" is represented in the following Figure 36.

BIOCHAR-ENRICHED STOCKHOLM STRUCTURAL SOIL

Providing trees with durable planting beds built with locally sourced materials is a key goal for the City of Stockholm. Enriching the Stockholm structural soil with biochar enhances the performance of the system as a carbon sink. It also helps provide better stormwater management (beyond volume reduction) by reducing leaching of pollutants to the water table.

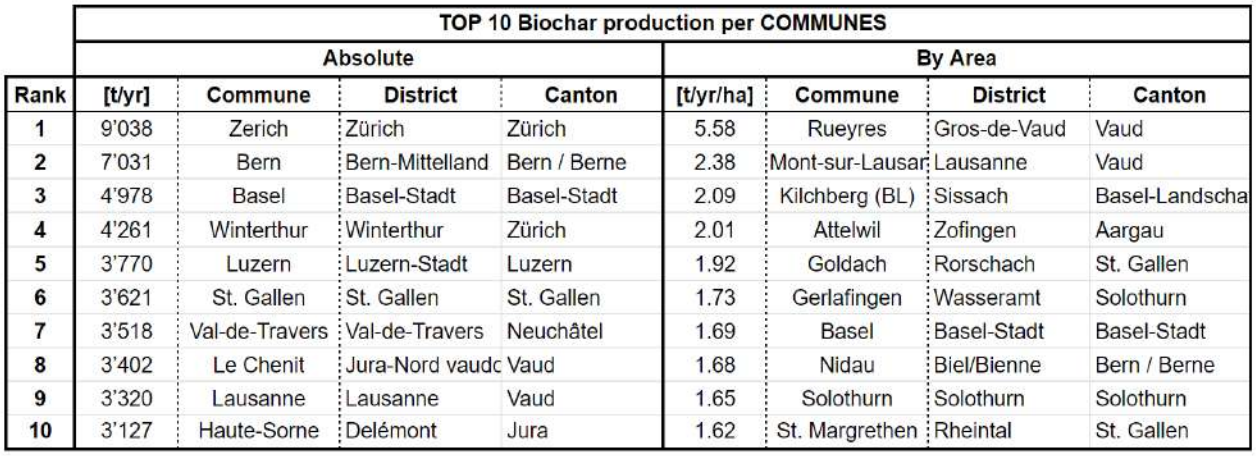
1. Paved surface and base course
2. Stormwater gutter
3. Aeration well: inlet for water and oxygen/carbon dioxide exchange
4. Surface grate
5. Tree guard
6. Root collar at nursery growing level
7. Stone mulch, crushed rock 4/8 mm
8. Crushed rock 2/6 mm with 25 volume percent mix of biochar with added nutrients and compost (50/50)
9. Concrete frame
10. Geotextile
11. Leveling layer, crushed rock 8/11 mm
12. Aeration layer, crushed rock 32/63 mm
13. Stone-biochar matrix, crushed rock 32/90 mm with 15 volume percent mix of biochar with added nutrients and compost (50/50)
14. Biochar
15. Gas exchange (oxygen and carbon dioxide)

Figure 36: Description of the Stockholm system, source: BJÖRN EMBREN 2020 [51]

The city of Lausanne counts nowadays 8'000 trees, but wants to make this number rise to 12'000 by planting 4'000 new trees by 2030. If we make the conservative assumption that approximately 1 ton of biochar, mixed with compost, is needed for the desired volume under the tree, then the city of Lausanne could store 4'000 t of biochar, removing approximately 10'000 tCO_2eq from the atmosphere. If the city of Lausanne applied the same system to all its trees including the already existing ones, it would represent the sequestration of approximately 30'000 tons of carbon dioxide.

Where to optimally put pyrolysis units to start ?

To answer this question, the TOP 10 of the communes with the highest potentials in absolute values and normalized per area has been computed. Results are presented in the following table 9.



	TOP 10 Biochar production per COMMUNES							
	Absolute				By Area			
Rank	**[t/yr]**	**Commune**	**District**	**Canton**	**[t/yr/ha]**	**Commune**	**District**	**Canton**
1	9'038	Zerich	Zürich	Zürich	5.58	Rueyres	Gros-de-Vaud	Vaud
2	7'031	Bern	Bern-Mittelland	Bern / Berne	2.38	Mont-sur-Lausar	Lausanne	Vaud
3	4'978	Basel	Basel-Stadt	Basel-Stadt	2.09	Kilchberg (BL)	Sissach	Basel-Landscha
4	4'261	Winterthur	Winterthur	Zürich	2.01	Attelwil	Zofingen	Aargau
5	3'770	Luzern	Luzern-Stadt	Luzern	1.92	Goldach	Rorschach	St. Gallen
6	3'621	St. Gallen	St. Gallen	St. Gallen	1.73	Gerlafingen	Wasseramt	Solothurn
7	3'518	Val-de-Travers	Val-de-Travers	Neuchâtel	1.69	Basel	Basel-Stadt	Basel-Stadt
8	3'402	Le Chenit	Jura-Nord vaudc	Vaud	1.68	Nidau	Biel/Bienne	Bern / Berne
9	3'320	Lausanne	Lausanne	Vaud	1.65	Solothurn	Solothurn	Solothurn
10	3'127	Haute-Sorne	Delémont	Jura	1.62	St. Margrethen	Rheintal	St. Gallen

Table 9: Top 10 of the communes with the highest biochar production capacity

It is not surprising to find in the TOP 10 of Absolute values the biggest cities of Switzerland, as they are dense and gather a lot of activities. It can be seen that Basel is in both list, so it mean that biochar production in Basel would not be only important in size but also in intensity, acting as a hot spot for biochar. Therefore, the recommendation of this thesis would be to install biochar unit in the biggest cities that have smaller but more intense hot spot communes around them. As Basel or Lausanne with Le Mont-sur-Lausanne just next to it.

Resources needed and barriers to deployment

Regarding the legal aspect, the EBC certificate is trying to make the legislation change regarding the type of biomass accepted to produce biochar. For now, only the woody biomass is accepted in Switzerland, but the list has started to be extended to other types in Europe and the Ithaka Institute produced a list of possible feedstocks that meet the required standards [52].

If we would need to imagine a plausible deployment of biochar to reach the potential described in the PART 2 for 2050, this would take the shape of the following exponential curve :

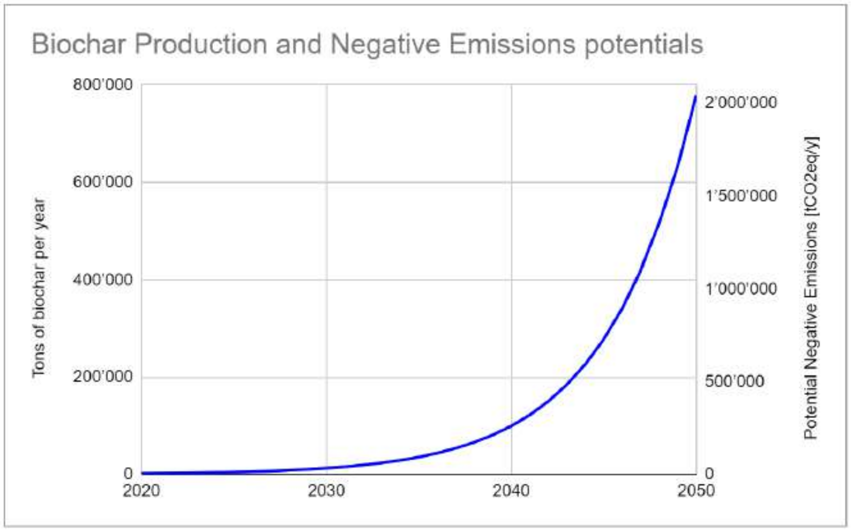


Figure 37: Biochar realistic deployment to reach potential presented in PART II

As the current biochar production capacity is around 2000 t/yr, such a deployment implies a constant annual growth rate of 22.84% p.a. Which is high, but more reasonable than the 85% assumed by EBI. At this growth rate, Switzerland would have cumulatively stored 10 Millions tons of CO_2 by 2050, before stabilising at the annual rate of 2 Mt CO_2eq/yr of negative emissions.

To estimate what it would take to deploy biochar in such a way, this study looked at the capital expenditures for the installation of a pyrolysis unit and the operational costs created by the running of the plant but also its variable costs as salary, maintenance, consumption etc. including an estimation of the number of workers needed as Human Resources.

Haeldermans et al. 2020 [45] looked at the costs of a large pyrolysis unit that could produce up to 2000 t of biochar per year. It assumes a total CAPEX of 14 M CHF undertaking the biochar production plant, the storage and buildings, ground surfaces to buy and ground works, office and laboratory equipment and additional machinery. For the OPEX, it represents approximately 4 M CHF per year, including the 16 staff costs and other costs such as maintenance, insurance, marketing, ICT, certification, transportation etc.

A learning curve was implemented to the analysis to make the costs (both CAPEX/OPEX and persons needed) decrease by 10% at each cumulative doubling. It can be seen than in the simulation of the costs, the decrease due to the learning curve was discrete and happen at once at the moment of the cumulative doubling. This is unrealistic, the correct behaviour would be a smooth and constant decreasing, but this simulation still gives a correct order of magnitude of the costs evolution if the learning curve assumption is correct.

The results of this costs analysis are presented in the following Figures 38 and 39.

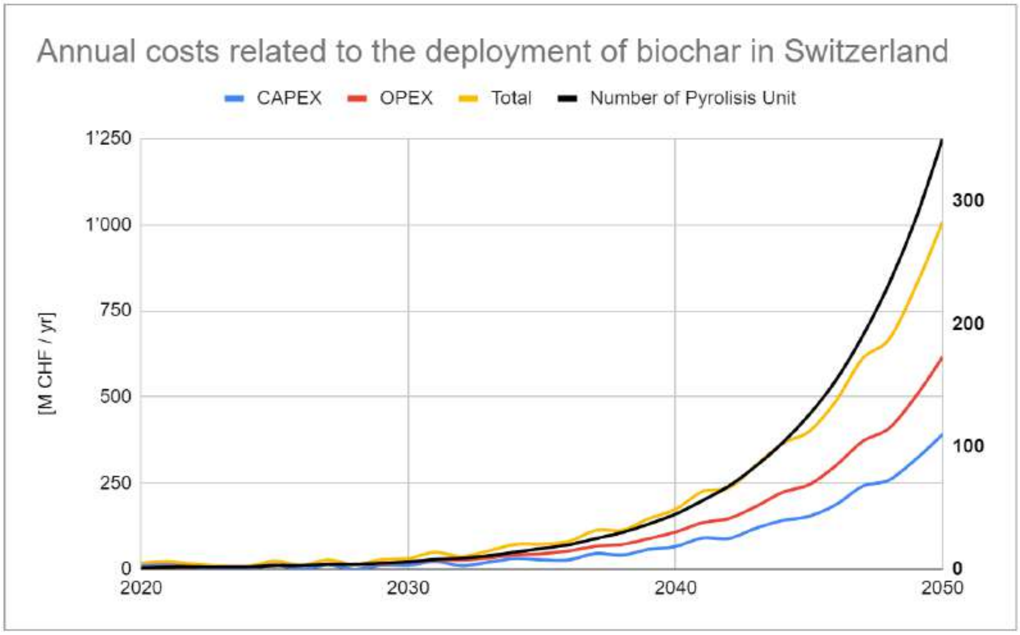


Figure 38: Annual costs related to the deployment of Biochar

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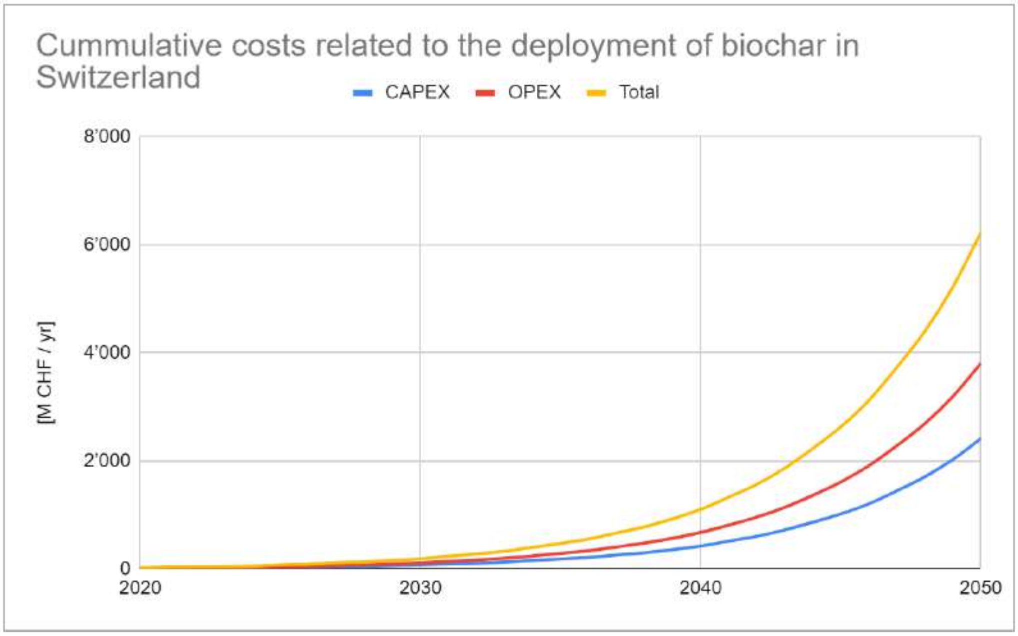


Figure 39: Cumulative costs related to the deployment of Biochar

Therefore, Switzerland would need more than 5'600 workers to run 350 pyrolysis units needed by 2050. It represents a cumulative investment of 6 B CHF, followed by annual operational costs of 617 M CHF / y. But if we include the revenues from biochar sells, or even electricity sells from the conversion of syngas, the net cumulative costs could drop to 4 B CHF. Thanks to the learning curve, if this deployment happen, the price of biochar will also drop, from 1000 CHF/t in 2020 to 430 CHF/t in 2050, making the cost of negative emissions drops from 385 CHF/CO_2eq to 165 CHF/CO_2eq. Complete costs calculations are available in the Annex XVIII .

3.2 Peatlands renaturation

Renaturation costs

According to Dr. Lena Gubler, the range of renaturation costs is between 22'000 CHF/ha and 480'000 CHF/ha with the mean at 78'000 CHF/ha [53]. This range will be taken as minimal, expected and maximal values in the following Figure 41.

According to the FOEN *"BIOP Support"* report of 2017 [54], the renaturation costs for fens are approximately 28'000 CHF/ha, and the maintenance and monitoring costs for raised bogs and fens are respectively 2'846 and 2'123 CHF/ha/yr.

It is assumed that the area covered by a project of renaturation is 5 ha, and that it requires 5 full time equivalent persons from civil engineering and landscaping workers during 1 year to achieve the renaturation, based on experts interviews.

Finally a learning curve decreasing the costs by 8% at each cumulative doubling of the rewetted area is assumed starting in 2020 with 100 ha assumed to be rewetted, for a conservative assumption. The following Figures 40, 42 and 43 show respectively the variation in costs among the scopes 1, 2 and 3.

Costs estimation for Scope 1

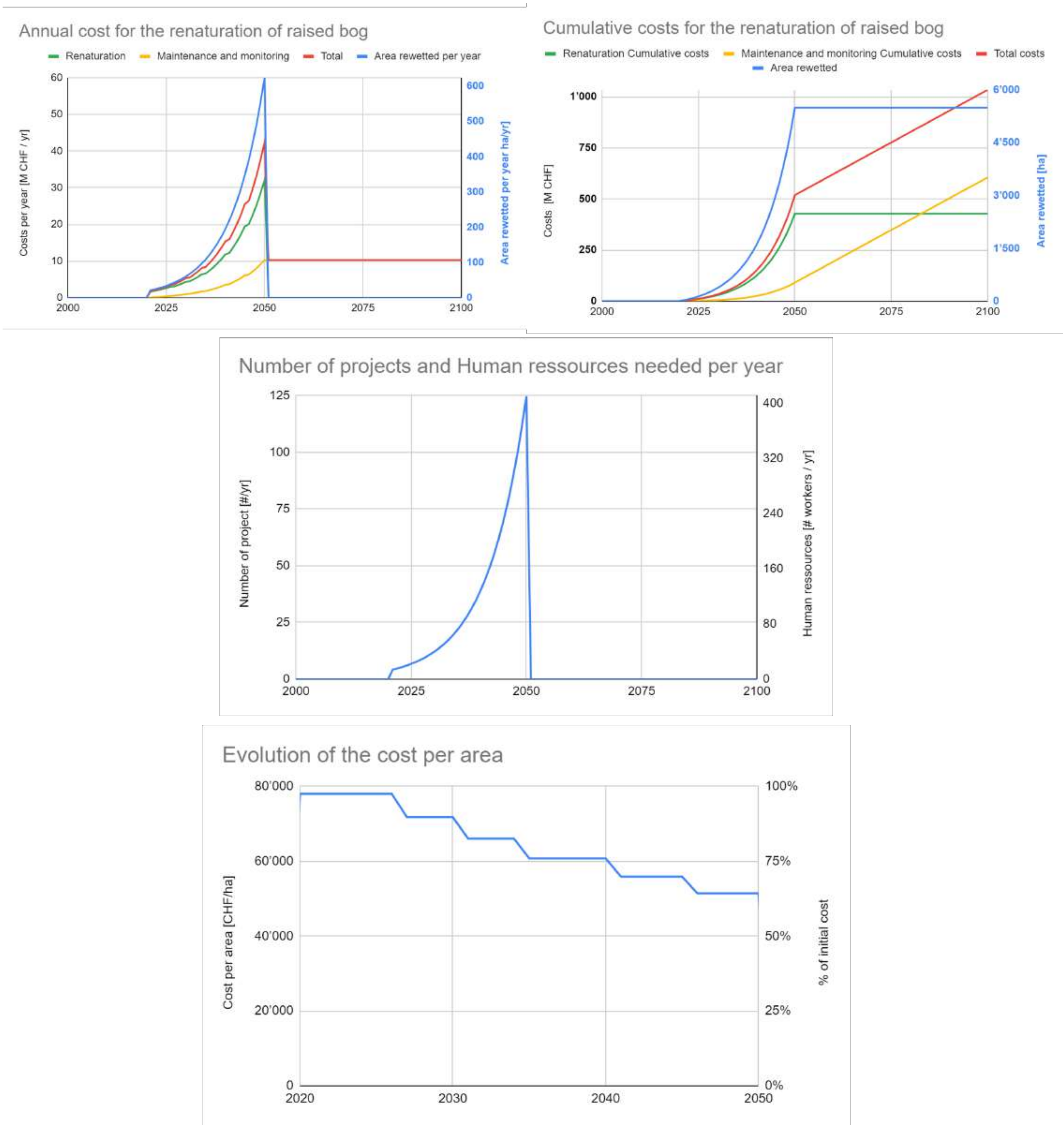


Figure 40: Costs analysis for Scope 1

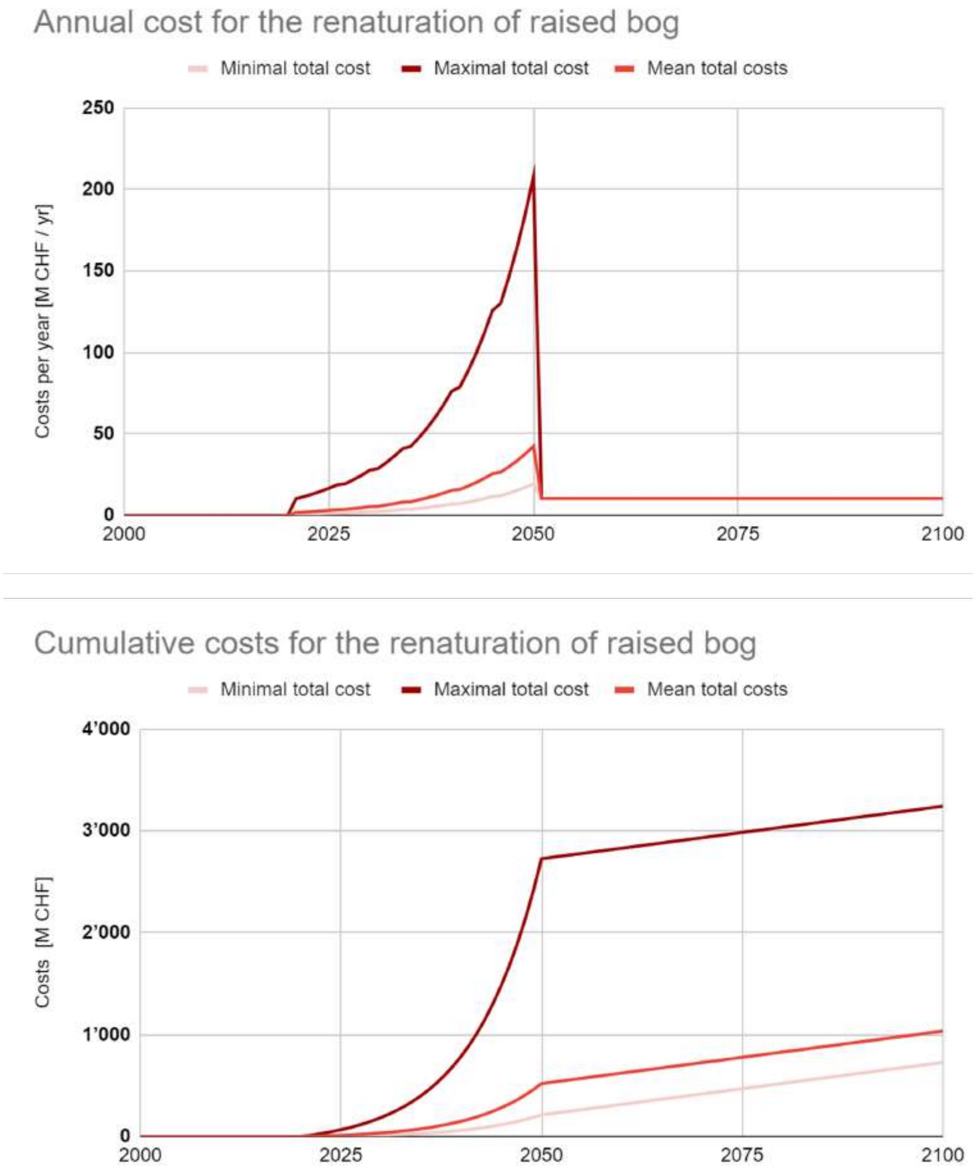


Figure 41: Minimal and maximal range of costs according to Dr. Lena Gubler [53]

It can be seen that the range of costs greatly varies and can bring uncertainties to the viability of renaturation projects. Costs depend on the topography of the peatlands, the state of degradation, and accessibility, the presence of trees or not, and all the administrative procedures.

In addition it should be noted that one of the most limiting factors, among others, is the lack of formed and available staff in the cantonal administration, to plan and concretize renaturation projects.

