SCALING LAND-BASED MITIGATION SOLUTIONS IN SWITZERLAND

LAND-BASED MITIGATION NARRATIVES

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Table of Contents

1. Introduction 3

2. Scoping of land based mitigation and negative emission solutions 5

2.1 Overview of potential of LMTs in Switzerland 5

2.1.1 Introduction 5

2.1.2 Technologies dependent on biomass / photosynthesis 6

2.1.3 Land management practices 7

2.2 Determining the LMT scope for national level simulation modelling 9

2.3 Discussion on short-listing LMTs 12

2.3.1 Competition for biomass between BECCS & biochar 12

2.3.2 Limited potential of cropland management but low competition and cost effectiveness 14

2.3.3 Biochar and Agroforestry as innovative options with potential co-benefits but adoption barriers 16

3. Co-design of LMT narratives 18

3.1 Introduction 18

3.2 BECCS based on domestic biomass 18

3.2.1 Introduction 18

3.2.2 Policy context 19

3.2.3 Current land use and potential land-use competition 19

3.2.4 Climate risks & sensitivities 20

3.2.5 Economic implications 21

3.2.6 Co-benefits and trade-offs 21

3.2.7 Risks associated with scaling up 21

3.2.8 Research gaps 22

3.3 Biochar 22

3.3.1 Introduction 22

3.3.2 Policy context 23

3.3.3 Current land use and potential land-use competition ... 23
3.3.4 Climate risks & sensitivities ... 24
3.3.5 Economic implications ... 24
3.3.6 Co-benefits and trade-offs ... 25
3.3.7 Risks associated with scaling up ... 25
3.3.8 Research gaps ... 26
3.4 Reduced tillage, conservation/organic agriculture ... 26
3.4.1 Introduction ... 26
3.4.2 Policy context ... 27
3.4.3 Current land use and potential land-use competition ... 27
3.4.4 Climate risks & sensitivities ... 28
3.4.5 Economic implications ... 28
3.4.6 Co-benefits and trade-offs ... 29
3.4.7 Risks associated with scaling up ... 29
3.4.8 Research gaps ... 29
3.5 Agroforestry and landscape elements ... 30
3.5.1 Introduction ... 30
3.5.2 Policy context ... 31
3.5.3 Current land use and potential land-use competition ... 31
3.5.4 Climate risks & sensitivities ... 32
3.5.5 Economic implications ... 33
3.5.6 Co-benefits and trade-offs ... 33
3.5.7 Risks associated with scaling up ... 34
3.5.8 Research gaps ... 34
4. Conclusions ... 35
5. References ... 36

1. Introduction

This report includes a description of a generic nation-wide transition scenario for the implementation of land-based mitigation technologies and practices for the AFOLU sector (agriculture, forestry, and other land use sectors) in Switzerland. The report shows outcomes of a series of research steps that have been conducted in this country since the start of the project in June 2020 until the end of 2022:

First, we performed an initial scoping of key LMTs in the case study country. The scoping resulted in a long list of broad LMT portfolios that could be viable within the various case study countries.

Second, following this long list, we developed a short-list LMT portfolio containing key LMTs that would be the most relevant for a given country context. All case study country partners were asked to propose and validate their LMT portfolio through complementary (policy) literature review and with the help of stakeholder interviews (i.e. external validation by relevant country experts and stakeholders). Ex-ante no specific guidance of criteria for LMT portfolio short-listing was provided to allow for a free and open co-design process with stakeholders. The scoping process and results are presented in section 2 of this report (step 1 & 2). In Switzerland, the long-list was derived from key policy documents, while the short-listing for the narratives was done by interviews with key LMT stakeholders from Agroscope, WSL, BAFU and BLW.