Costs estimation for Scope 2

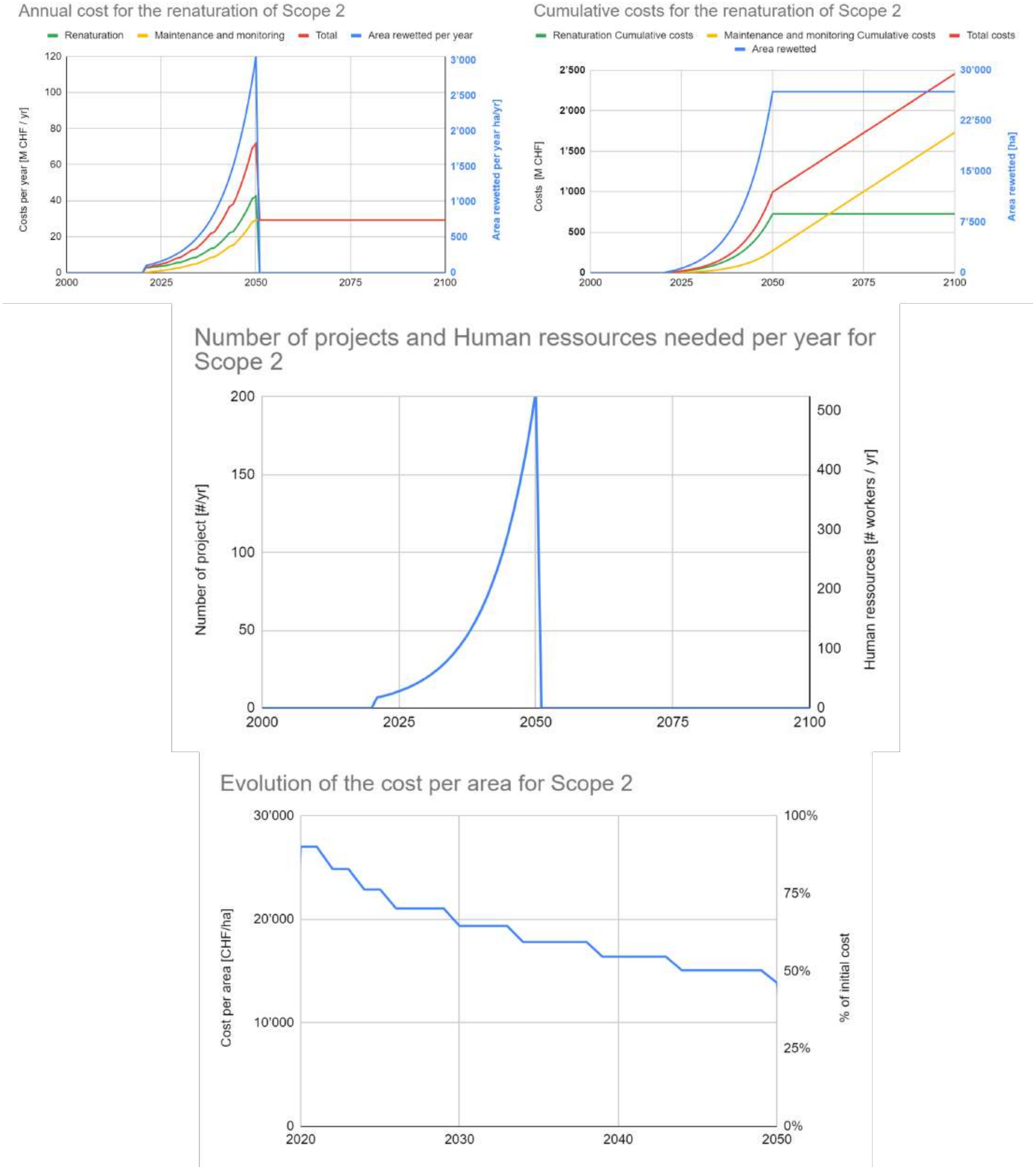


Figure 42: Costs analysis for Scope 2

Costs estimation for Scope 3

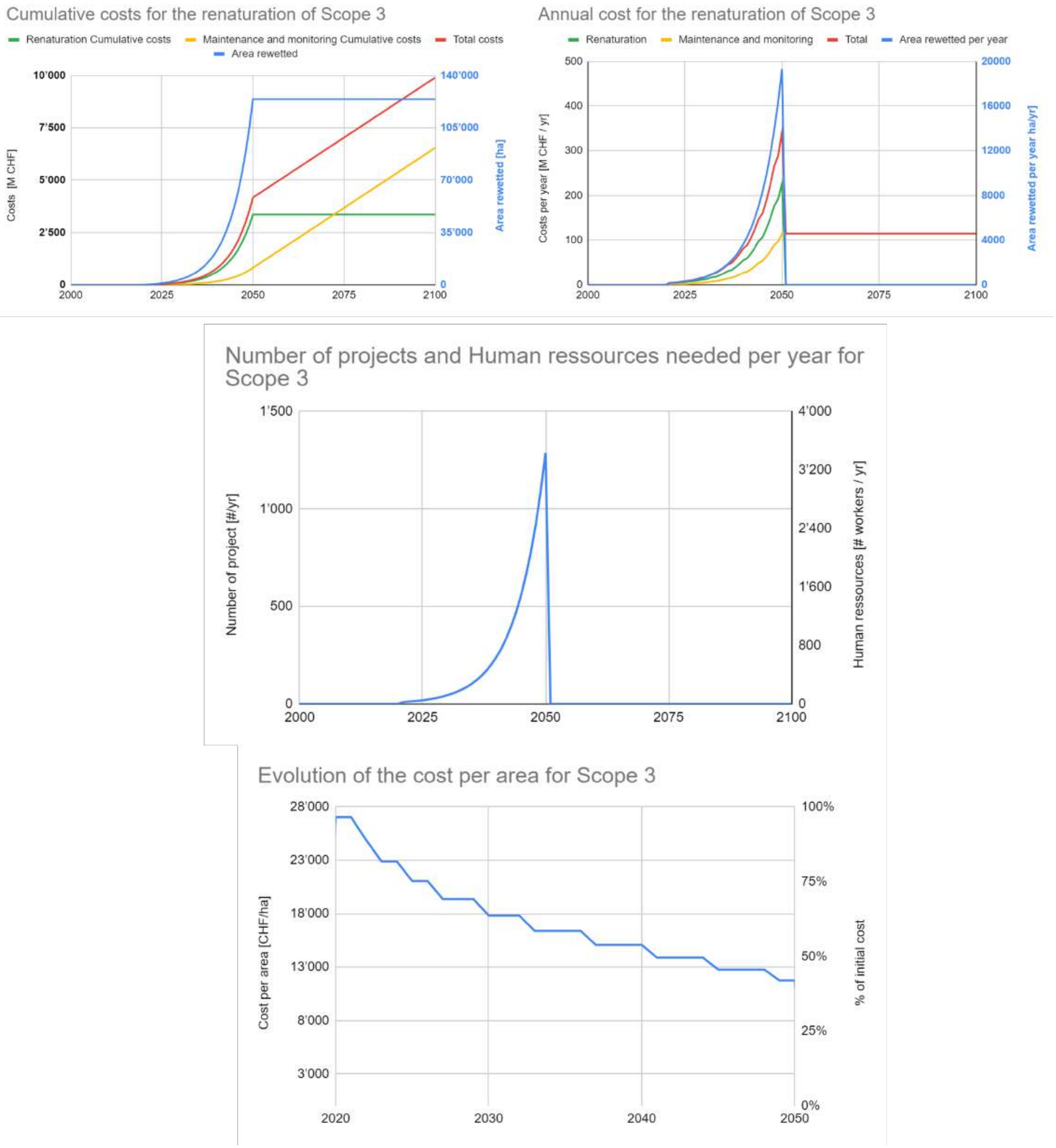
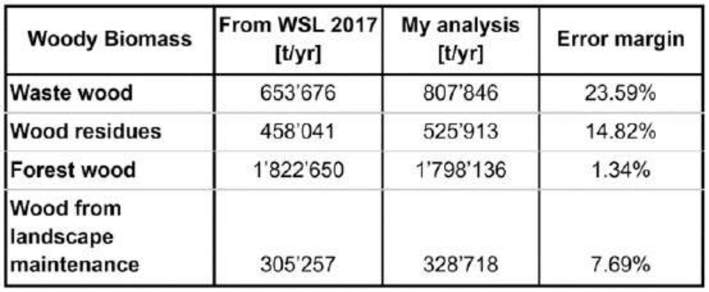


Figure 43: Costs analysis for Scope 3

Discussion

Regarding biochar, the values obtained for the national sustainable biomass potential in dry weight for the 4 woody biomass were compared to the one downloadable from the WSL 2017 report [13], to check the consistency of the data obtained. The following margins or errors are displayed in the table bellow.



Woody Biomass	From WSL 2017 [t/yr]	My analysis [t/yr]	Error margin
Waste wood	653'676	807'846	23.59%
Wood residues	458'041	525'913	14.82%
Forest wood	1'822'650	1'798'136	1.34%
Wood from landscape maintenance	305'257	328'718	7.69%

Table 10: Results comparison with WSL 2017 [13]

The order of magnitude is correct. Further analysis are needed to explain the uncertainties.

Is it noted that the potentials calculated in this thesis are maximal potentials under the assumption that all the sustainable biomass available is reallocated to biochar production.

Indeed, it can be observed that the national biomass potential offered in WSL 2017 account for an "already used potential" in the energy sector that is subtracted to the sustainable potential to obtain what is called the "*Additional sustainable potential*". Unfortunately, the data are not available at the communal scale, they are only available at the national scale since the data of this already used potential comes directly from important biomass processing plants that transport and collect biomass in all Switzerland. Taking the percentage of biomass already used over the sustainable potential, and applying it to the communal level would have been a methodological error, since the share of biomass types greatly varies among the communes, and the biomass can be processed far away from where it was sourced. So it was decided that this thesis would explore a scenario in which all the biomass sustainability available was decided to be reallocated to biochar production, with the possibility to also produce heat and electricity thanks to the pyrolysis plants.

Regarding the Peatlands analysis and the constitution of the OSMOSE Model, several points need to be discussed.

- First, Data relative to the national inventories of peatlands are more than 30 years old, some of them were reviewed since then and updated, but it is a minority. This could lead to an overestimation of current health of the raised bog.
- Uncertainties regarding the methane peak behaviour are important. The Methane peak is strongly dependent on the rewetting measure and its implementation. The presence of vegetated areas (vascular plants, that does not belong in a peat bog) or not is important since if they are flooded they ferment. Then the Methane peak is higher if flooded in excess than if there is no flooding but the water level is simply raised to the surface of the soil. This is

for these reasons that the buffer of 10% was included in the model, 10% is generally the value taken to compensate the possible Methane emissions and emissions from the renaturation work as transportation (approximately 5%) and another 5% for the risk buffer regarding possible leakage and unforeseen events in the behaviour of the Carbon Sink.

- Uncertainties regarding the time needed for an ecosystem before being considered as fully renaturated are important and depend on factors such as the presence of chemical fertilisers, pesticides, and raised bog endemic vegetation, which are not considered in the model due to the lack of data.
- The fully renaturation potential assuming that after 15 years the ecosystem behave as natural is unlikely to happen for Scope 2 and Scope 3. Apparently, the level of degradation due to the intensive use of organic soils as croplands or grasslands makes the return to a near-natural state nearly impossible in such a short time frame. This would require not only rewetting, but also landscaping work the reconstitute the endemic vegetation. However, some transition periods from drained soils to wet culture can be beneficial both for climate and farmers, since it would help to remove nutrient or pesticides accumulated in the soil.
- Finally, last but not least, the scope 3 represents an important variation of 50% between the lower and upper estimates from Wüst-Galley et al. 2020 [28]. By taking an average of 1'250 km^2, the Scope 3's results are to be taken as a maximum estimate that are not linked to a conservative scenario. It represents more the highest range possible that we could expect from the renaturation of Organic soils in Switzerland, assuming that 100% of the peatlands historically presumed were not entirely destroyed and could be restored.

Conclusion

While wetlands are classified as "unproductive vegetation", this thesis invites to redefine the notion of productivity itself with a systemic approach. It emphasizes that the habitability of Earth is due to ecosystems, not to humans, and that ecosystem services are guarantors of human well being in socio-ecological systems. Nature based Solutions tend to restore them with climate, biodiversity and food sovereignty co-benefits that could allow Switzerland to thrive and appear as a leading example for the ecological transition the world needs.

For biochar and peatlands, this work set the general framework where these solutions lie, by exploring the historical context, socio-economic context, and scientific phenomena behind those topics.

It was revealed that biochar production from sustainable biomass potential could contribute to the Swiss Long Term Climate strategy by providing around 2 Mt CO_2eq of negative emissions per year if properly deployed toward 2050, 40% of the remaining Swiss emissions at this time. The emission of 125'000 t CO_2eq per year could be avoided from raised bog, until generating 50'000 t $CO_2eq/$yr of negative emissions. Those potentials respectively rise to the avoidance of 800'000 t $CO_2eq/$yr with a possible generation of 200'000 t$CO_2eq/$yr of negative emissions for Scope 2 (all identified organic soils), and the avoidance of 4 Mt $CO_2eq/$yr with a possible generation of 1 Mt $CO_2eq/$yr of negative emissions for scope 3 (all non-localised potential organic soils).

These estimations were obtained by the creation of two databases, of biomass potential and organic soils, and two models to transform two databases into GHG emissions potentials.

The OSMOSE model developed in this project computes the emissions resulting from the rewetting of organic soils in Switzerland according to a configurable set of parameters. Such a model could be useful for communes, cantons, or even the Federal Office of the Environment, to identify organic soils emissions on their territories and include in their respective Climate Plans an order of magnitude for the emissions reduction potential resulting from their rewetting. It could also be useful to businesses working on the trade of carbon credits from nature-based solutions on the voluntary carbon market to identify the most promising projects of renaturation.

Recommendations for Future Researches

Throughout this thesis, discovering the vastness of the research topics offered to possibility to identify some recommendations for future works.
First, there are some possible direct continuations to this project. It could be possible to :

- Find more detailed emissions factors depending on vegetation types,
- Develop regional scales for organic soils,
- Compare the data obtained to the cropping areas in Switzerland to assess the impact of rewetting on food security and diet change,
- Perform a more accurate estimate of the costs analysis including component-based learning curves,
- Make Detailed researches on the types of monitoring needed,
- Break the costs per cantons to estimate the respective efforts each need to do
- Establish Guidelines for developing Biochar production and Peatlands renaturation in the light of a Swiss Negative Emissions Fund Pilot Program.

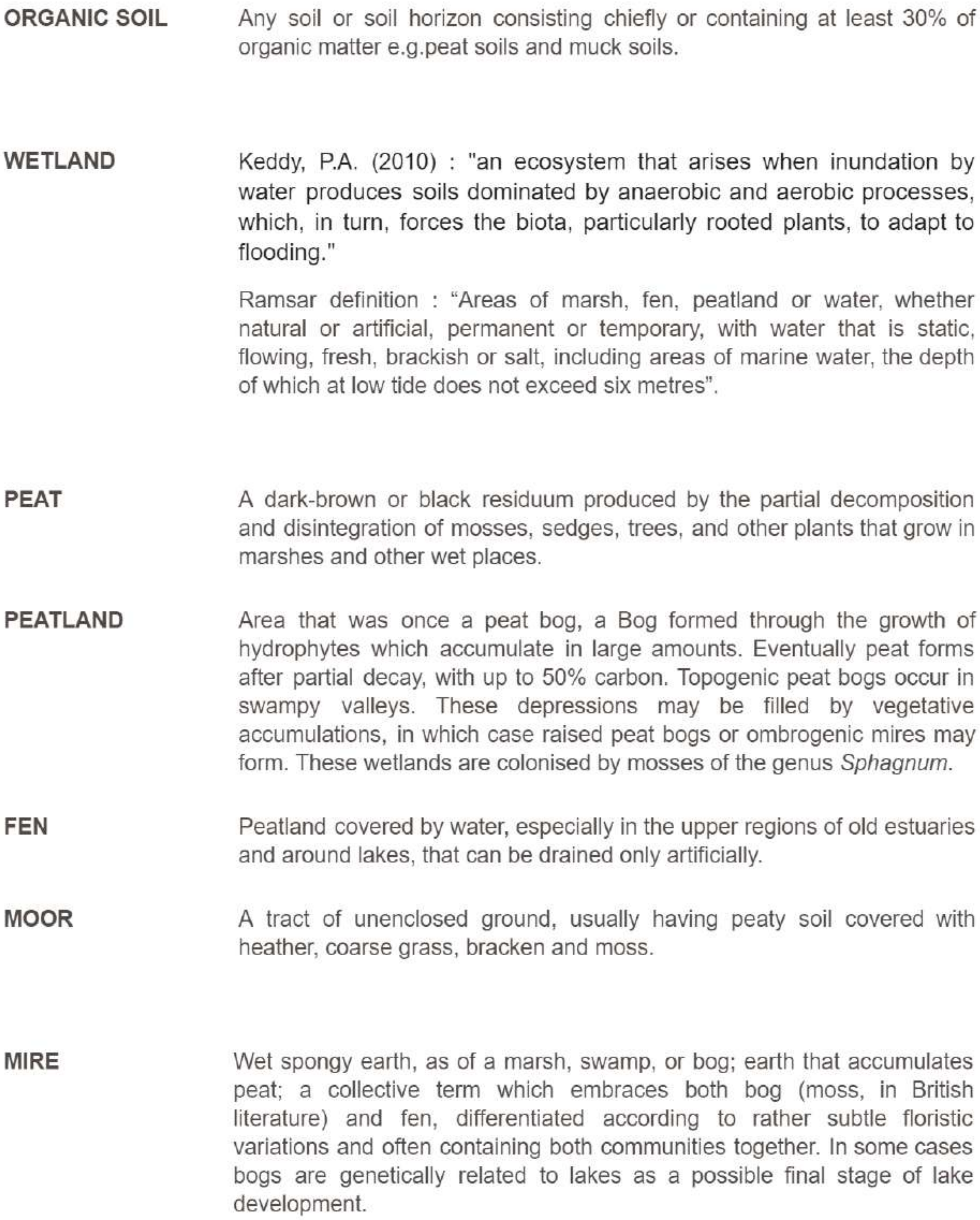
Some relevant gaps in the literature were observed and research would be worth exploring the following topics :

- Develop communal and cantonal estimates for the already used biomass potential.
- Develop tiers 3 methodology for emissions factors in Switzerland.
- Do more researches on the Methane peak phenomena.
- Develop agriculture practices, industry practices and market opportunities for reeds products to create an incentive for organic soils transition from intensive agriculture to a full renaturation scenario via a paludiculture stage.
- Develop the use of biochar in urban area.

Finally, it is to be noted that the research questions addressed in this thesis are really topical, and a lot of works were done in parallel to this thesis, but will unfortunately be released only after its conclusion. For example, Dr. Sonja Keel and the Agroscope Division for Climate and Agriculture are currently preparing a paper on soil carbon sequestration potential that will include biochar. The Federal Office of the Environment, via M. Michael Bock, is currently preparing a factsheet to do an overview of the potential of biochar in Switzerland, and the Federal Council is preparing a report to answer to the BOURGEOIS POSTULAT No. 19.3639 on Soil Carbon Sequestration. Also, some persons work on the mapping organic soils to propose an updated version of the work done by Dr. Chloé Wüst-Galley [18]. All these announcements make the research in these topics very promising.

Annexes

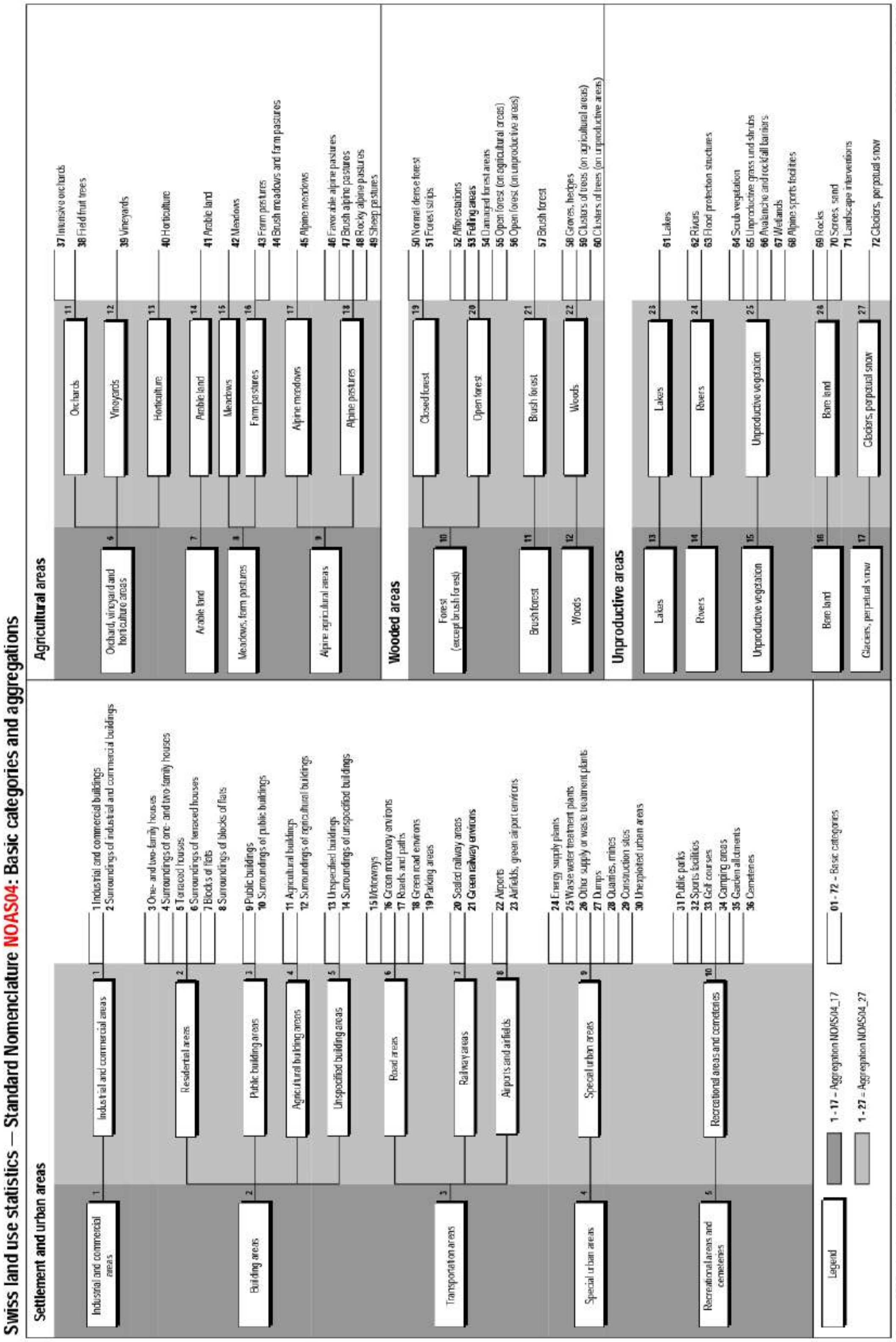
I. Glossary



ORGANIC SOIL	Any soil or soil horizon consisting chiefly or containing at least 30% of organic matter e.g.peat soils and muck soils.
WETLAND	Keddy, P.A. (2010) : "an ecosystem that arises when inundation by water produces soils dominated by anaerobic and aerobic processes, which, in turn, forces the biota, particularly rooted plants, to adapt to flooding." Ramsar definition : "Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static, flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six metres".
PEAT	A dark-brown or black residuum produced by the partial decomposition and disintegration of mosses, sedges, trees, and other plants that grow in marshes and other wet places.
PEATLAND	Area that was once a peat bog, a Bog formed through the growth of hydrophytes which accumulate in large amounts. Eventually peat forms after partial decay, with up to 50% carbon. Topogenic peat bogs occur in swampy valleys. These depressions may be filled by vegetative accumulations, in which case raised peat bogs or ombrogenic mires may form. These wetlands are colonised by mosses of the genus *Sphagnum*.
FEN	Peatland covered by water, especially in the upper regions of old estuaries and around lakes, that can be drained only artificially.
MOOR	A tract of unenclosed ground, usually having peaty soil covered with heather, coarse grass, bracken and moss.
MIRE	Wet spongy earth, as of a marsh, swamp, or bog; earth that accumulates peat; a collective term which embraces both bog (moss, in British literature) and fen, differentiated according to rather subtle floristic variations and often containing both communities together. In some cases bogs are genetically related to lakes as a possible final stage of lake development.

SWAMP	A swamp may be defined as a vegetated area perennially flooded or saturated with groundwater. It differs from a marsh in that the latter normally has a period of desiccation.
MARSH	A transitional land-water area, covered at least part of the time by surface water or saturated by groundwater at, or near the surface. Characterised by aquatic and glass-like vegetation, usually without peat accumulation.
RIVERINE	Situated beside or of a river. (1) *Perennial* a. Permanent rivers and streams, also waterfalls. b. Inland deltas. (2) *Temporary* b. Seasonal and irregularly flowing rivers and streams. c. Riverine floodplains, including river flats, flooded river basins and seasonally flooded grasslands.

II. Standard Nomenclature NOAS04 from the Swiss land use statistics

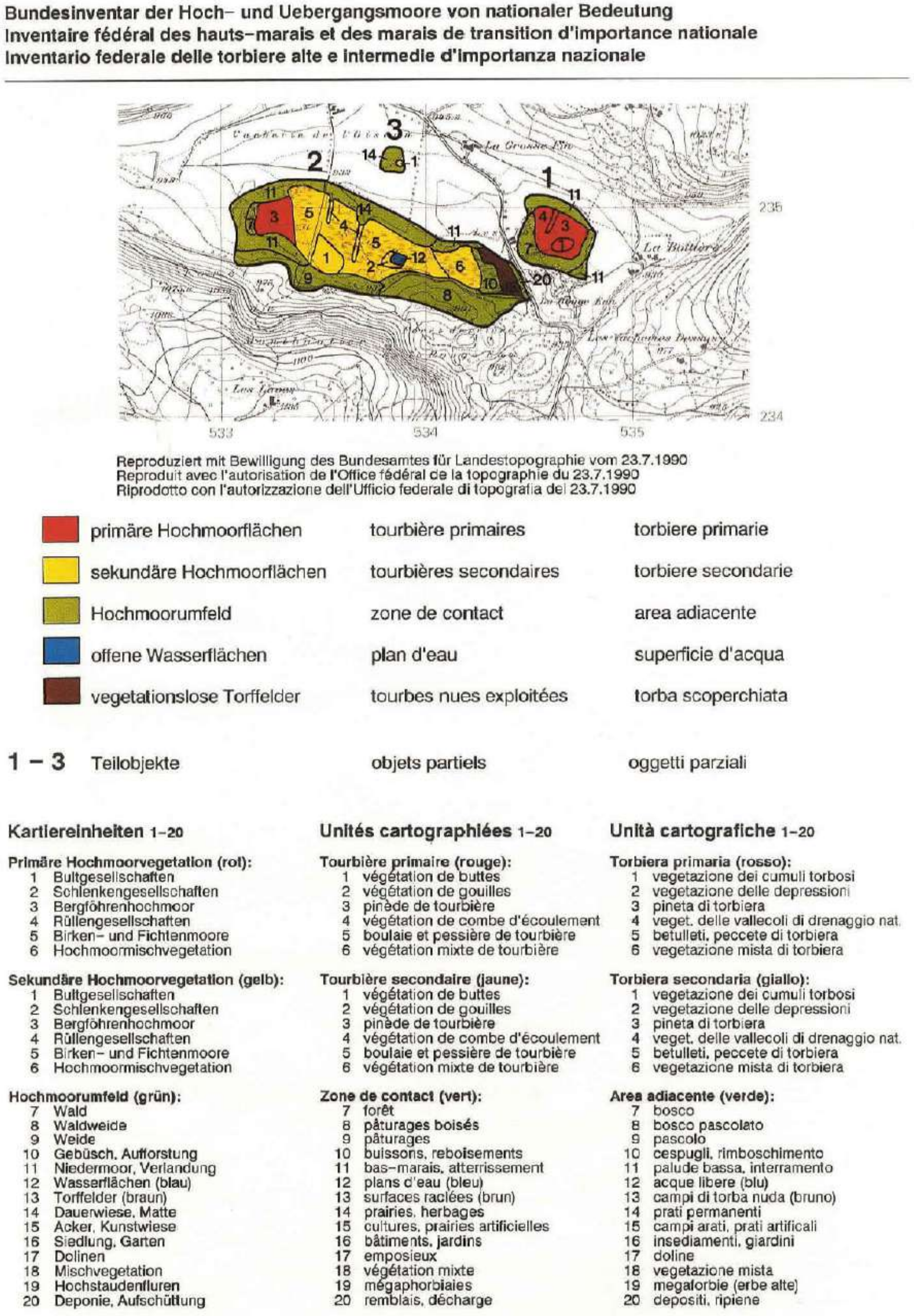


Source: SFSO – Land use statistics

© SFSO, Neuchâtel 2013

Figure 44: Standard Nomenclature NOAS04 from the Swiss land use statistics [29]

III. Legend of the Raised bogs inventory



Bundesinventar der Hoch- und Uebergangsmoore von nationaler Bedeutung
Inventaire fédéral des hauts-marais et des marais de transition d'importance nationale
Inventario federale delle torbiere alte e intermedie d'importanza nazionale

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Riprodotto con l'autorizzazione dell'Ufficio federale di topografia del 23.7.1990

🟥	primäre Hochmoorflächen	tourbière primaires	torbiere primarie
🟨	sekundäre Hochmoorflächen	tourbières secondaires	torbiere secondarie
🟩	Hochmoorumfeld	zone de contact	area adiacente
🟦	offene Wasserflächen	plan d'eau	superficie d'acqua
🟫	vegetationslose Torffelder	tourbes nues exploitées	torba scoperchiata
1 – 3	Teilobjekte	objets partiels	oggetti parziali

	Kartiereinheiten 1–20	**Unités cartographiées** 1–20	**Unità cartografiche** 1–20
	Primäre Hochmoorvegetation (rot):	**Tourbière primaire (rouge):**	**Torbiera primaria (rosso):**
1	Bultgesellschaften	végétation de buttes	vegetazione dei cumuli torbosi
2	Schlenkengesellschaften	végétation de gouilles	vegetazione delle depressioni
3	Bergföhrenhochmoor	pinède de tourbière	pineta di torbiera
4	Rüllengesellschaften	végétation de combe d'écoulement	veget. delle vallecoli di drenaggio nat.
5	Birken- und Fichtenmoore	boulaie et pessière de tourbière	betulleti, peccete di torbiera
6	Hochmoormischvegetation	végétation mixte de tourbière	vegetazione mista di torbiera
	Sekundäre Hochmoorvegetation (gelb):	**Tourbière secondaire (jaune):**	**Torbiera secondaria (giallo):**
1	Bultgesellschaften	végétation de buttes	vegetazione dei cumuli torbosi
2	Schlenkengesellschaften	végétation de gouilles	vegetazione delle depressioni
3	Bergföhrenhochmoor	pinède de tourbière	pineta di torbiera
4	Rüllengesellschaften	végétation de combe d'écoulement	veget. delle vallecoli di drenaggio nat.
5	Birken- und Fichtenmoore	boulaie et pessière de tourbière	betulleti, peccete di torbiera
6	Hochmoormischvegetation	végétation mixte de tourbière	vegetazione mista di torbiera
	Hochmoorumfeld (grün):	**Zone de contact (vert):**	**Area adiacente (verde):**
7	Wald	forêt	bosco
8	Waldweide	pâturages boisés	bosco pascolato
9	Weide	pâturages	pascolo
10	Gebüsch, Aufforstung	buissons, reboisements	cespugli, rimboschimento
11	Niedermoor, Verlandung	bas-marais, atterrissement	palude bassa, interramento
12	Wasserflächen (blau)	plans d'eau (bleu)	acque libere (blu)
13	Torffelder (braun)	surfaces raclées (brun)	campi di torba nuda (bruno)
14	Dauerwiese, Matte	prairies, herbages	prati permanenti
15	Acker, Kunstwiese	cultures, prairies artificielles	campi arati, prati artificali
16	Siedlung, Garten	bâtiments, jardins	insediamenti, giardini
17	Dolinen	emposieux	doline
18	Mischvegetation	végétation mixte	vegetazione mista
19	Hochstaudenfluren	mégaphorbiaies	megaforbie (erbe alte)
20	Deponie, Aufschüttung	remblais, décharge	depositi, ripiene

Figure 45: Official legend of the raised bog inventory

IV. Description of Tier 1, 2 and 3 Methodologies for drained and rewetted Organic Soils

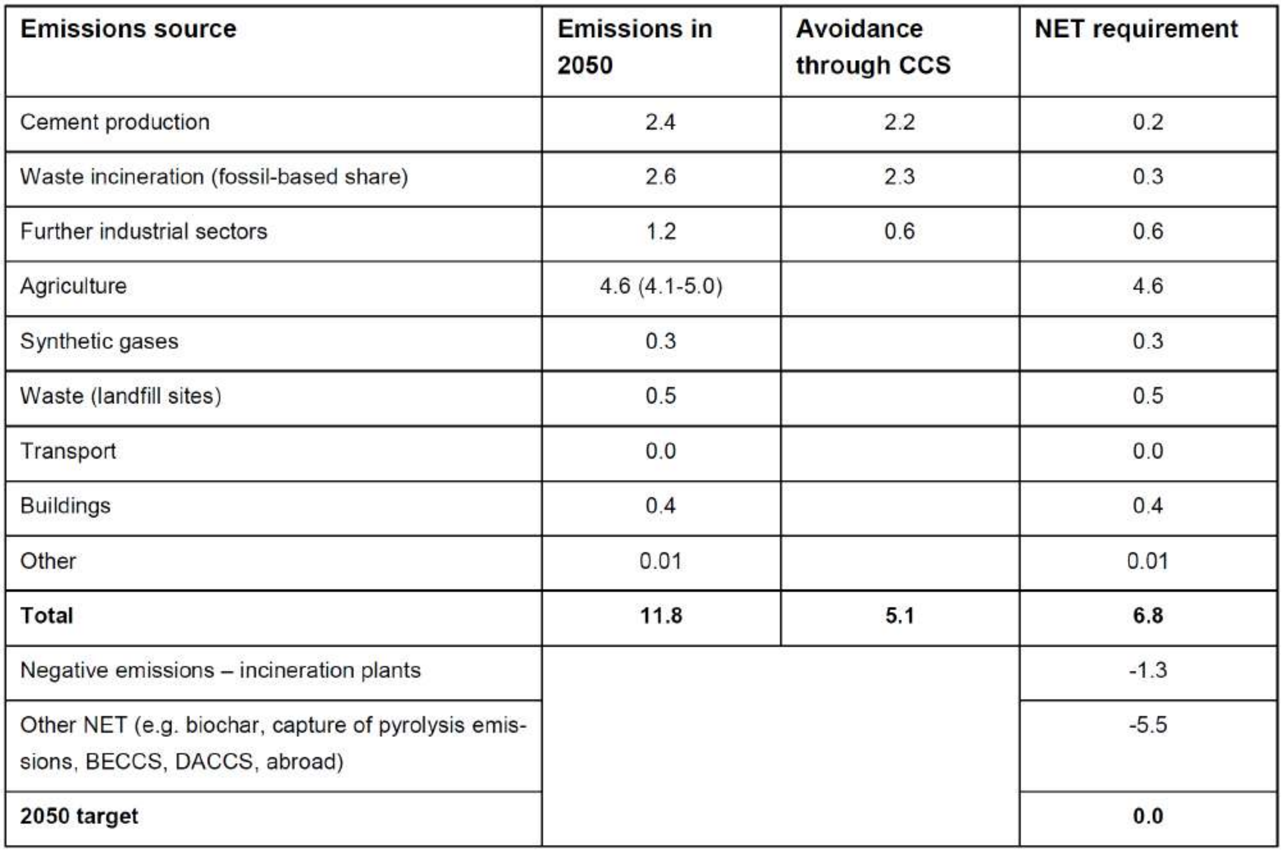
The following description is taken from the IPCC Wetland Supplement 2013 Chapter 2 and 3.

Tier 1 are simple methods with default values for vast regional areas described by climate zone. Under Tier 1, the basic methodology for estimating annual GHG emissions/removals from rewetted organic soils consists in the multiplication of the nationally derived area of rewetted organic soils is multiplied by an emission factor, which is disaggregated by climate zone and where applicable by nutrient status (nutrient poor and nutrient rich). Tier 1 methodology is applicable from the year of rewetting.

Tier 2 methodology uses country-specific emission factors and parameters, spatially disaggregated to reflect regionally important practices and dominant ecological dynamics. It may be appropriate to subdivide activity data and emission factors according to the present vegetation composition which is a representation of the water table depth and soil properties or by land use prior to rewetting (e.g. Forest, Grassland, Cropland, Wetland).

Tier 3 are more complex approaches, possibly models. However, it should be compatible with lower tiers. A Tier 3 methodology involves a comprehensive understanding and representation of the dynamics of GHG emissions and removals on drained and rewetted organic soils, including the effect of site characteristics, soil characteristics, vegetation composition, soil temperature and mean water table depth. These could be integrated into a dynamic, mechanistic-based model or through a measurement-based approach. These parameters, in addition to further parameters such as water flows and residence time of water, could also be used to describe all types of Carbon lost, as Dissolved Organic Carbon (DOC) and fires, from the system using process-based models that incorporate hydrology amongst other factors.

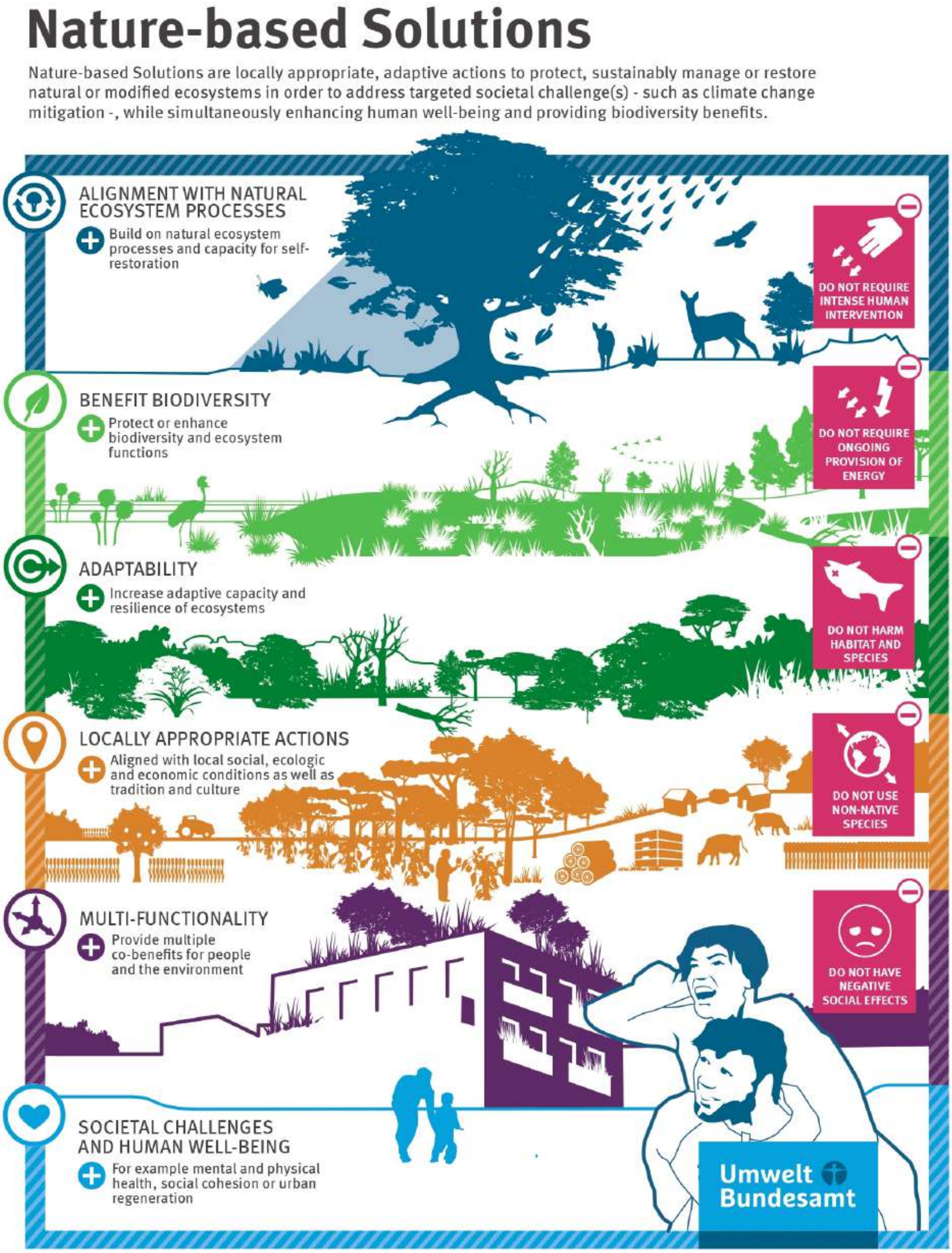
V. Swiss Long-Term Climate Strategy



Emissions source	Emissions in 2050	Avoidance through CCS	NET requirement
Cement production	2.4	2.2	0.2
Waste incineration (fossil-based share)	2.6	2.3	0.3
Further industrial sectors	1.2	0.6	0.6
Agriculture	4.6 (4.1-5.0)		4.6
Synthetic gases	0.3		0.3
Waste (landfill sites)	0.5		0.5
Transport	0.0		0.0
Buildings	0.4		0.4
Other	0.01		0.01
Total	**11.8**	**5.1**	**6.8**
Negative emissions – incineration plants			-1.3
Other NET (e.g. biochar, capture of pyrolysis emissions, BECCS, DACCS, abroad)			-5.5
2050 target			**0.0**

Table 11: Possible remaining emissions in 2050 and approaches to avoid or offset them according to the ZERO basis scenario of EP 2050+ (figures in million tonnes of). Source: Switzerland's Long-Term Climate Strategy, 2021 [6]

VI. Nature-Based Solutions


Nature-based Solutions

Nature-based Solutions are locally appropriate, adaptive actions to protect, sustainably manage or restore natural or modified ecosystems in order to address targeted societal challenge(s) - such as climate change mitigation -, while simultaneously enhancing human well-being and providing biodiversity benefits.

This graphic has been developed by Öko-Institut and Ecologic Institut on behalf of the German Environment Agency. It is based on Reise et al. (2021): Nature-based Solutions and global climate protection. Climate Change xx/2021. Dessau-Roßlau. Download at: [Link]. Design: Erik Tuckow, sichtagitation.de.