Third, after the short-listed LMT portfolios were validated, the LANDMARC case study country partners were asked to develop national scaling narratives or storylines for each LMT included in their portfolio. The assessments focusses on climate risks, vulnerabilities as well as socio-economic co-benefits and trade-offs associated with upscaling LMTs in the case study countries. The analysis is based on a broad range of information/literature sources, and stakeholder consultations conducted. This process is supported through a risk and impact assessment (i.e. an online survey and workshops/seminar/webinars) conducted through the LANDMARC tasks 4.1, 4.2 and 5.2. Several key insights from these risk assessment interviews are explicitly mentioned in the narrative document. The results of this analysis are a set of LMT narratives which are presented in section 3 of this report.

The research steps are designed to enable both an **analysis of the risks and (climate) impacts of scaling up land-based mitigation and negative emission solutions**. As such this report mainly contributes to objectives 2, 3 and 4 of the six LANDMARC key objectives (see Table 1).

Table 1: LANDMARC project objectives.

	Project key objectives
1	Determine the potential and effectiveness of LMTs in GHGs mitigation using Earth Observation (EO)
2	Improve climate resilience of LMT solutions at the local level for large-scale implementation
3	Assess the risks, co-benefits, and trade-offs of scaling up local LMTs nationally
4	Scaling up LMT solutions to the continental and global level to assess effectiveness
5	Improve current methodologies to estimate emissions and removals for LMTs
6	LMT capacity building and develop new tools and services for decision making

While the results shown in this report represent a mostly qualitative storyline describing the context and impact of scaling up LMTs in a country context, they also enable project partners to proceed with the translation of the outcomes in a manner so that they can serve as direct model input.

Furthermore, these national level assessments provide a testing ground and empirical basis for the continental, and global assessment of the realistic scaling potential of land-based mitigation and negative emission solutions implemented in Work Packages 6 and 7 of the LANDMARC project (***Objective 4***).

2. Scoping of land based mitigation and negative emission solutions

2.1 Overview of potential of LMTs in Switzerland

2.1.1 Introduction

In a recent report of September 2020, the Swiss Federal Council provides a list of possible LMTs for Switzerland which is combined with a first assessment of the technical potential, realistic potential as well as the range of cost for different LMTs (Federal Council of Switzerland, 2020). The characterization of LMTs within the report is largely based on a review article by Minx et al. (2018), who categorized the most promising LMTs globally, and the potential of these LMTs is assessed for Switzerland in particular. The overview includes a list of the technical potential and pricing of each of the different LMTs (Table 2) as well as a conservative estimation of the actual realisable potential based on stakeholder estimations. The actual realisable potential is much lower than the technical potential, due to the consideration of cost and due to competing use of available biomass between different LMTs.

Table 2: LMT potential in Switzerland

LMTs	Technical potential (2050)		Additional comments	Costs for achieving negative emissions	
	Mt CO_2/y	total		CHF/ton	EUR/ton[a]
BECCS (post-combustion CO_2-capture)	5.1		potential if all available biomass is used	50 - 250	46 - 230
Enhanced weathering (using concrete)	2.5			20 - >1000	18 - >920
Direct Air Carbon Capture (DACC)		2500	total theoretical geological storage potential	40 - 1000	37 - 920
Soil carbon sequestration	2.7		only possible for a few decades	0 - 80	0 - 74
Afforestation, Reforestation and permanent use of wood	3.1		including substitution effects of 1 - 2 Mt CO_2	1 - 100	1 - 92
Biochar	2.2		potential if almost all available biomass is used	10 - 135	9 - 124
Stakeholder estimated theoretically realistic potential (Portfolio of all LMTs, considering competition between different LMTs)	**6**				

[a]Exchange rate of Feb. 05,2021 (1 CHF = 0.92€), rounded to whole numbers

Source: adapted from Federal Council of Switzerland (2020)