Figure 46: NbS infographic from Umwelt Bundesamt 2022 [35]

VII. Metrics to measure Nature-Based Solutions co-benefits

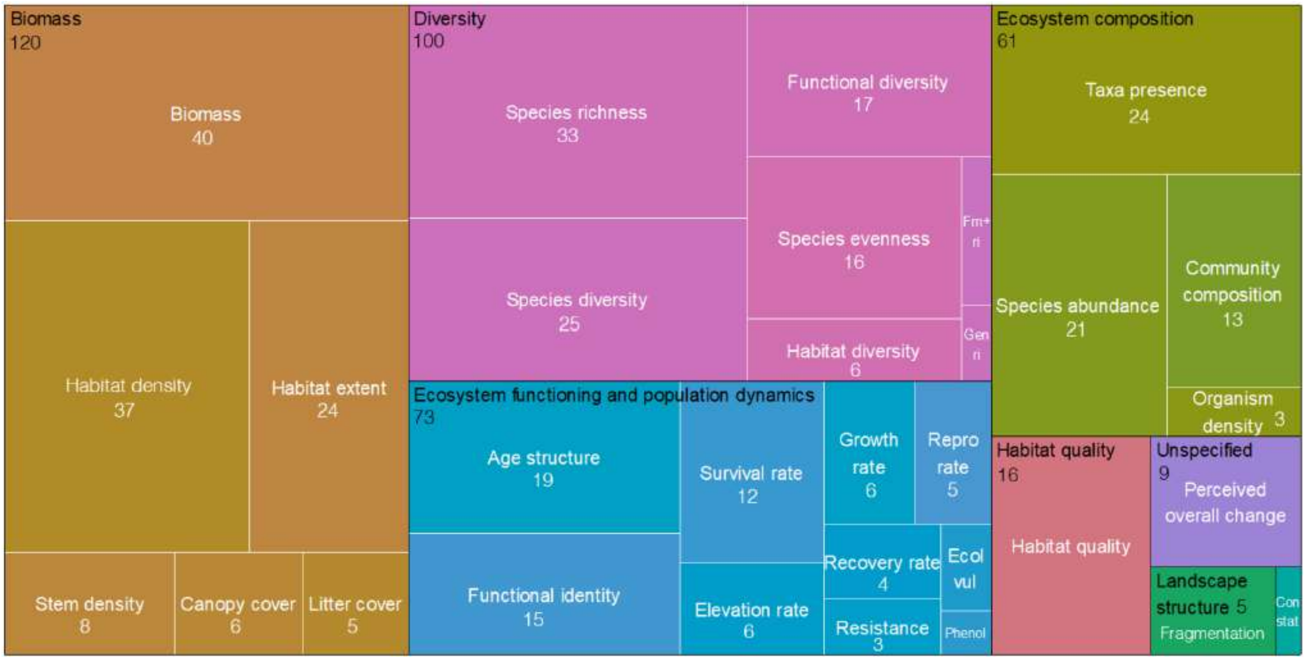
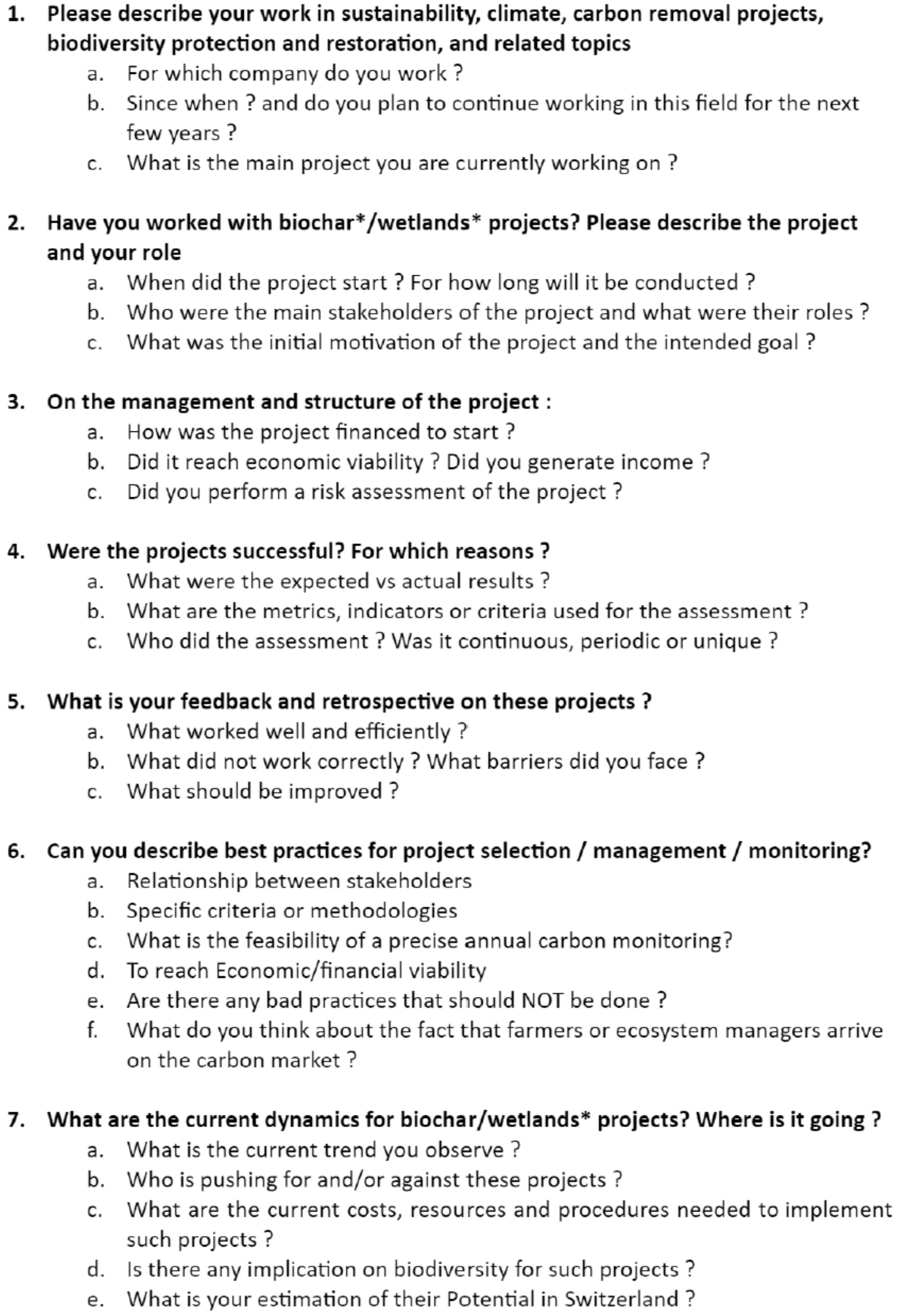


Figure 47: Frequency of use of ecosystem health metrics. Source : Key et al. 2021 [36]

Frequency of use of ecosystem health metrics are grouped by broad metric categories. Box areas are proportional to frequency of use of ecosystem health metrics; metric names are in white; broad metric category names are in black; colours correspond to broad metric categories. 385 outcomes are represented here, across 109 interventions. Gen ri = generic richness; Fm+ ri = family and above richness; Repro rate = reproductive rate; Ecol vul = ecological vulnerability; Phenol = phenology; Con stat = conservation status. Two metrics that were defined a priori were not used at all by the studies: genetic diversity and phylogenetic diversity.

VIII. Complete set of questions from the unstructured interview series



1. **Please describe your work in sustainability, climate, carbon removal projects, biodiversity protection and restoration, and related topics**
    a. For which company do you work ?
    b. Since when ? and do you plan to continue working in this field for the next few years ?
    c. What is the main project you are currently working on ?

2. **Have you worked with biochar*/wetlands* projects? Please describe the project and your role**
    a. When did the project start ? For how long will it be conducted ?
    b. Who were the main stakeholders of the project and what were their roles ?
    c. What was the initial motivation of the project and the intended goal ?

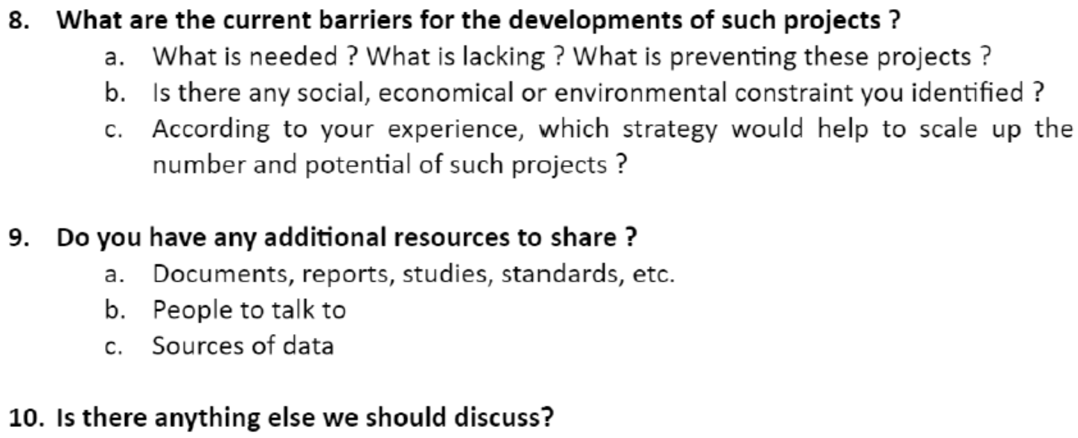
3. **On the management and structure of the project :**
    a. How was the project financed to start ?
    b. Did it reach economic viability ? Did you generate income ?
    c. Did you perform a risk assessment of the project ?

4. **Were the projects successful? For which reasons ?**
    a. What were the expected vs actual results ?
    b. What are the metrics, indicators or criteria used for the assessment ?
    c. Who did the assessment ? Was it continuous, periodic or unique ?

5. **What is your feedback and retrospective on these projects ?**
    a. What worked well and efficiently ?
    b. What did not work correctly ? What barriers did you face ?
    c. What should be improved ?

6. **Can you describe best practices for project selection / management / monitoring?**
    a. Relationship between stakeholders
    b. Specific criteria or methodologies
    c. What is the feasibility of a precise annual carbon monitoring?
    d. To reach Economic/financial viability
    e. Are there any bad practices that should NOT be done ?
    f. What do you think about the fact that farmers or ecosystem managers arrive on the carbon market ?

7. **What are the current dynamics for biochar/wetlands* projects? Where is it going ?**
    a. What is the current trend you observe ?
    b. Who is pushing for and/or against these projects ?
    c. What are the current costs, resources and procedures needed to implement such projects ?
    d. Is there any implication on biodiversity for such projects ?
    e. What is your estimation of their Potential in Switzerland ?



8. **What are the current barriers for the developments of such projects ?**
    a. What is needed ? What is lacking ? What is preventing these projects ?
    b. Is there any social, economical or environmental constraint you identified ?
    c. According to your experience, which strategy would help to scale up the number and potential of such projects ?

9. **Do you have any additional resources to share ?**
    a. Documents, reports, studies, standards, etc.
    b. People to talk to
    c. Sources of data

10. **Is there anything else we should discuss?**

IX. Complete list of names and functions of the experts interviewed

1. Ing. Tristan Mariethoz - Canton of Vaud
2. Dr. Roman Hüppi - First Climate
3. Dr. Mélanie Siegrist - myclimate
4. Prof. Meret Aeppli - EPFL
5. Dr. Nikolas Hagemann - Ithaka Institute and Agroscope
6. M. Benjamin Herbreteau - SofiesGroup
7. Prof. Samuel Abiven - ENS and CNRS
8. Prof. Claire Guenat - Pédologist - ex-EPFL
9. Dr. François Füllemann - Pedologist for the canton of Vaud
10. M. Emmanuel Graz - City of Lausanne
11. PhD. Candidate Xavier Dupla - Hepia and UNIL
12. Dr. Lena Gubler - WSL
13. Ing. Sebastien Tschanz - Canton of Neuchâtel
14. Prof. Edward Mitchell - University of Neuchâtel
15. M. Michael Bock - FOEN Climate division
16. Prof. Oliver Thees - WSL
17. Ing. Dr. Philippe Grosvernier - Lin'eco
18. Dr. Jens Leifeld - Agroscope
19. Dr. Chloé Wüst-Galley - Agroscope
20. Dr. Sonja Keel - Agroscope

Mail exchange and data sharing

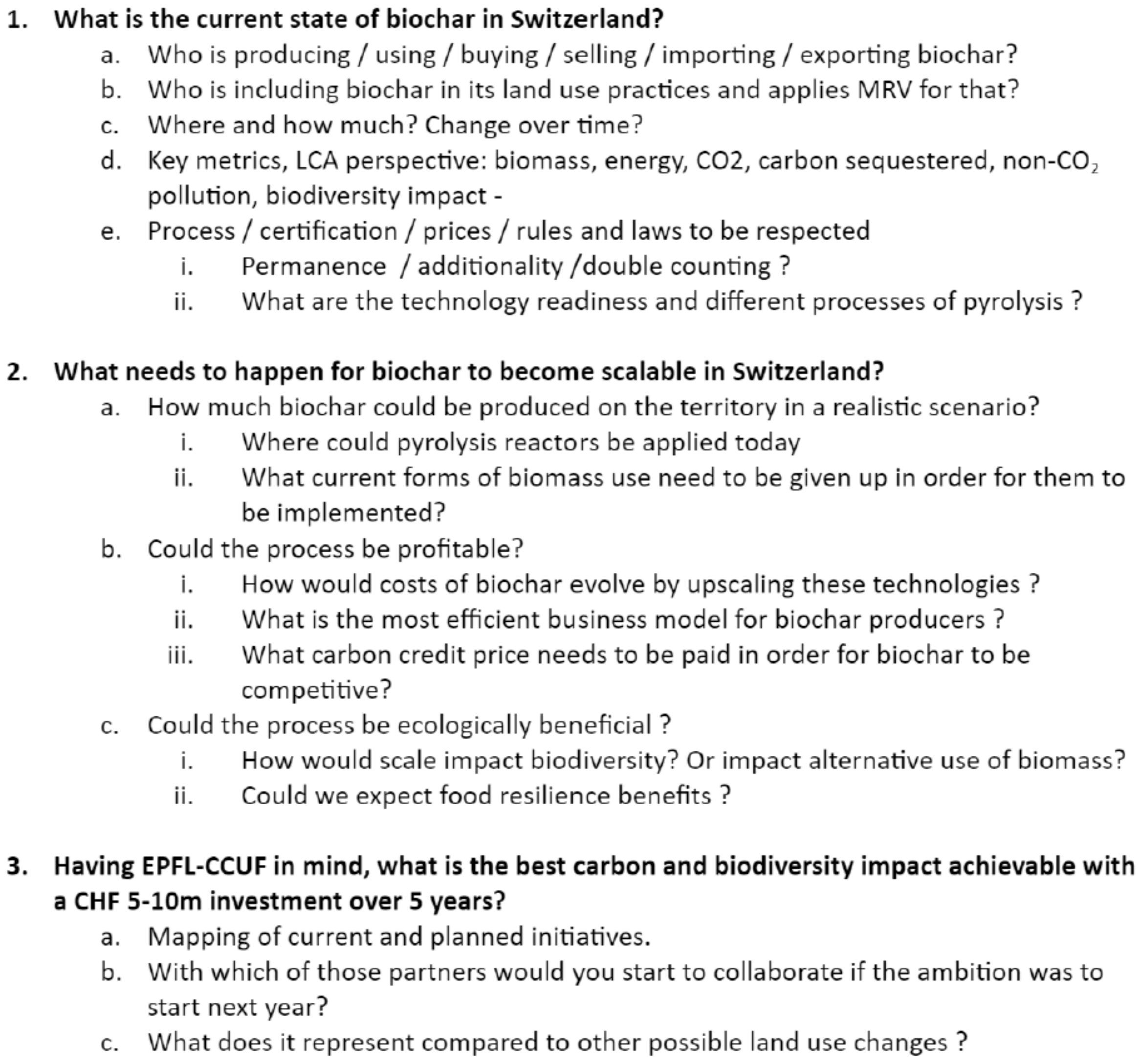
1. M. Stephane Bourgos - Berner Fachhochschule
2. M. Christophe Hunziker - WSL
3. Dr. Hans-Peter Schmidt - EBC and Ithaka Institute
4. Prof. Pascal Boivin - Hepia
5. M. Gian-Reto Walther - FOEN

X. Figure of excel table synthesising the interview transcripts

List	Number	1	2
Zoom	**Title + Name**	**Eng. Tristan Mariethoz**	**PhD Roman Hüppi**
Notes	**Job**	**Chef Projet Climat**	**Scientific advisor - Biochar expert**
Concept	**Organism**	**Canton de Vaud - DGE-ARC**	**First Climate**
	Full transcript	[LINK]	LINK
1	**Please describe your work in sustainability, climate, carbon removal projects, biodiversity protection and restoration, and related topics**		
1.a	For which company do you work ?	Canton de Vaud	First climate
1.b	Since when ? and do you plan to continue working in this field for the next few years ?	2015 and will continue	2021 and will continue
1.c	What is the main project you are currently working on ?	Cordination of efforts and scientific validation	Just starting biochar certification
2	**Have you worked with biochar*/wetlands* projects? Please describe the project and your role**	1) Adaptation of wetland (VD) to cliamte change 2) Drain of Plaine des Orbes and GHG emissions	1) PhD thesis on the reduction of N2O emissions 2) Field pilot in Uri canton
2.a	When did the project start ? For how long will it be conducted ?	1) Juillet 2019, 1 year 2) 2018, 2 years	1) 2015 - 4 years 2) 2020
2.b	Who were the main stakeholders of the project and what were their roles ?	people from DGE, soil science, biodiv, some madated expe	2) university Zurich, canton Uri, biochar producer, feedstocl
2.c	What was the initial motivation of the project and the intended goal ?	Prospective studies : 1) identify futur risks due to climate change 2) evluate possibility increase food producton without incre	Practical implementation fo a new circular economy loop
3	**On the management and structure of the project :**		
3.a	How was the project financed to start ?	Federal office and Canton	-Innoseed -Canton -Internal fund for time of researcf at university
3.b	Did it reach economic viability ? Did you generate income ?	NA	No, looked promissing with new CO2 law, but no more robu
3.c	Did you perform a risk assessment of the project ?	NA (it was one)	Yes, canton was sceptical, seend a lot of reference to show
4	**Were the projects successful? For which reasons ?**	Do not know	Yes for the result, a bit less for the explanation
4.a	What were the expected vs actual results ?	Diagnostic and risk assesment	Show N2O reduction and understand why
4.b	What are the metrics, indicators or criteria used for the assessment ?	Data are ok, political decision are uncertain	-N2O emission, Yield, Leaching, stability in soil
4.c	Who did the assessment ? Was it continuous, periodic or unique ?	Experts mention above, periodic data on several years	Thesis
5	**What is your feedback and retrospective on these projects ?**	Do not know enough the project for that	
5.a	What worked well and efficiently ?	NA	The willingness of each stakeholder, the lab measurements
5.b	What did not work correctly ? What barriers did you face ?	NA	The absence of political and economical incentives
5.c	What should be improved ?	NA	-Interaction between stakeholder, increase CO2 pricing, mc
6	**Can you describe best practices for project selection / management / monitoring?**		
6.a	Relationship between stakeholders	Identify synergies and possible conflict and work on it	There needs to be new interaction between the source of tl
6.b	Specific criteria or methodologies	Do not know	Count that >90% is stable, try to seperate biochar and soil
6.c	What is the feasibility of a precise annual carbon monitoring?	Seems difficult, because of spatial and temporal evolution	Still open to research, super difficult, but First climate on th
6.d	To reach Economic/financial viability	NA	Increase CO2 pricing + economy of scale
6.e	Are there any bad practices that should NOT be done ?	-That these practises replace the reduction needed in GHG -That farmers just apply biochar without really caring of the	-Burn it again, release PAHs from combustion -Overestimation and too many side effect expected
6.f	What do you think about the fact that farmers or ecosystem managers arrive on the carbon market ?	Do not like it, difficult to define the perimeter, spatial and te	Good thing, spread good practises, and offert financial sup

Figure 48: Spreadsheet synthesising the interview transcriptions

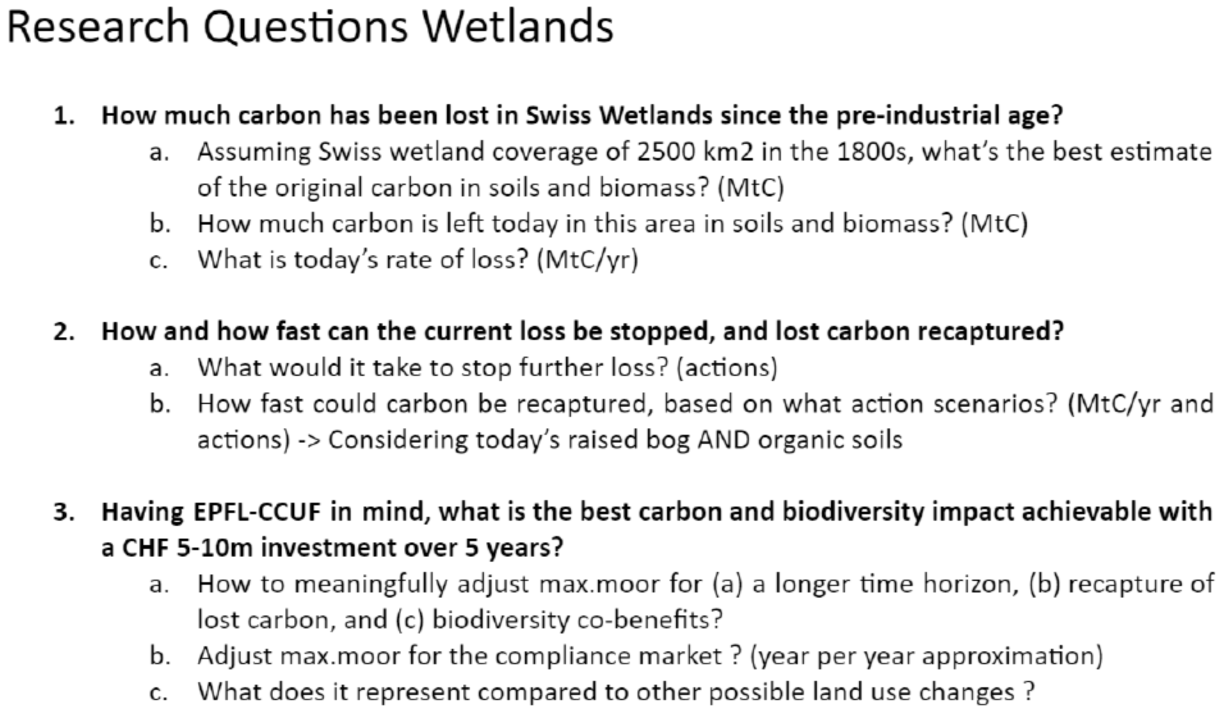
XI. Detailed research questions after the interview process



1. **What is the current state of biochar in Switzerland?**
   a. Who is producing / using / buying / selling / importing / exporting biochar?
   b. Who is including biochar in its land use practices and applies MRV for that?
   c. Where and how much? Change over time?
   d. Key metrics, LCA perspective: biomass, energy, CO2, carbon sequestered, non-CO$_2$ pollution, biodiversity impact -
   e. Process / certification / prices / rules and laws to be respected
      i. Permanence / additionality /double counting ?
      ii. What are the technology readiness and different processes of pyrolysis ?

2. **What needs to happen for biochar to become scalable in Switzerland?**
   a. How much biochar could be produced on the territory in a realistic scenario?
      i. Where could pyrolysis reactors be applied today
      ii. What current forms of biomass use need to be given up in order for them to be implemented?
   b. Could the process be profitable?
      i. How would costs of biochar evolve by upscaling these technologies ?
      ii. What is the most efficient business model for biochar producers ?
      iii. What carbon credit price needs to be paid in order for biochar to be competitive?
   c. Could the process be ecologically beneficial ?
      i. How would scale impact biodiversity? Or impact alternative use of biomass?
      ii. Could we expect food resilience benefits ?

3. **Having EPFL-CCUF in mind, what is the best carbon and biodiversity impact achievable with a CHF 5-10m investment over 5 years?**
   a. Mapping of current and planned initiatives.
   b. With which of those partners would you start to collaborate if the ambition was to start next year?
   c. What does it represent compared to other possible land use changes ?



Research Questions Wetlands

1. **How much carbon has been lost in Swiss Wetlands since the pre-industrial age?**
    a. Assuming Swiss wetland coverage of 2500 km2 in the 1800s, what's the best estimate of the original carbon in soils and biomass? (MtC)
    b. How much carbon is left today in this area in soils and biomass? (MtC)
    c. What is today's rate of loss? (MtC/yr)

2. **How and how fast can the current loss be stopped, and lost carbon recaptured?**
    a. What would it take to stop further loss? (actions)
    b. How fast could carbon be recaptured, based on what action scenarios? (MtC/yr and actions) -> Considering today's raised bog AND organic soils

3. **Having EPFL-CCUF in mind, what is the best carbon and biodiversity impact achievable with a CHF 5-10m investment over 5 years?**
    a. How to meaningfully adjust max.moor for (a) a longer time horizon, (b) recapture of lost carbon, and (c) biodiversity co-benefits?
    b. Adjust max.moor for the compliance market ? (year per year approximation)
    c. What does it represent compared to other possible land use changes ?

XII. Detailed description of the EBC certification classes

The following description are direct citation of the 'European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.' Version 10.1 from 10th Jan 2022

"To keep pace with the growing number of biochar uses, the EBC has introduced a number of certification classes. According to the requirements and safety regulations of the different applications, different parameters are controlled, and limit values apply. With the publication of EBC v10.0, the certification class EBC-BasicMaterials is introduced as the basic and fundamental certification class. It defines what can be considered a biochar or not according to the EBC and complies with all requirements of the EU-REACH regulation. All present and future certification classes meet at least the requirements of EBC-BasicMaterials and thus meet all requirements of the EU-REACH regulation, too. All EBC-certification classes are entitled for Csink certification.

The definition of a certification class (e.g., EBC-Urban or EBC-ConsumerMaterials) is a statement of admissibility of biochar for a given purpose regarding applicable laws, regulations, and relevant industry standards. The assignment to a certification class is not a statement about the excellence of biochar (i.e., good, better, or best biochars for a specific purpose/use) – but it does distinguish between biochars that are admissible or inadmissible for a defined form of application (e.g., in agriculture or construction). Each application and thus certification class has its specific requirements. Every biochar and biochar-based product must be labelled according to the EBC certification class under which it is traded. If, e.g., a biochar is sold as a building material it must be labelled as EBC-BasicMaterial. An EBC-Agro labelled biochar cannot be traded as building material. EBC-Feed labelled biochar cannot be sold as soil amendment.

However, the biochar of one production batch can fulfil the requirements of several certification classes. Different packaging units from one and the same production batch can thus be sold under different labels (e.g., EBC-Feed, EBC-Agro, and EBC-ConsumerProducts). However, a packaging unit must not be labelled with more than one certification class.

Biochar with EBC-Feed certification meets all requirements of the EU feed regulation. In addition to the EBC-Feed certification, a biochar producer must be approved as a feed producer in accordance with the respective national requirements. For this purpose, the EBC advises producers of feed biochar and biochar-based feed products to obtain a complementary GMP+ certification as animal feed producers. EBC and GMP+ collaborate regarding biochar analysis and risk assessment and both sides strongly recommend double certification of biochar feed products. EBC-Feed biochar must not be sold as a soil amendment unless the certification confirms that the required additional certification parameters as defined for the certification classes EBC-Agro and EBC-AgroOrganic are fulfilled, and the biochar is labelled accordingly.

Biochars certified with EBC-Agro and EBC-AgroOrganic meet all requirements of the new EU fertilizer product regulation. Several EU countries such as Austria, Sweden, and Hungary have approved the use of biochar according to the requirements of EBC-Agro. Based on these national approvals, such biochars can be exported and used in all other EU countries. Several EU and EFTA countries apply their own restrictions for the agricultural use of biochar. Switzerland, for example, requires the certification according to EBC-AgroOrganic; however, they only allow woody biomass as a feedstock for pyrolysis. Germany currently requires a minimum carbon content of 80% for biochar that must be produced from untreated wood. Sweden has defined limits beyond the EU regulation and EBC-Agro, which are covered by the Sweden Annexe of the EBC. The

EBC-AgroOrganic certificate meets all requirements of the EU Commission regulation on organic production. The respective specifications and limit values are continuously adapted to align with the ongoing development of relevant European legislation and scientific advances.

EBC-Urban provides a strong standard for the use of biochar in tree planting, park maintenance, sidewalk embellishments, ornamental plants, and rainwater drainage and filtration. The main risk of all those uses is ground- and surface water contamination and work safety, which EBC-Urban certification prevents effectively. As the urban use of biochar is not subject to agricultural legislation, some parameters, and their respective limit values were replaced by limit values that are better adapted to the special matrix of biochar. For example, the EBC-Urban limit value for PAHs is limited to the eight carcinogenic PAHs using the same limit value as for EBC-Feed and EBC-Agro. PAHs are ubiquitous in urban environments (e.g., from tyre abrasion and car exhaust), and urban soil applied biochar which is a strong adsorber of PAHs will act as a net adsorber of those environmental toxins when low biochar PAH-contents are guaranteed (as is the case when EBC-Urban biochar is used).

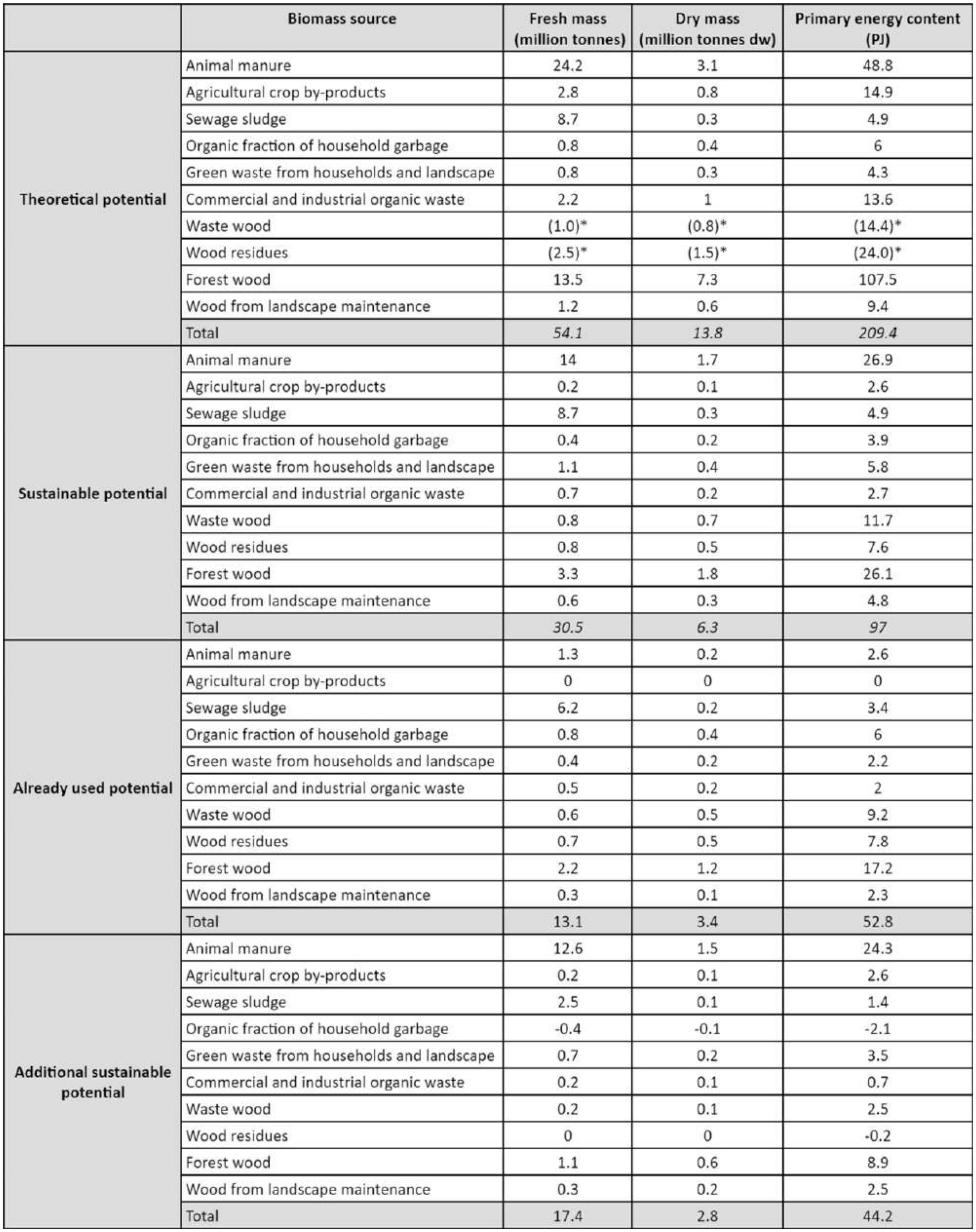
Biochar certified under EBC-Urban must not be used as soil amendment for food or feed production. If biochar shall be used in urban community gardens or home-gardening projects, EBC-Agro or EBC-AgroOrganic quality is recommended. EBC-Urban can further be used for remediation of polluted soils, sediments or groundwater, the production of ornamental plants, and tree nurseries for non-food species. EBC-Agro and EBC-AgroOrganic fulfill all requirements of EBC-Urban and can be used for any urban soil applications.

The certification classes EBC-ConsumerMaterials and EBC-BasicMaterials cover all necessary environmental requirements for non-soil applications. EBC-ConsumerMaterials is destined for biochar to be used in products that may come into direct skin contact with consumers or food-grade products. Examples would be takeaway coffee cups, plastic computer cases, toothbrushes, carpets, textiles, flowerpots, freshwater pipes, etc. However, this does not include medical and healthcare products or food. The biochar must be included in the consumer products in such a way that no coal dust is released because of product use.

The EBC-BasicMaterials certificate guarantees sustainably produced biochar, which can be used in basic industry such as to produce building materials, road construction asphalt, electronics, sewage drains, and composite materials like skis, boats, cars, rockets without risk to the environment and users. However, precautions in handling, storing, and labelling the materials are required, as described in the dedicated sections of the EBC. Both EBC-ConsumerMaterials and EBC-BasicMaterials must not be used in agriculture or other soil applications such as planting urban trees, remediating polluted areas, or mine reclamation.

EBC-BasicMaterials must not be sold directly to private customers (B2C) but is traded exclusively to other businesses (B2B) where adequate handling (i.e., avoidance of dust generation, respiratory protection, avoidance of skin contact) can be ensured. EBC-BasicMaterials defines what can be considered “biochar” and used as a sustainable raw material. Other solid residues obtained from pyrolysis or gasification of biomass that exceed EBC-BasicMaterials limit values must be considered as (potentially) toxic waste and must be disposed of as waste material according to local, national, or international laws. Pyrolytic products from feedstock that are not listed on the EBC feedstock positive list (e.g., industrial wastes or fossil carbon like lignite) should not be considered biochar and must not be traded under the EBC label".

XIII. Swiss biomass potential at the national level



	Biomass source	Fresh mass (million tonnes)	Dry mass (million tonnes dw)	Primary energy content (PJ)
Theoretical potential	Animal manure	24.2	3.1	48.8
	Agricultural crop by-products	2.8	0.8	14.9
	Sewage sludge	8.7	0.3	4.9
	Organic fraction of household garbage	0.8	0.4	6
	Green waste from households and landscape	0.8	0.3	4.3
	Commercial and industrial organic waste	2.2	1	13.6
	Waste wood	(1.0)*	(0.8)*	(14.4)*
	Wood residues	(2.5)*	(1.5)*	(24.0)*
	Forest wood	13.5	7.3	107.5
	Wood from landscape maintenance	1.2	0.6	9.4
	Total	*54.1*	*13.8*	*209.4*
Sustainable potential	Animal manure	14	1.7	26.9
	Agricultural crop by-products	0.2	0.1	2.6
	Sewage sludge	8.7	0.3	4.9
	Organic fraction of household garbage	0.4	0.2	3.9
	Green waste from households and landscape	1.1	0.4	5.8
	Commercial and industrial organic waste	0.7	0.2	2.7
	Waste wood	0.8	0.7	11.7
	Wood residues	0.8	0.5	7.6
	Forest wood	3.3	1.8	26.1
	Wood from landscape maintenance	0.6	0.3	4.8
	Total	*30.5*	*6.3*	*97*
Already used potential	Animal manure	1.3	0.2	2.6
	Agricultural crop by-products	0	0	0
	Sewage sludge	6.2	0.2	3.4
	Organic fraction of household garbage	0.8	0.4	6
	Green waste from households and landscape	0.4	0.2	2.2
	Commercial and industrial organic waste	0.5	0.2	2
	Waste wood	0.6	0.5	9.2
	Wood residues	0.7	0.5	7.8
	Forest wood	2.2	1.2	17.2
	Wood from landscape maintenance	0.3	0.1	2.3
	Total	13.1	3.4	52.8
Additional sustainable potential	Animal manure	12.6	1.5	24.3
	Agricultural crop by-products	0.2	0.1	2.6
	Sewage sludge	2.5	0.1	1.4
	Organic fraction of household garbage	-0.4	-0.1	-2.1
	Green waste from households and landscape	0.7	0.2	3.5
	Commercial and industrial organic waste	0.2	0.1	0.7
	Waste wood	0.2	0.1	2.5
	Wood residues	0	0	-0.2
	Forest wood	1.1	0.6	8.9
	Wood from landscape maintenance	0.3	0.2	2.5
	Total	17.4	2.8	44.2

Figure 49: Swiss biomass potential at the national level from WSL 2017 [13]

XIV. Biochar Production Potential from biomass Categories at Cantonal level

It is possible to convert the legend from the biochar potential in t/yr/ha to the negative emissions potential in tCO_2eq/yr/ha, by multiplying it by a factor of 2.63.

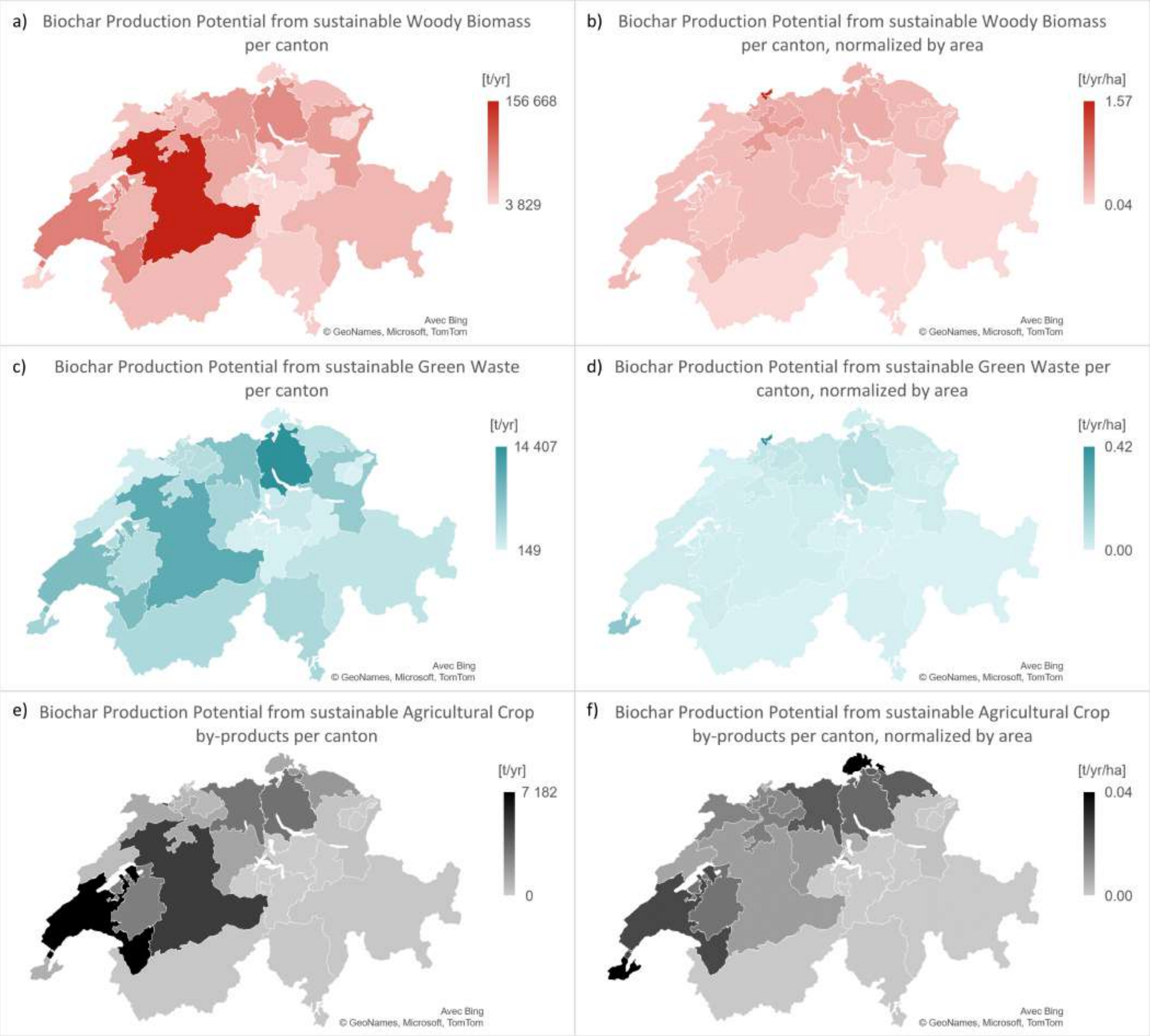


Figure 50: Biochar Production Potential from biomass types at Cantonal level

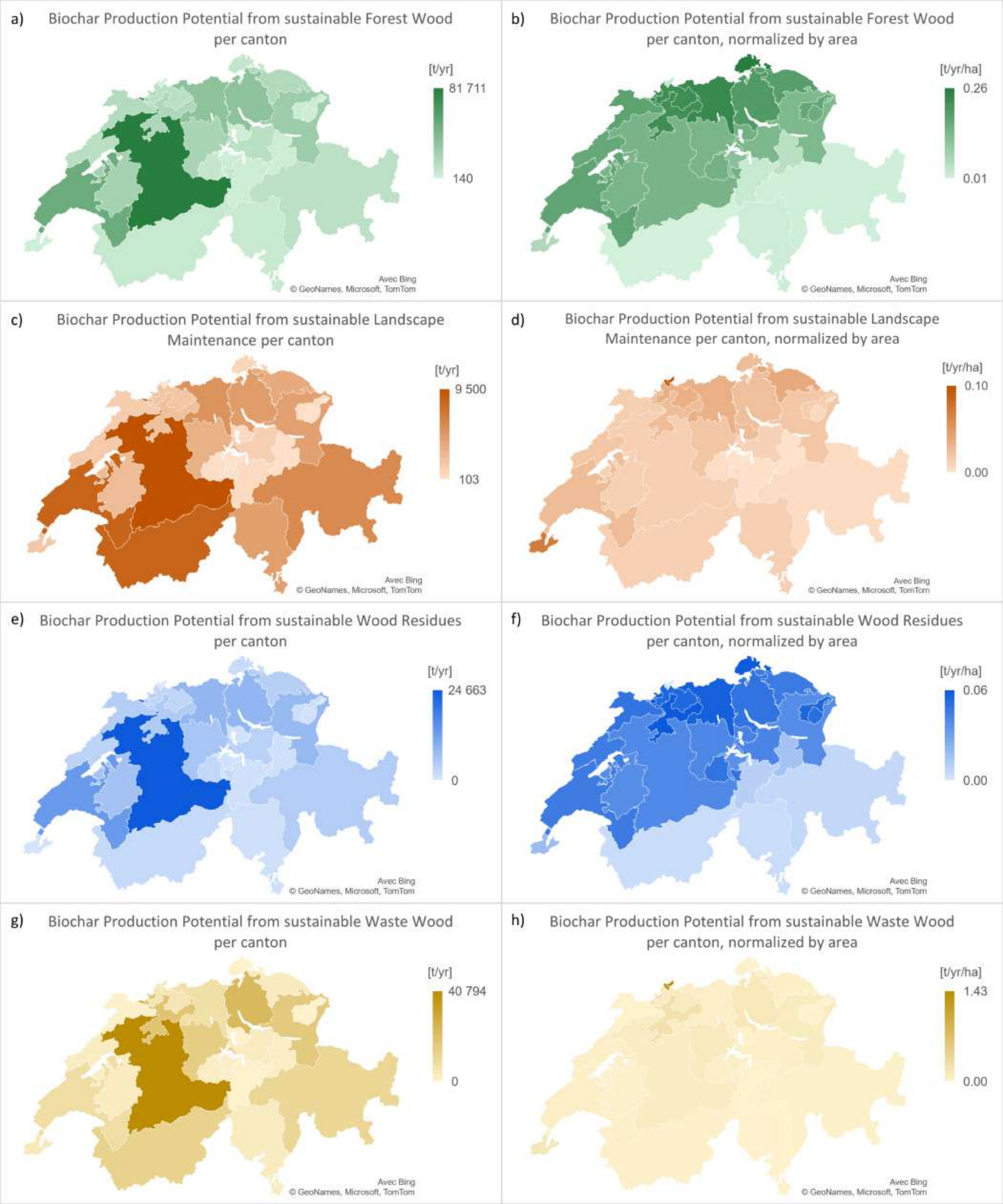


Figure 51: Biochar Production Potential from biomass types at Cantonal level

XV. Biochar Production Potential from biomass types at Communal level

A. Total woody biomass - Absolute Values

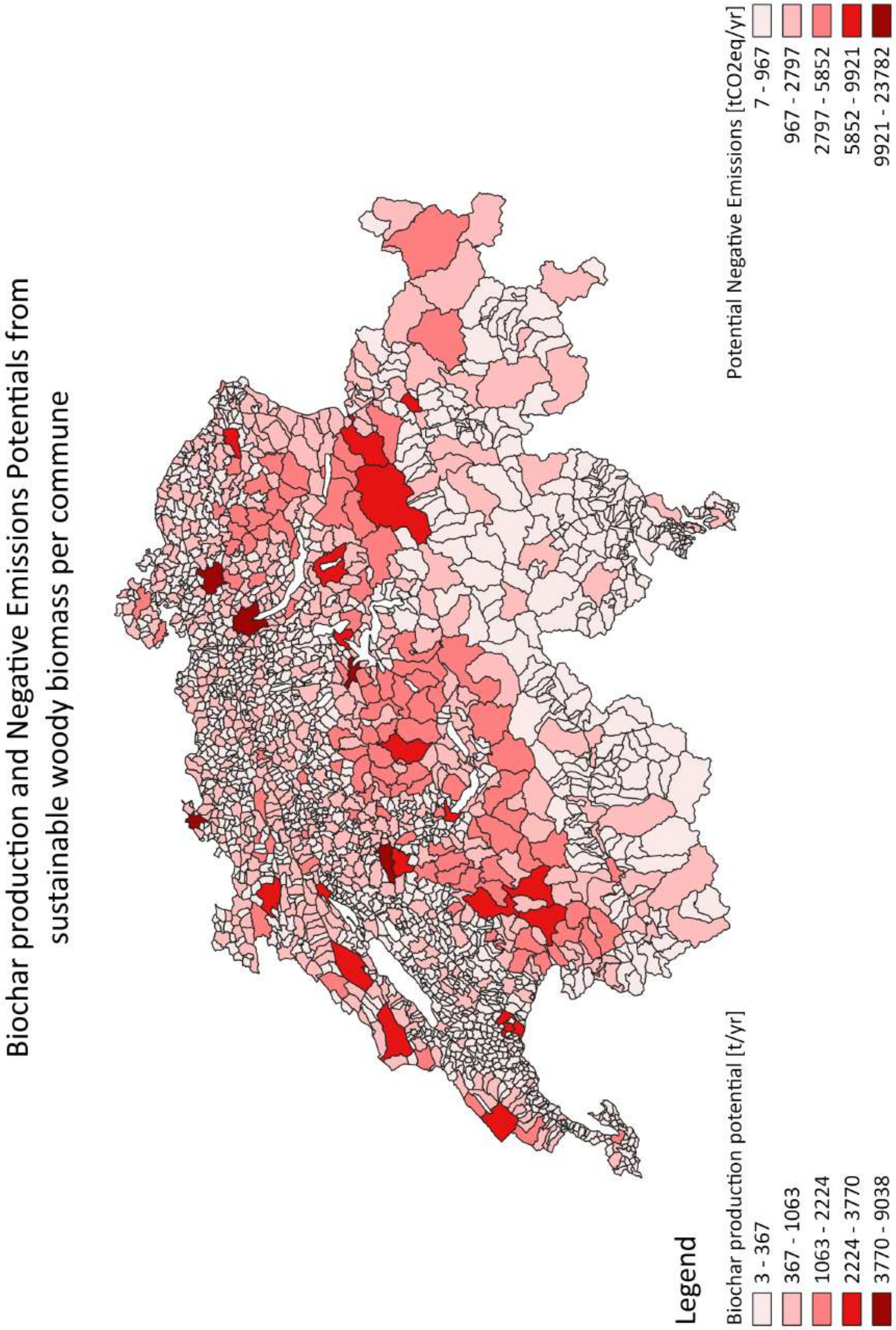


Figure 52: Biochar Production and Negative emissions Potentials from sustainable woody biomass at Communal level in absolute values