2.1.2 Technologies dependent on biomass / photosynthesis

BECCS

The largest potential of all land-based mitigation technologies in Switzerland is attributed to BECCS. The BECCS technology is considered to have a technical potential of storing 5.1 Mt CO_2 per year, which is about double the amount of CO_2 compared to other LMTs. The source of biomass for BECCS may come from oil crops, sugar crops or starch crops, as well as from forestry or organic waste products which could be energetically used and the CO_2 then stored (Beuttler et al., 2019). Options for BECCS are also seen in the combination with other LMTs, such as the capturing of CO_2 from biogas or biochar production. It is important to note that the estimated technical potential in Switzerland for each LMTs (Table 1) is based on the assumption that all currently available biomass of Switzerland is used for that LMTs. Therefore, a direct competition for biomass exists between all biomass based LMTs and maximizing one (e.g. BECCS) means lowering the potential of another (e.g. storage in permanent wooden products). This would mean that other biomass based LMTs, such as a long-term storage in wood products and production of biochar are not possible if the full BECCS potential would be realized. BECCS could also lead to a competition for land with food production (Beuttler et al., 2019), yet since Switzerland is a net importer of food products (Federal Statistical Office of Switzerland, 2020a) the feasibility of such replacements is highly questionable and most likely not wanted by policy makers. About half of the BECCS potential (2.1 Mt CO_2 per year) could be realized relatively easily and without much competition for biomass. This corresponds to the amount of CO_2 that to date is already released from energetic use of biomass, which could be captured by CCS technology, without requiring further biomass than already in use. However, to date there is no policy in Switzerland that supports BECCS and no BECCS plant in Switzerland (Federal Council of Switzerland, 2020).

Biochar

The theoretical potential of biochar to mitigate CO_2 emissions in Switzerland has been estimated to be 2.2 Mt CO_2 per year, based on an estimated market demand of 600.000 t biochar per year, with a maximum national production potential estimated to be 900.000 t per year (Beuttler et al., 2019). This number does, however, not account for the potential competition between the use of biomass for biochar and other uses of biomass, such as BECCS. It was estimated that the total amount of biomass in Switzerland that is sustainably available is 6.3 Mt biomass on dry matter base per year, of which 3.4 Mt are already in use to date (Thees et al., 2017). The actually realizable potential of all LMTs that rely on biomass is therefore lower than the sum of their individual potentials, which are each assuming that all biomass is used for one LMT. Yet, potential synergies exist between biochar production and BECCS. About 38% of the biomass carbon is released as CO_2 during the production of biochar (Beuttler et al., 2019), and this CO_2 could be stored by BECCS technology. Hence, the highest efficiency of biochar production in terms of LMTs would be if biochar production and BECCS would be coupled.

A factor that may interfere with the broadscale adoption of biochar is the lack of knowledge on potential negative side effects of biochar application, such as negative effects on the soil microbiome. Also, there seems to be insufficient knowledge on the long-term stability of biochar in the soil, with the current estimate being that biochar may be stable for decades up to a few centuries in European soils. There seems thus to be a debate between different political actors and stakeholders, whether biochar should be broadly applied. For example, a recent policy paper stressed the potential risks and unwanted negative side effects and warned against large scale applications until the lack of knowledge on the potential risks as well as on the stability are addressed (Federal Council of Switzerland, 2020). On the other hand, a recent policy advisory report by a number of scientist in the field claimed a high potential for biochar, suggesting that biochar application may also slow turnover of soil organic carbon and thus provide more sequestration potential than just the amount of carbon stored in the biochar itself (Beuttler et al., 2019).

2.1.3 Land management practices

Afforestation and enhanced forest management

According to the Swiss Federal Office for the Environment, about a third of Switzerland is already covered by forest (FOEN, 2019). Due to a high pressure on land for other uses and Switzerland being already a net importer of food products (Federal Statistical Office of Switzerland, 2020a), there is simply no available land for a large-scale afforestation in Switzerland. Yet, due to climate change, the tree line is expected to continue to move upwards, which is expected to increase the potential areas for forests (Federal Council of Switzerland, 2020). In their report, the Federal Council of Switzerland (2020) postulates that Swiss forests have been a net sink of CO_2 over the last 30 years, storing about 2.5 Mt CO_2 per year in forest biomass and forest soils. They note, however, that due to already high carbon stocks, the potential of the forests to store more carbon may be limited. The carbon sinks of deadwood in the forest are already high and they have the additional risk of being released due to higher turnover under higher temperatures (Federal Council of Switzerland, 2020). Thus, the largest potentials for forest based LMTs in Switzerland are seen in management practices that make better use of the existing forest and forest products as potential carbon sinks, through enhanced management of forests and of the biomass extracted from forests. An extraction and a more efficient use of forest biomass in products and for energy is therefore suggested. The additionally extracted biomass should, where feasible, be stored in long-lasting wooden products. Additionally, all energetic use of wood biomass, either waste products or wooden products after their lifetime, should be coupled with BECCS to maximize the potential of forests for carbon sequestration.