B. Total woody biomass - Normalised per area

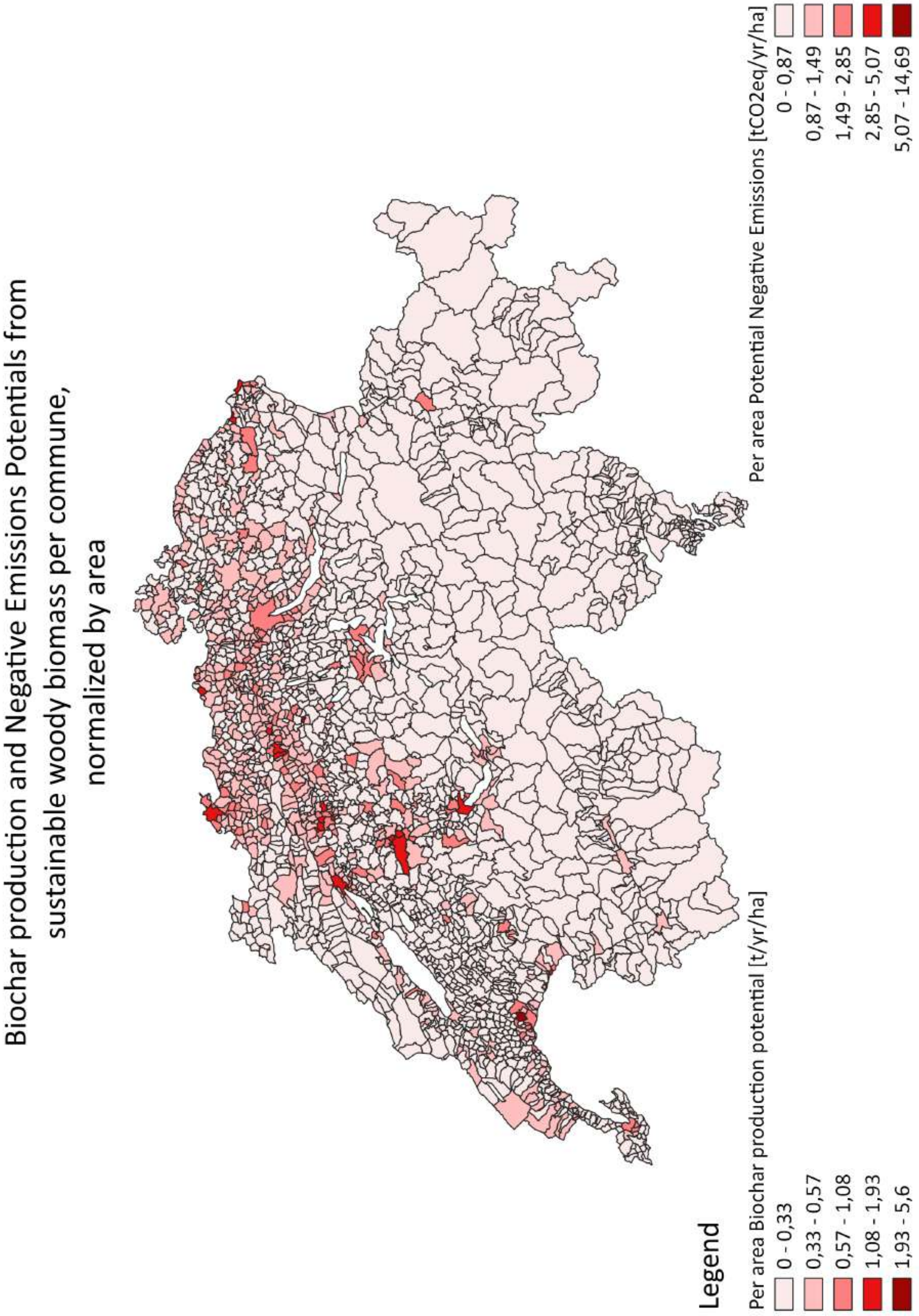


Figure 53: Biochar Production and Negative emissions Potentials from sustainable woody biomass at Communal level, normalised per area

C. Forest wood - Absolute Values

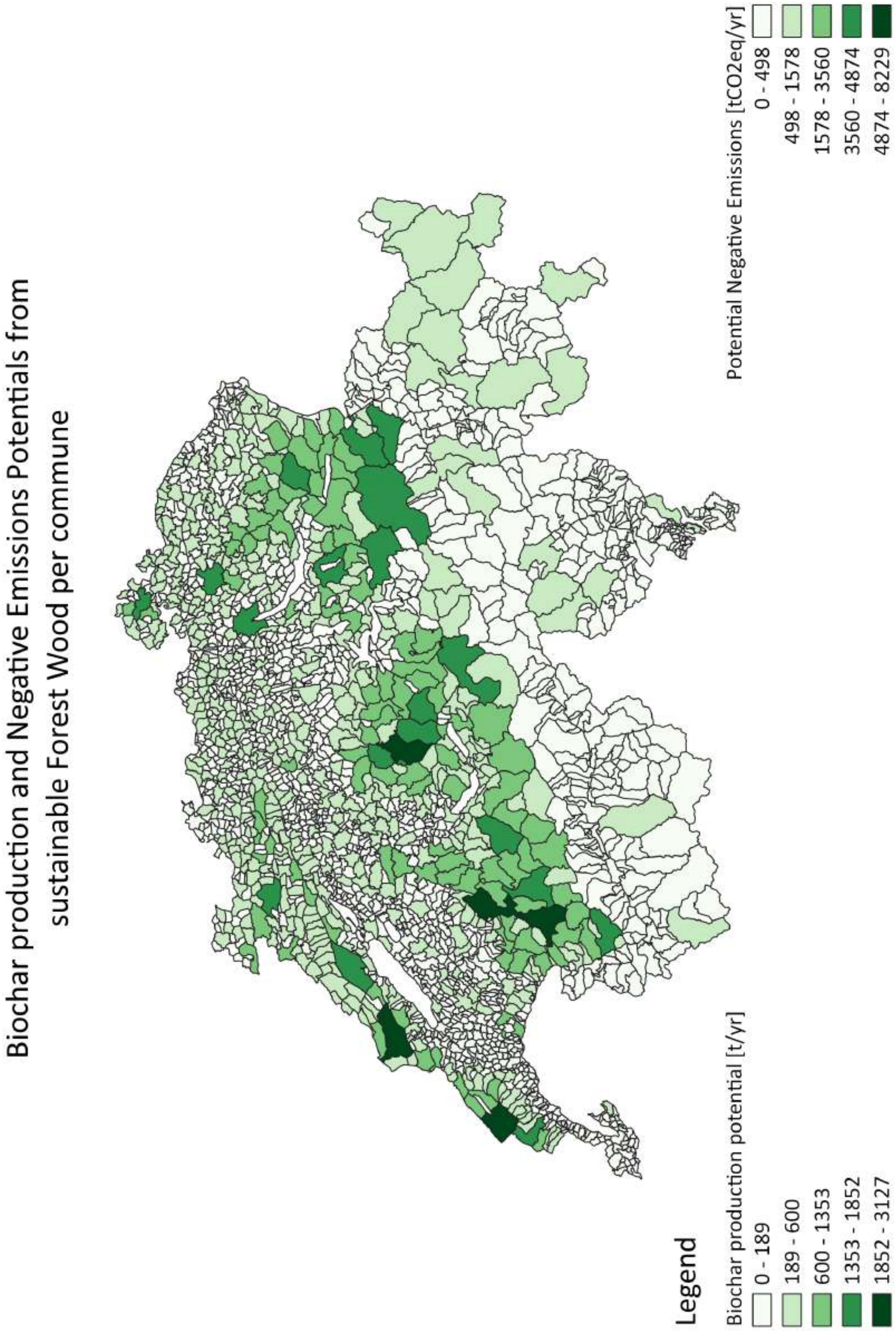


Figure 54: Biochar Production and Negative emissions Potentials from sustainable Forest wood at Communal level in absolute values

D. Forest wood - Normalised per area

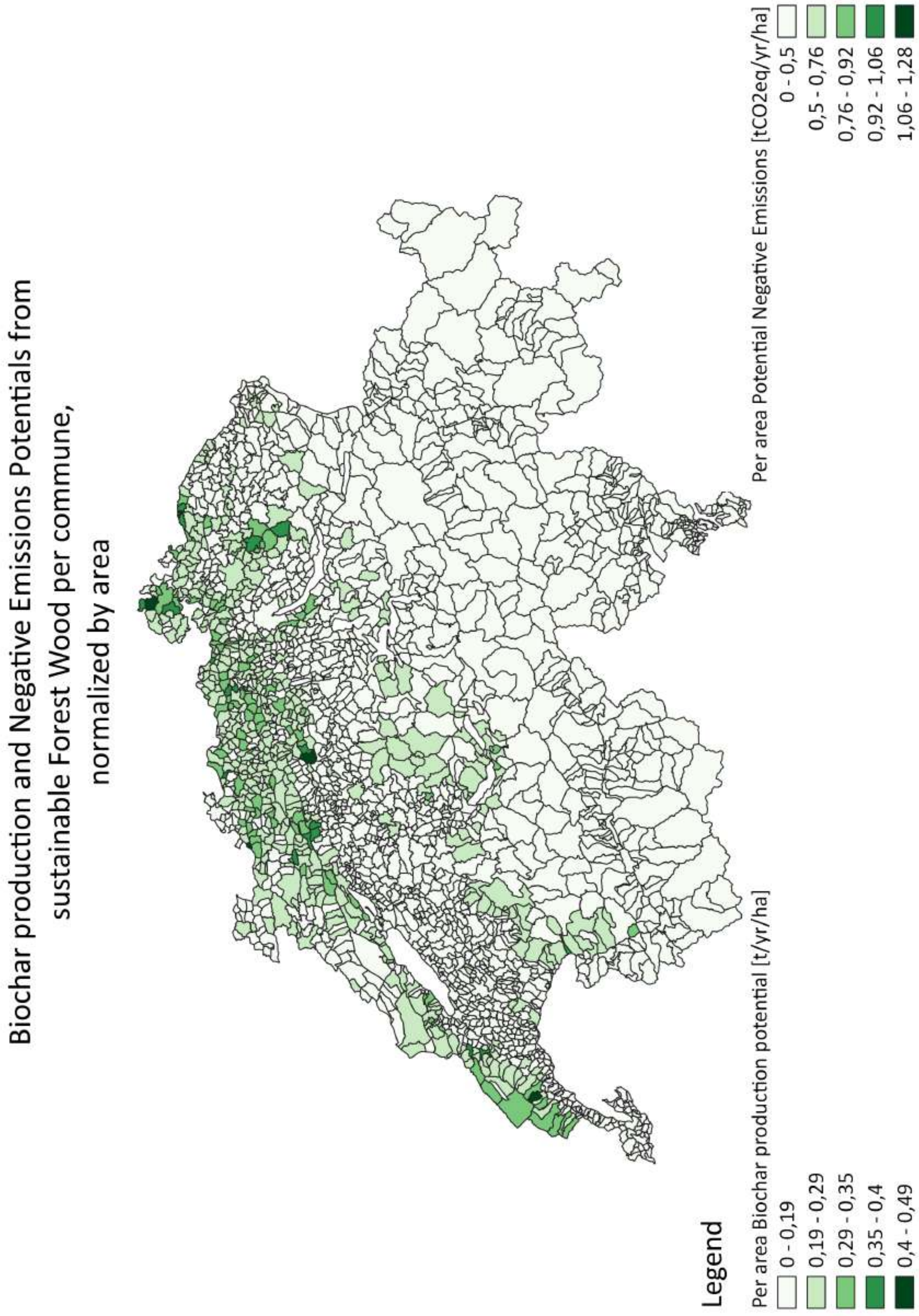


Figure 55: Biochar Production and Negative emissions Potentials from sustainable Forest wood at Communal level, normalised per area

E. Wood residues biomass - Absolute Values

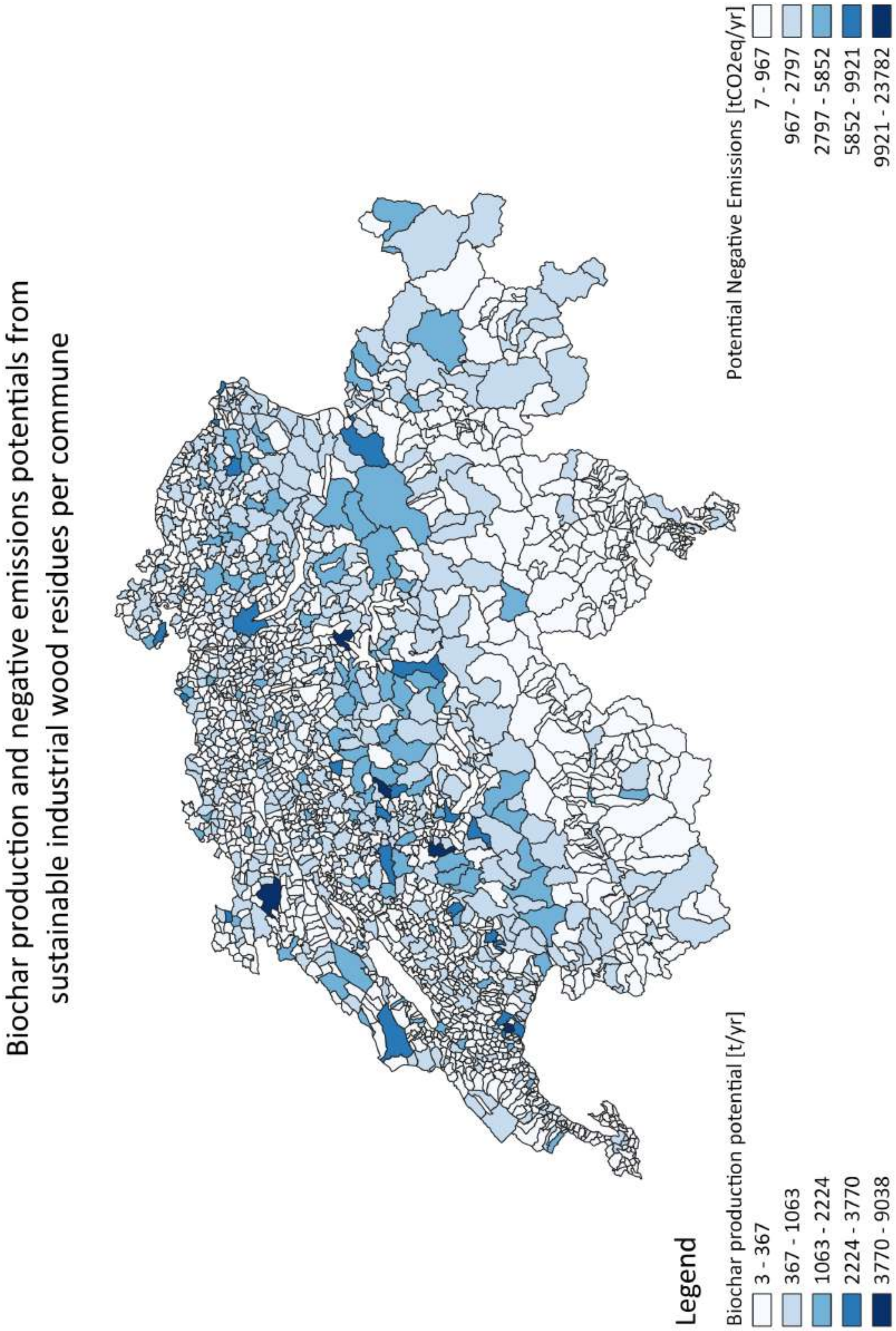


Figure 56: Biochar Production and Negative emissions Potentials from sustainable Wood residues at Communal level in absolute values

F. Wood residues biomass - Normalised per area

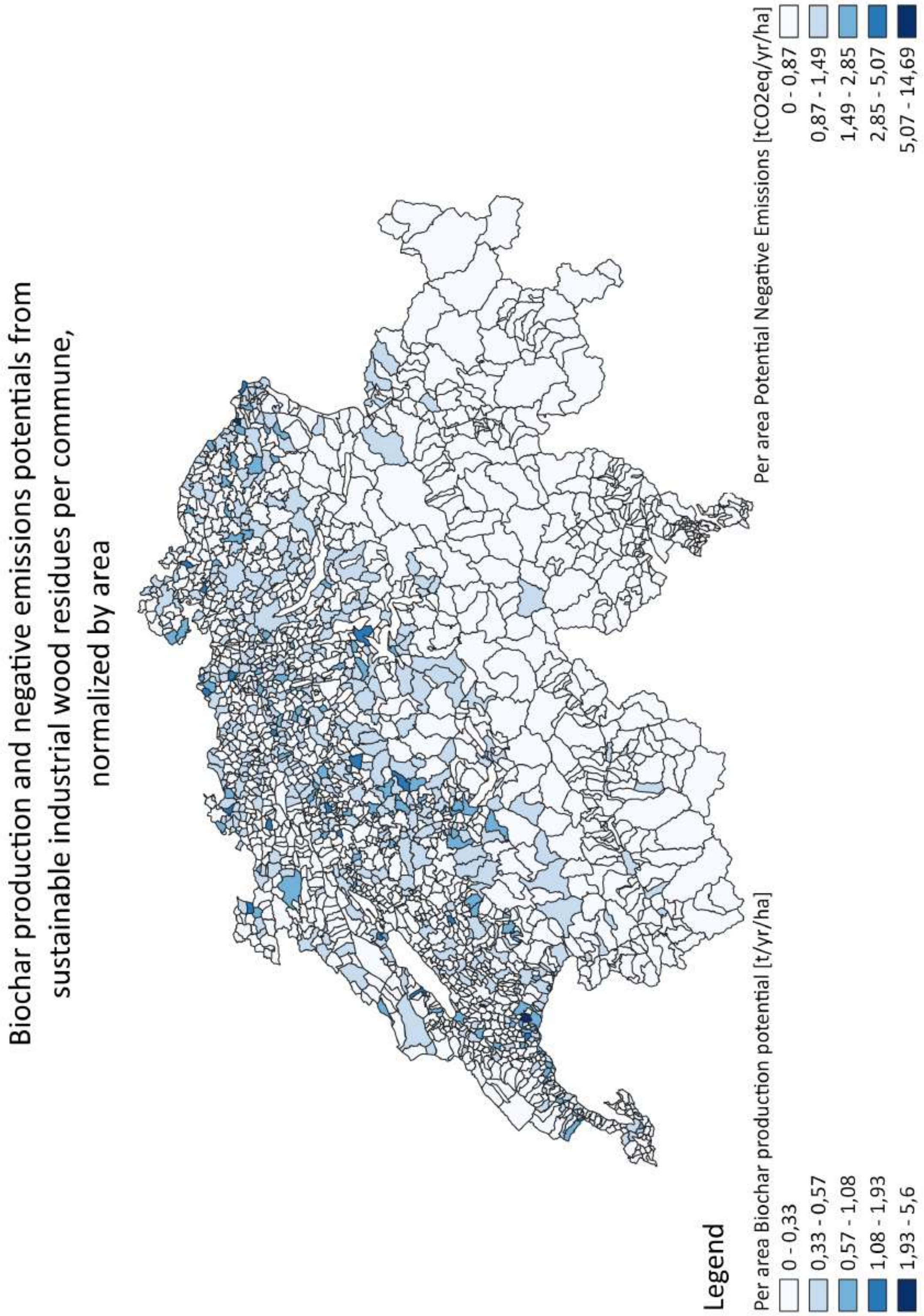


Figure 57: Biochar Production and Negative emissions Potentials from sustainable Wood residues at Communal level, normalised per area

G. Wood from landscape maintenance - Absolute Values

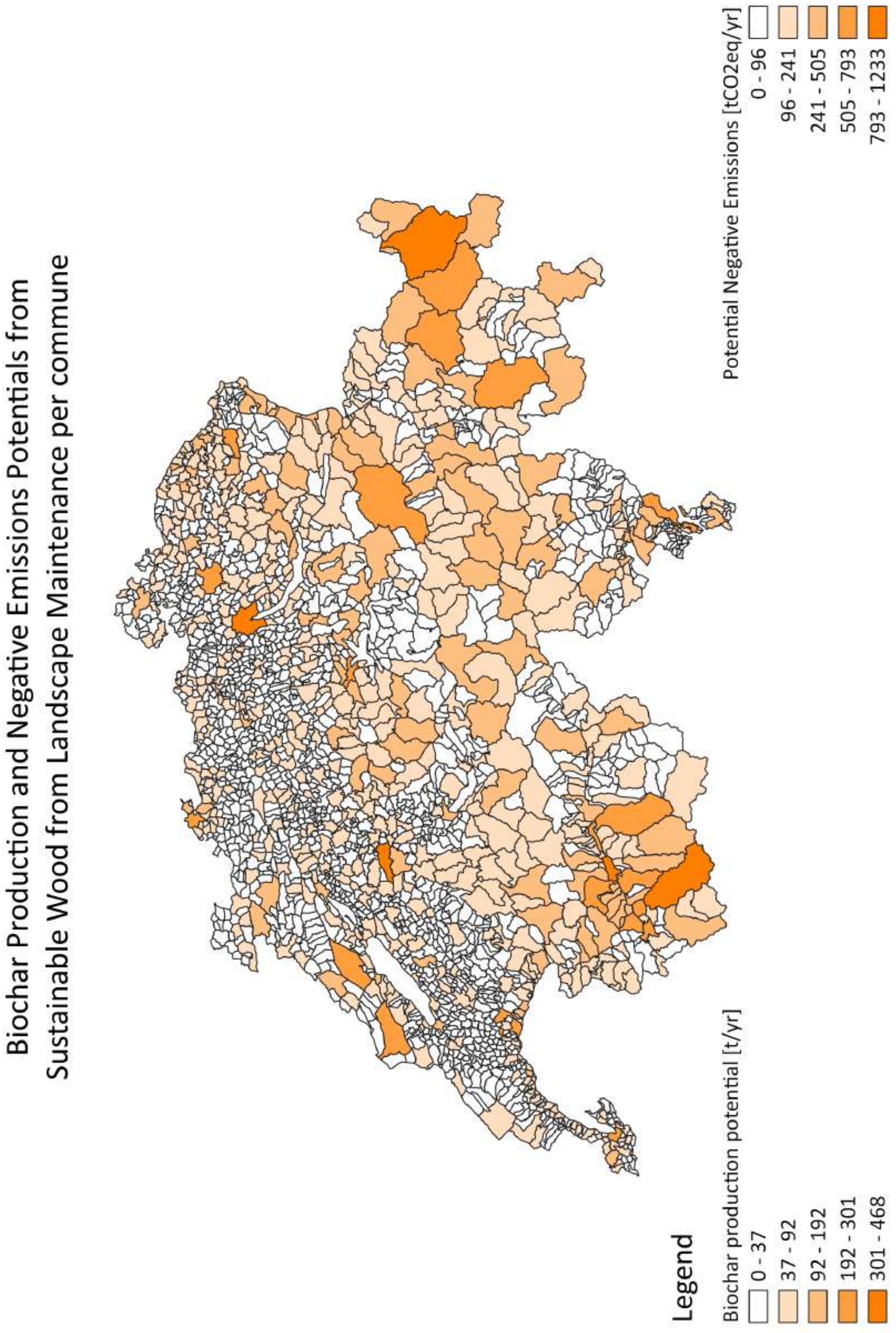


Figure 58: Biochar Production and Negative emissions Potentials from sustainable Wood from landscape maintenance at Communal level in absolute values

H. Wood from landscape maintenance - Normalised per area

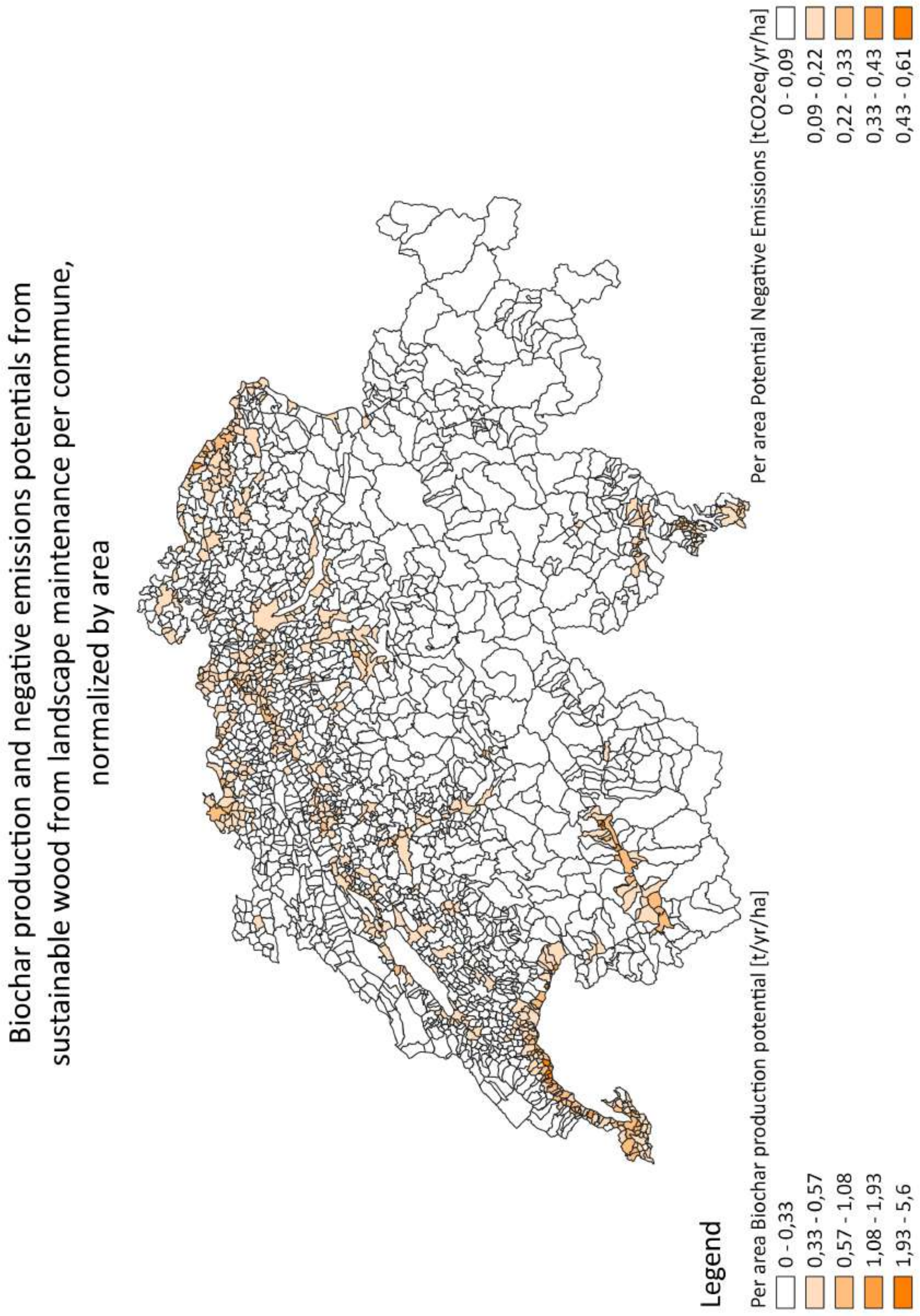


Figure 59: Biochar Production and Negative emissions Potentials from sustainable Wood from landscape maintenance at Communal level, normalised per area

I. Waste Wood - Absolute Values

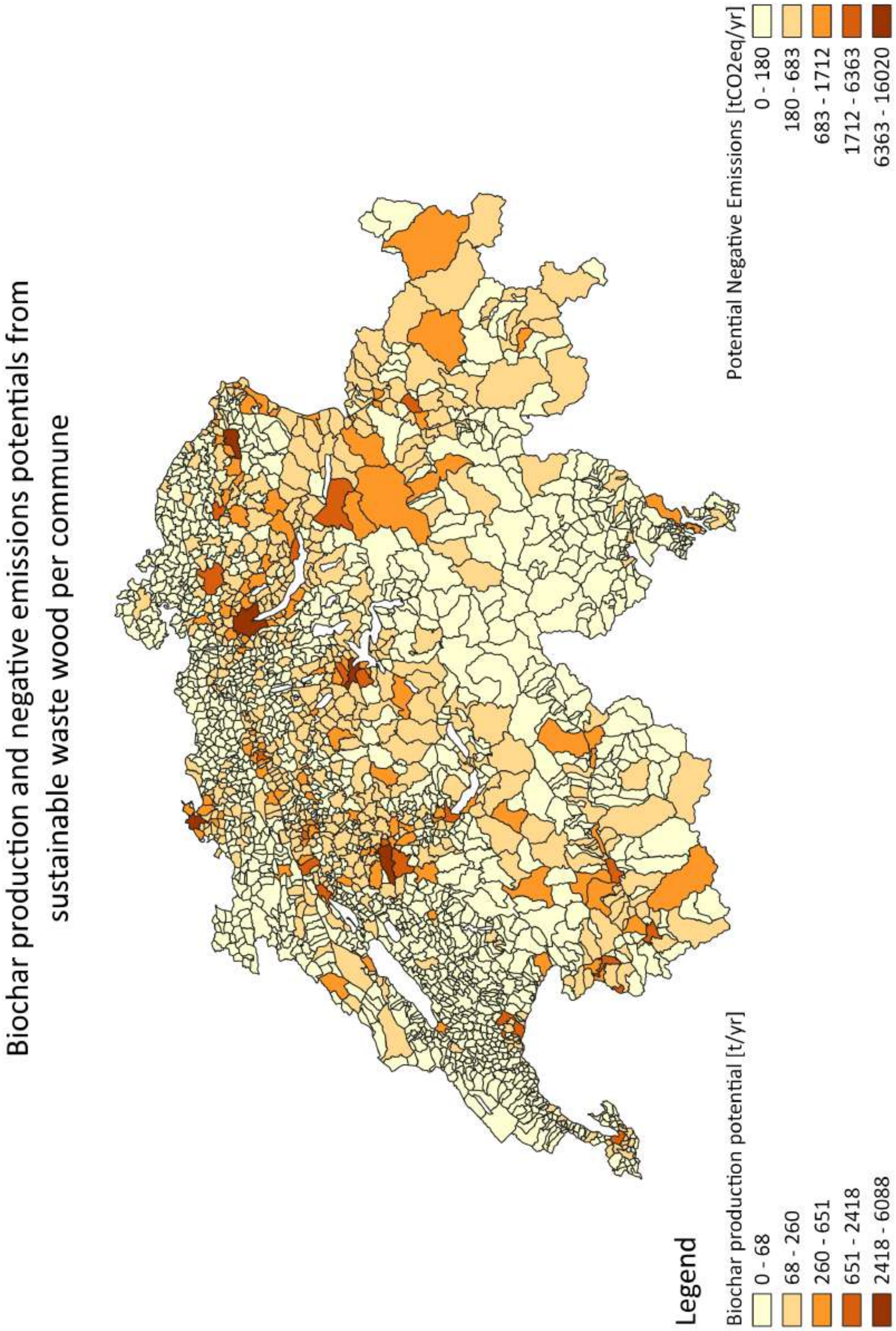


Figure 60: Biochar Production and Negative emissions Potentials from sustainable Waste Wood at Communal level in absolute values

J. Waste Wood - Normalised per area

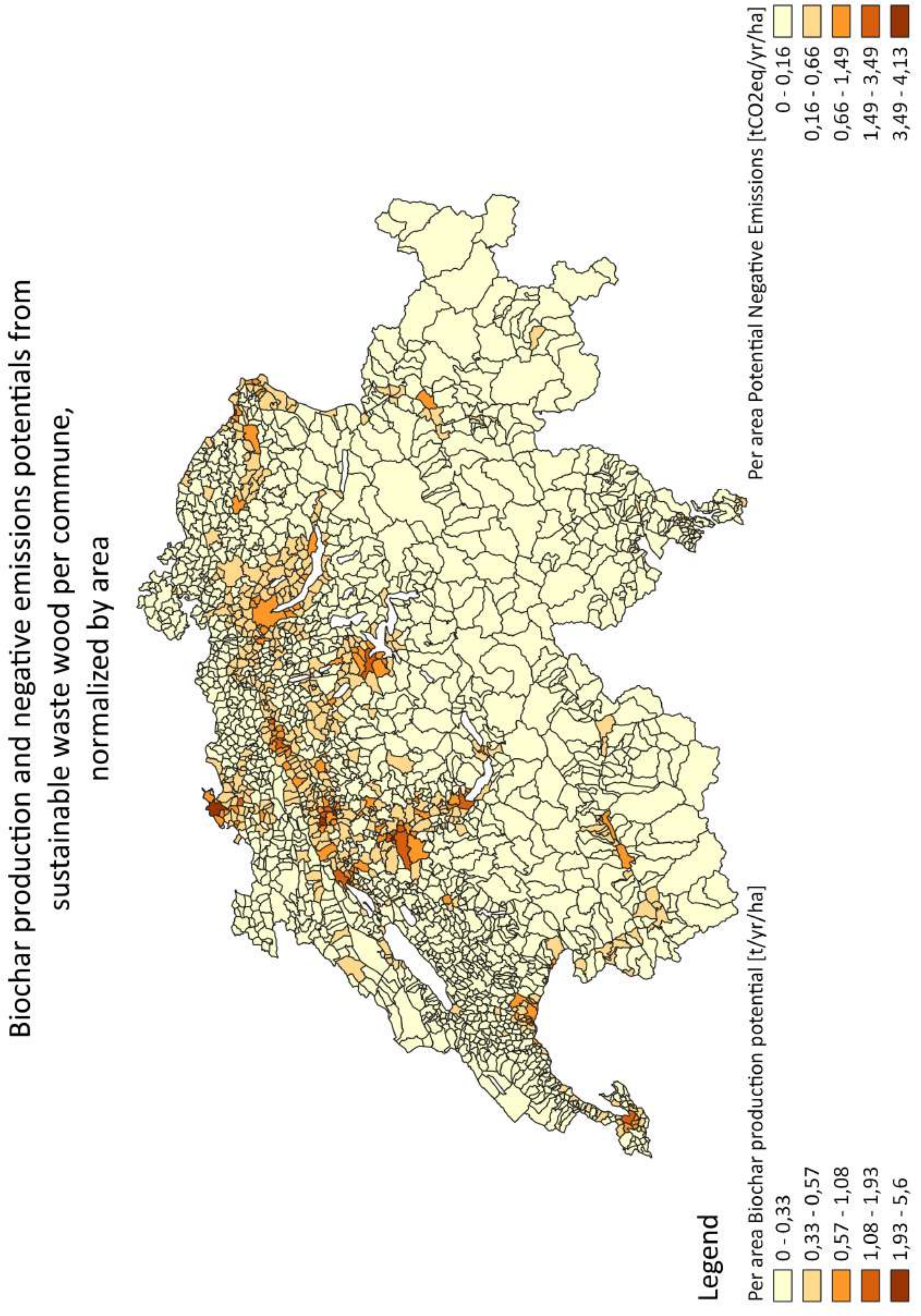


Figure 61: Biochar Production and Negative emissions Potentials from sustainable Waste Wood at Communal level, normalised per area

K. Agricultural crop by-products - Absolute Values

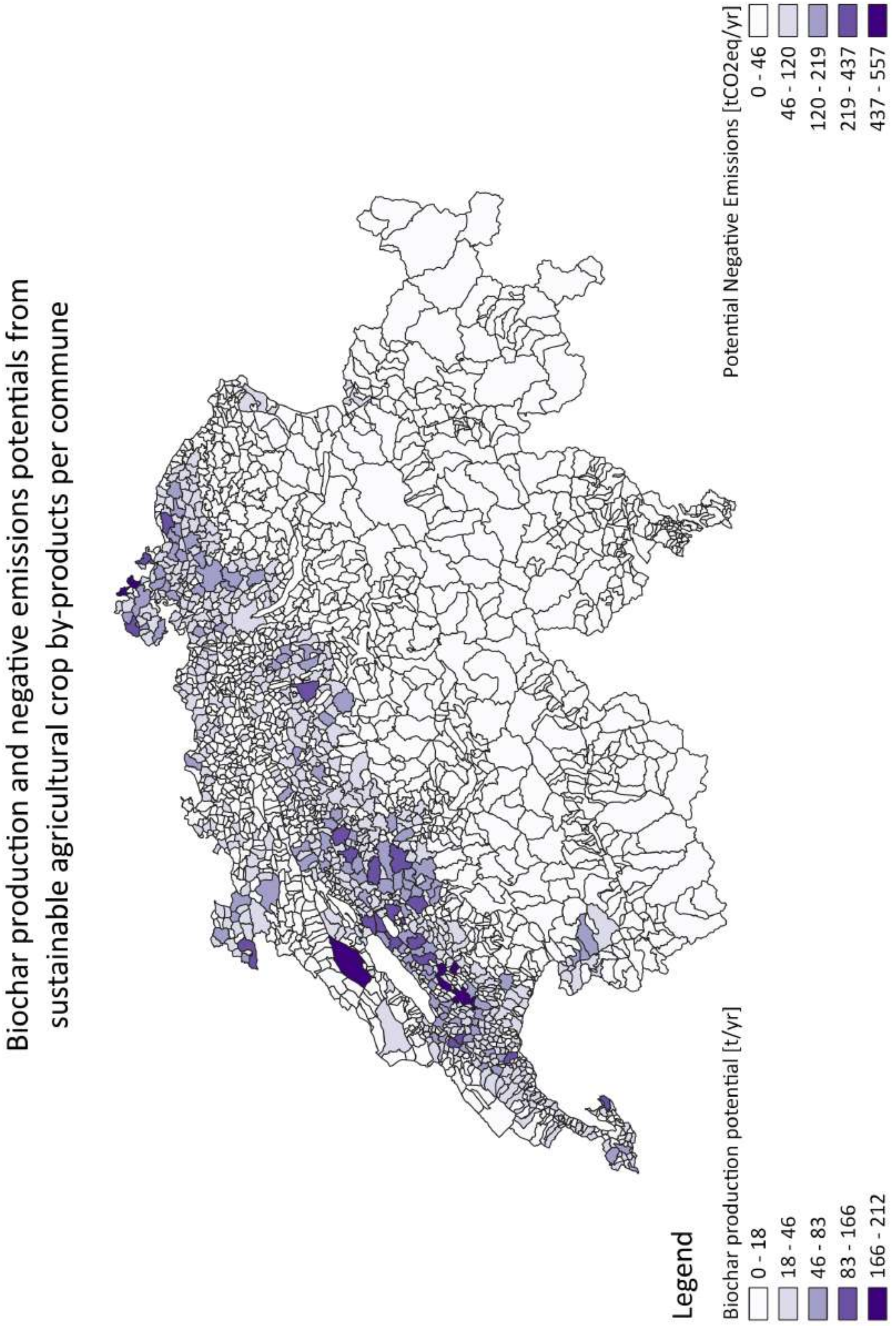


Figure 62: Biochar Production and Negative emissions Potentials from sustainable Agricultural crop by-products at Communal level in absolute values

L. Agricultural crop by-products - Normalised per area

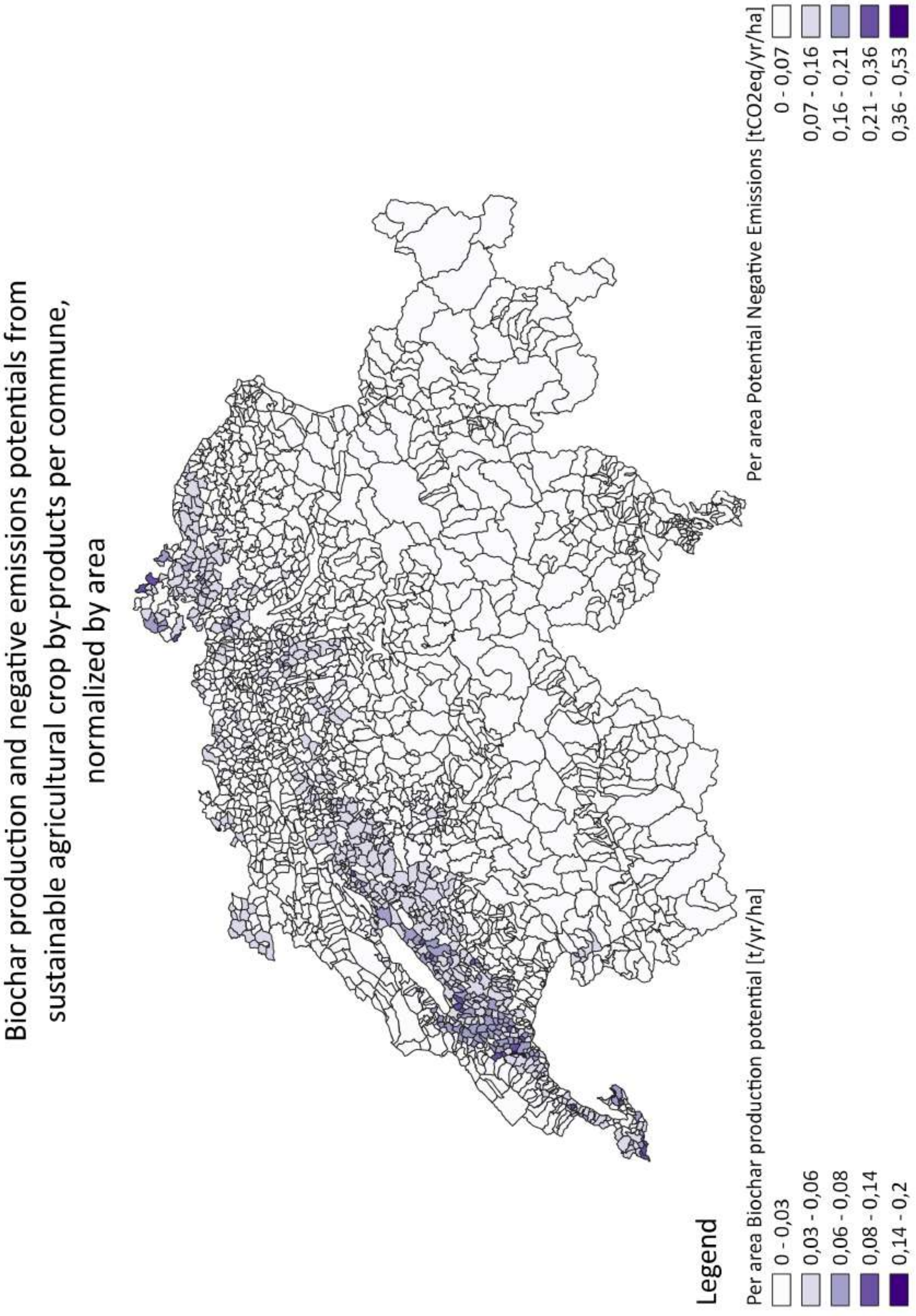


Figure 63: Biochar Production and Negative emissions Potentials from sustainable Agricultural crop by-products at Communal level, normalised per area

M. Green waste from households and landscape - Absolute Values

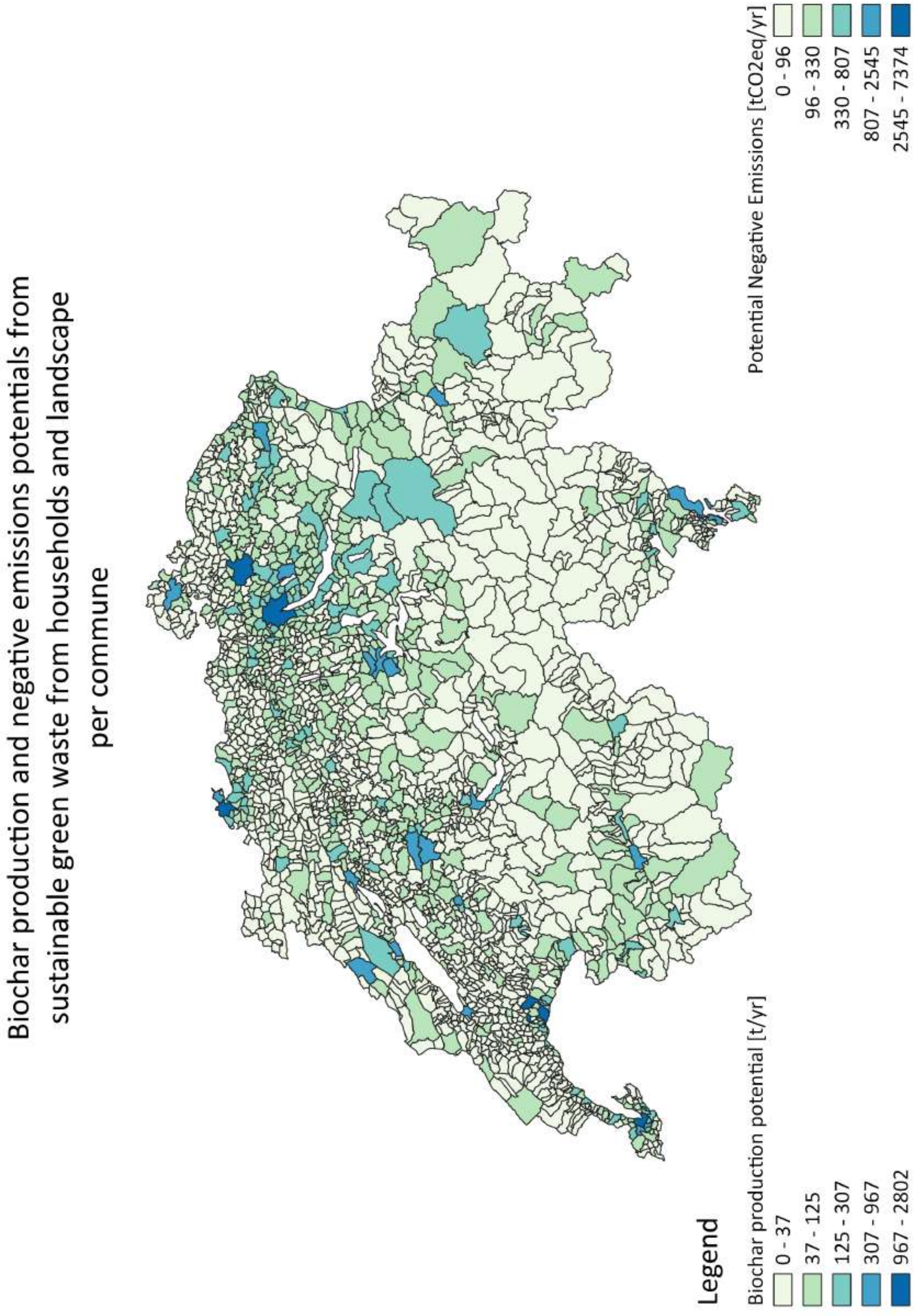


Figure 64: Biochar Production and Negative emissions Potentials from sustainable Green waste from households and landscape at Communal level in absolute values

N. Green waste from households and landscape - Normalised per area

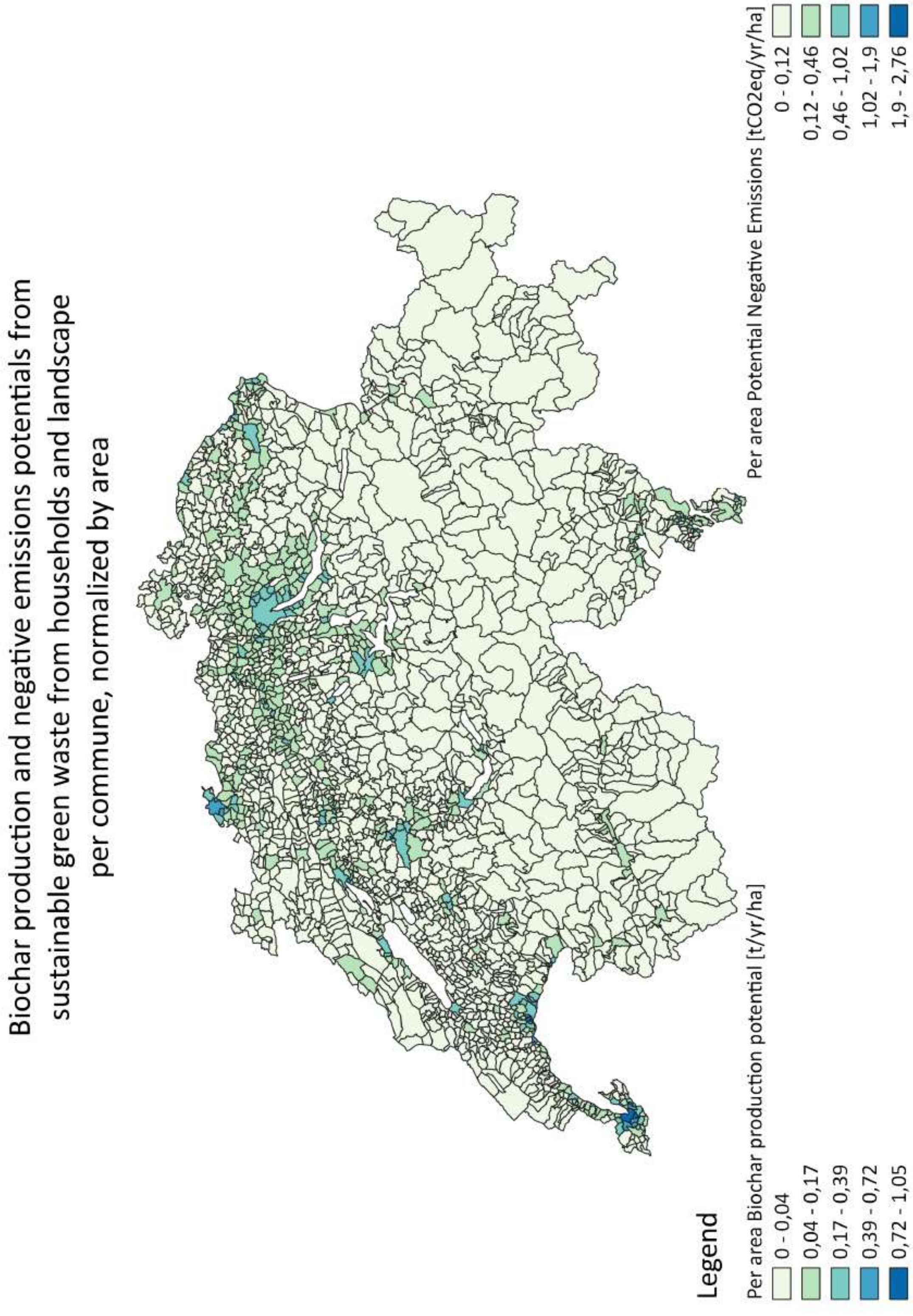
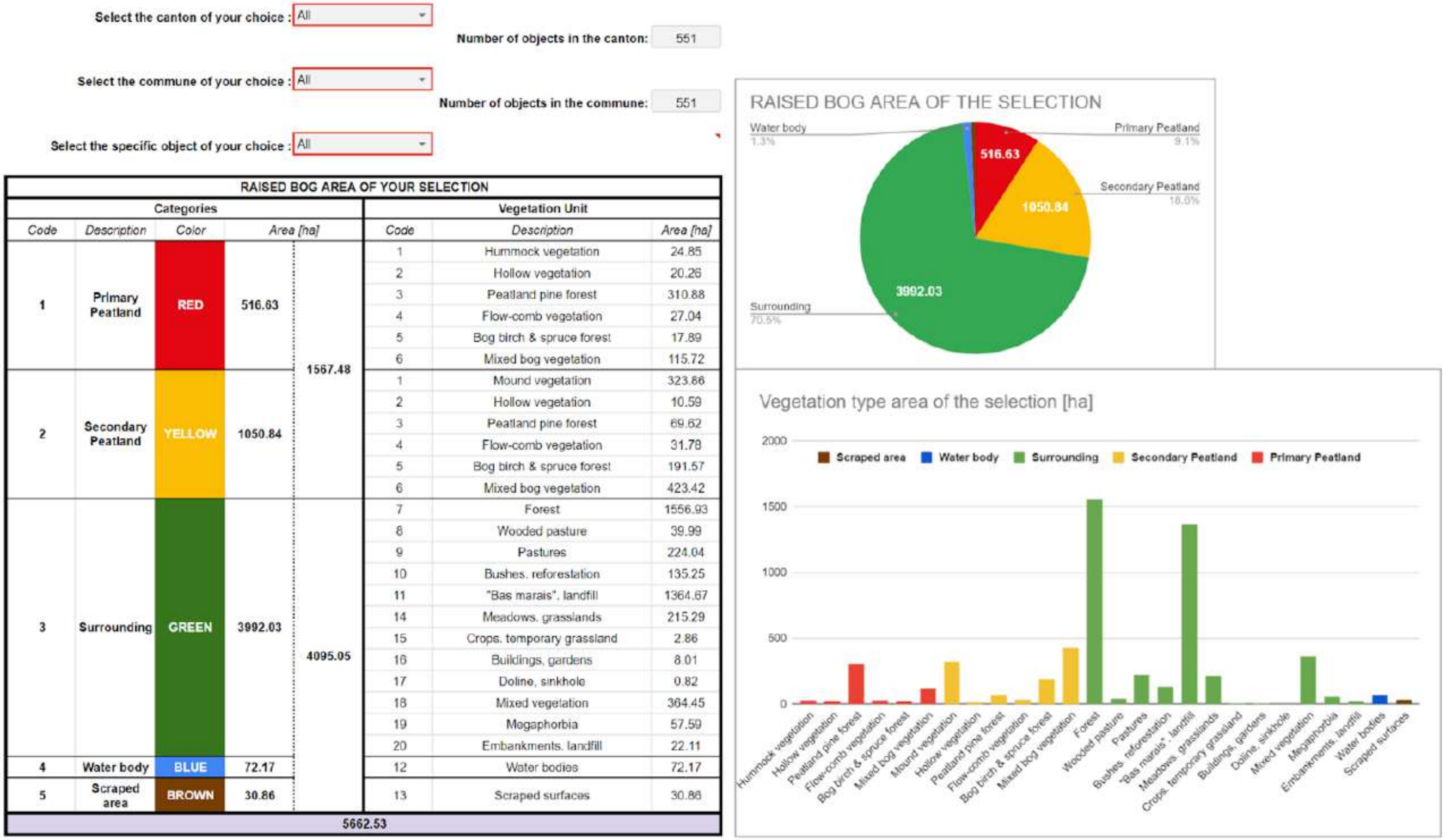


Figure 65: Biochar Production and Negative emissions Potentials from sustainable Green waste from households and landscape at Communal level, normalised per area

XVI. Peatlands' Exploration and visualisation tool



Select the canton of your choice : All

Number of objects in the canton: 551

Select the commune of your choice : All

Number of objects in the commune: 551

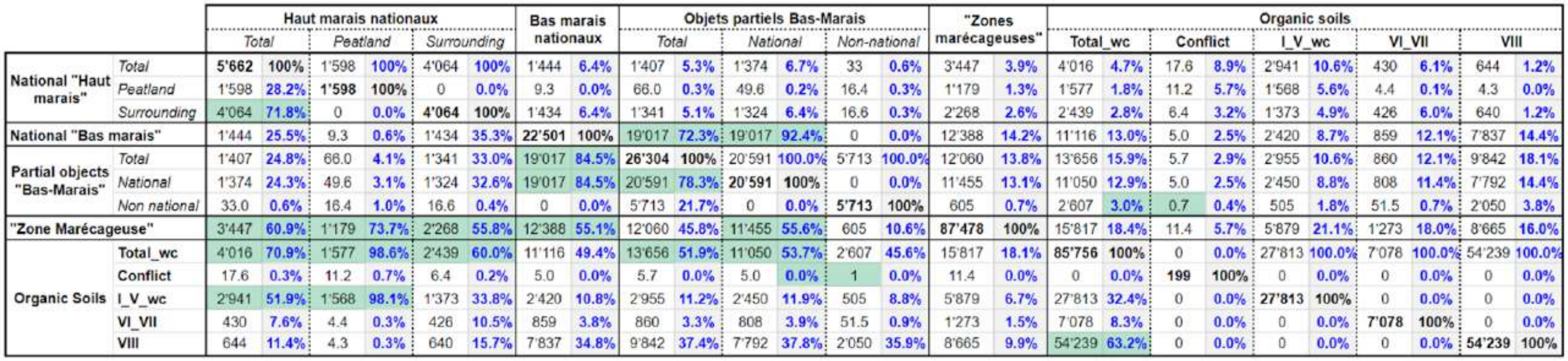
Select the specific object of your choice : All

RAISED BOG AREA OF YOUR SELECTION

Categories					Vegetation Unit		
Code	*Description*	*Color*	*Area [ha]*		*Code*	*Description*	*Area [ha]*
1	Primary Peatland	RED	516.63	1567.48	1	Hummock vegetation	24.85
					2	Hollow vegetation	20.26
					3	Peatland pine forest	310.88
					4	Flow-comb vegetation	27.04
					5	Bog birch & spruce forest	17.89
					6	Mixed bog vegetation	115.72
2	Secondary Peatland	YELLOW	1050.84		1	Mound vegetation	323.86
					2	Hollow vegetation	10.59
					3	Peatland pine forest	69.62
					4	Flow-comb vegetation	31.78
					5	Bog birch & spruce forest	191.57
					6	Mixed bog vegetation	423.42
3	Surrounding	GREEN	3992.03	4095.05	7	Forest	1556.93
					8	Wooded pasture	39.99
					9	Pastures	224.04
					10	Bushes, reforestation	135.25
					11	"Bas marais", landfill	1364.67
					14	Meadows, grasslands	215.29
					15	Crops, temporary grassland	2.86
					16	Buildings, gardens	8.01
					17	Doline, sinkhole	0.82
					18	Mixed vegetation	364.45
					19	Megaphorbia	57.59
					20	Embankments, landfill	22.11
4	Water body	BLUE	72.17		12	Water bodies	72.17
5	Scraped area	BROWN	30.86		13	Scraped surfaces	30.86
5662.53							

Figure 66: Exploration and visualisation tool for the raised bogs database

XVII. Overlapping table of the different inventories



		Haut marais nationaux						Bas marais nationaux		Objets partiels Bas-Marais						"Zones marécageuses"		Organic soils									
		Total		*Peatland*		*Surrounding*				*Total*		*National*		*Non-national*				**Total_wc**		**Conflict**		**I_V_wc**		**VI_VII**		**VIII**	
National "Haut marais"	*Total*	**5'662**	**100%**	1'598	100%	4'064	100%	1'444	6.4%	1'407	5.3%	1'374	6.7%	33	0.6%	3'447	3.9%	4'016	4.7%	17.6	8.9%	2'941	10.6%	430	6.1%	644	1.2%
	Peatland	1'598	28.2%	**1'598**	**100%**	0	0.0%	9.3	0.0%	66.0	0.3%	49.6	0.2%	16.4	0.3%	1'179	1.3%	1'577	1.8%	11.2	5.7%	1'568	5.6%	4.4	0.1%	4.3	0.0%
	Surrounding	4'064	71.8%	0	0.0%	**4'064**	**100%**	1'434	6.4%	1'341	5.1%	1'324	6.4%	16.6	0.3%	2'268	2.6%	2'439	2.8%	6.4	3.2%	1'373	4.9%	426	6.0%	640	1.2%
National "Bas marais"		1'444	25.5%	9.3	0.6%	1'434	35.3%	**22'501**	**100%**	19'017	72.3%	19'017	92.4%	0	0.0%	12'388	14.2%	11'116	13.0%	5.0	2.5%	2'420	8.7%	859	12.1%	7'837	14.4%
Partial objects "Bas-Marais"	*Total*	1'407	24.8%	66.0	4.1%	1'341	33.0%	19'017	84.5%	**26'304**	**100%**	20'591	100.0%	5'713	100.0%	12'060	13.8%	13'656	15.9%	5.7	2.9%	2'955	10.6%	860	12.1%	9'842	18.1%
	National	1'374	24.3%	49.6	3.1%	1'324	32.6%	19'017	84.5%	20'591	78.3%	**20'591**	**100%**	0	0.0%	11'455	13.1%	11'050	12.9%	5.0	2.5%	2'450	8.8%	808	11.4%	7'792	14.4%
	Non national	33.0	0.6%	16.4	1.0%	16.6	0.4%	0	0.0%	5'713	21.7%	0	0.0%	**5'713**	**100%**	605	0.7%	2'607	3.0%	0.7	0.4%	505	1.8%	51.5	0.7%	2'050	3.8%
"Zone Marécageuse"		3'447	60.9%	1'179	73.7%	2'268	55.8%	12'388	55.1%	12'060	45.8%	11'455	55.6%	605	10.6%	**87'478**	**100%**	15'817	18.4%	11.4	5.7%	5'879	21.1%	1'273	18.0%	8'665	16.0%
Organic Soils	**Total_wc**	4'016	70.9%	1'577	98.6%	2'439	60.0%	11'116	49.4%	13'656	51.9%	11'050	53.7%	2'607	45.6%	15'817	18.1%	**85'756**	**100%**	0	0.0%	27'813	100.0%	7'078	100.0%	54'239	100.0%
	Conflict	17.6	0.3%	11.2	0.7%	6.4	0.2%	5.0	0.0%	5.7	0.0%	5.0	0.0%	1	0.0%	11.4	0.0%	0	0.0%	**199**	**100%**	0	0.0%	0	0.0%	0	0.0%
	I_V_wc	2'941	51.9%	1'568	98.1%	1'373	33.8%	2'420	10.8%	2'955	11.2%	2'450	11.9%	505	8.8%	5'879	6.7%	27'813	32.4%	0	0.0%	**27'813**	**100%**	0	0.0%	0	0.0%
	VI_VII	430	7.6%	4.4	0.3%	426	10.5%	859	3.8%	860	3.3%	808	3.9%	51.5	0.9%	1'273	1.5%	7'078	8.3%	0	0.0%	0	0.0%	**7'078**	**100%**	0	0.0%
	VIII	644	11.4%	4.3	0.3%	640	15.7%	7'837	34.8%	9'842	37.4%	7'792	37.8%	2'050	35.9%	8'665	9.9%	54'239	63.2%	0	0.0%	0	0.0%	0	0.0%	**54'239**	**100%**

Table 12: Overlapping table of the different inventories

XVIII. Costs analysis for Biochar

	Biochar Production [t/y]	Biomass Requirement [t/y]	Potentail Negative emissions [tCO2e/y]	Cumul Potential NE [tCO2e]	New Pyrolysis unit needed [#/y]	Total Pyrolysis unit needed [#]	New capex [MCHF/y]	Cumul CAPEX [MCHF]	OPEX [MCHF/y]	Cumul Opex [MCHF]	Total cost per year [MCHF/y]	Cumul Total cost [MCHF]	Human ressources Pers.	Biochar price [CHF/t]	Revenue from biochar [MCHF/y]	% of the cost per year [%]	Net cost per year [MCHF/y]	Cumul net cost [MCHF]	Electricity sells revenues [MCHF/y]	% of the cost per year [%]	Net Net cost per year [MCHF/y]	Cumul Net net cost [MCHF]
2020	2'000	9'000	5'246	5'246	1	1	14	14	4	4	18	18	16	1000	2.0	11.1%	16	16	0.3	1.5%	16	16
2021	2'457	11'055	6'444	11'690	1	2	14	28	8	12	22	40	32	1000	2.5	11.1%	20	36	0.3	1.5%	19	35
2023	3'018	13'580	7'916	19'605	0	2	0	28	8	20	8	48	32	1000	3.0	37.0%	5	41	0.4	4.9%	5	40
2024	3'707	16'681	9'723	29'329	0	2	0	28	8	29	8	57	32	1000	3.7	45.4%	4	45	0.5	6.1%	4	44
2025	4'554	20'491	11'944	41'272	1	3	13	41	11	40	24	80	48	900	4.1	17.4%	20	65	0.5	2.3%	19	63
2026	5'593	25'171	14'671	55'944	0	3	0	41	11	51	11	91	48	900	5.0	45.7%	6	71	0.7	6.1%	5	68
2027	6'871	30'919	18'022	73'965	1	4	13	53	15	65	27	118	64	900	6.2	22.7%	21	92	0.8	3.0%	20	88
2028	8'440	37'980	22'136	96'103	0	4	0	53	13	79	13	132	64	810	6.8	51.7%	6	98	0.9	6.9%	5	94
2029	10'367	46'653	27'193	123'296	1	5	11	65	17	95	28	160	80	810	8.4	30.1%	19	118	1.1	4.0%	18	112
2030	12'735	57'308	33'403	156'700	1	6	11	76	20	115	31	191	96	810	10.3	33.1%	21	139	1.4	4.4%	19	132
2031	15'643	70'395	41'032	197'731	2	8	23	99	26	141	49	240	128	810	12.7	25.8%	36	175	1.7	3.5%	35	167
2032	19'216	86'471	50'402	248'133	1	9	10	109	27	168	37	277	144	729	14.0	37.9%	23	198	1.9	5.1%	21	188
2033	23'604	106'219	61'913	310'046	2	11	20	129	33	201	53	330	176	729	17	32.4%	36	234	2.3	4.3%	34	221
2034	28'995	130'476	76'052	386'098	3	14	31	160	42	242	72	402	224	729	21	29.2%	51	285	2.8	3.9%	48	270
2035	35'616	160'274	93'420	479'518	3	17	28	187	46	288	73	475	272	656	23	32.0%	50	335	3.1	4.3%	47	316
2036	43'750	196'876	114'754	594'272	3	20	28	215	54	342	81	556	320	656	29	35.4%	52	387	3.8	4.7%	49	365
2037	53'741	241'836	140'961	735'233	5	25	46	261	67	408	113	669	400	656	35	31.2%	78	465	4.7	4.2%	73	438
2038	66'014	297'065	173'153	908'386	5	30	41	302	72	481	114	783	480	590	39	34.3%	75	540	5.2	4.6%	69	507
2039	81'090	364'906	212'696	1'121'082	7	37	58	360	89	570	147	930	592	590	48	32.6%	99	639	6.4	4.4%	93	600
2040	99'609	448'241	261'270	1'382'351	8	45	66	426	108	678	175	1'105	720	590	59	33.7%	116	754	7.9	4.5%	108	708
2041	122'357	550'607	320'936	1'703'288	11	56	91	517	135	813	226	1'330	896	590	72	32.0%	154	908	9.7	4.3%	144	852
2042	150'300	676'350	394'229	2'097'517	12	68	89	606	147	961	237	1'567	1088	531	80	33.7%	157	1'065	10.7	4.5%	146	998
2043	184'624	830'809	484'260	2'581'777	16	84	119	725	182	1'143	301	1'868	1344	531	98	32.6%	203	1'268	13.1	4.4%	190	1'188
2044	226'787	1'020'543	594'852	3'176'629	19	103	141	867	223	1'366	365	2'233	1648	531	121	33.0%	244	1'512	16.1	4.4%	228	1'416
2045	278'579	1'253'606	730'699	3'907'328	23	126	154	1'021	246	1'612	400	2'633	2016	478	133	33.3%	267	1'779	17.8	4.5%	249	1'665
2046	342'199	1'539'895	897'571	4'804'899	28	154	187	1'208	301	1'913	488	3'121	2464	478	164	33.5%	324	2'103	21.9	4.5%	303	1'967
2047	420'348	1'891'564	1'102'551	5'907'449	36	190	241	1'449	371	2'284	612	3'733	3040	478	201	32.9%	411	2'514	26.9	4.4%	384	2'351
2048	516'343	2'323'545	1'354'343	7'261'792	43	233	259	1'709	409	2'693	668	4'402	3728	430	222	33.3%	446	2'961	29.7	4.4%	416	2'768
2049	634'262	2'854'177	1'663'637	8'925'429	53	286	319	2'028	502	3'196	822	5'223	4576	430	273	33.2%	549	3'509	36.5	4.4%	512	3'280
2050	779'109	**3'505'992**	**2'043'565**	**10'968'993**	65	351	392	2'420	617	3'812	1'008	6'232	**5616**	430	335	33.3%	673	4'182	44.9	4.4%	628	3'908

Figure 67: Costs analysis for Biochar

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