Agricultural management practices

A range of agricultural management practices could help to increase the amount of carbon stored in agricultural soils in Switzerland. The technical potential of this carbon sequestration is estimated to be about 2.7 Mt CO_2 per year (Federal Council of Switzerland, 2020). This potential is based on a very ambitious soil carbon sequestration, assuming that cropland could sequester 0.63 t of soil organic carbon per ha and year, which would require a combination of zero tillage, cover crops and leaving all crop residues on the field (Autret et al., 2016). Additionally, it assumes that all grasslands could sequester 0.28 t of soil organic carbon per ha and year and that on arable land, deep tillage is used on up to 5,000 ha per year to sequester additionally 0.21 Mt of carbon per year on 82,500 ha (about 2.5 t of carbon per ha and year; Beuttler et al., 2019). The potential of sequestering additional carbon by improved carbon input into soils (e.g. more cover crops or biogas slurry) is assumed to be very limited, because higher carbon stocks are usually associated with a higher turnover of carbon. Therefore, the mentioned potential of additionally sequestering 2.7 Mt CO_2 per year is assumed to be possible for only a few decades until a new steady state of carbon stocks at higher input rates is reached (Beuttler et al., 2019). Yet, an increase of carbon stocks in agricultural soils has many synergistic benefits, such as increased soil fertility and enhanced water and nutrient holding capacities. Additionally, the measures to increase soil organic carbon, such as improved crop rotations or cover crops, are generally not competing with other LMTs for biomass. In comparison to other LMTs, the implementation of improved agricultural management is also comparatively cheap.

The measures to increase the soil organic carbon content that are available, some of which are already regularly used by many farmers in Switzerland, can basically be split into two categories. One category is to increase the amount of carbon inputs into the soil, as a basis to increase the built-up of soil organic carbon. These include the use of cover crops, (partly) leaving residues on the field, returning organic residues and manures to the field, planting deep rooting crops, applying improved crop rotations including grass-clover leys and the use agroforestry techniques (Beuttler et al., 2019). The other category consists of measures that lower the turnover of carbon which is already present in the soil. Reduced tillage has been suggested to serve this purpose, yet it is debated to which extent tillage actually reduces soil organic carbon by disruption of soil aggregates (Six et al., 1999) and to which extent it just leads to a redistribution of carbon in the soil profile (Luo et al., 2010). Biochar has also been suggested to lower the turnover of soil organic carbon (Beuttler et al., 2019). A special case, combing elements of both categories, would be a one-time deep tillage of soils. Because carbon in deeper soil layers is lost at a slower pace than topsoil carbon, this transition of carbon rich soil material to the subsoil has been suggested as an effective method to increase soil organic carbon stocks (Beuttler et al., 2019). Apart from storing larger amounts of carbon in deeper soil layers, deep tillage moves carbon-poor soil material to the surface, where it can start to accumulate new carbon, which results in an overall carbon sequestration of the soil (Alcántara et al., 2016). However, deep tillage may cause unwanted side effects, such as a reduced topsoil fertility for decades or longer, thus it is questionable whether it would be feasible and whether farmers would be willing to accept it.

Apart from normally managed agricultural soils, there is a high potential to reduce GHG emissions from peatland soils under agricultural use, which are stated to lose around 9.5 t of carbon per ha per year (Beuttler et al., 2019). Therefore, rewetting agriculturally used peatlands would be a very cost-effective measure to reduce GHG emissions by 0.6 Mt CO_2 per year in whole Switzerland (Federal Council of Switzerland, 2020). However, reducing emissions from peatlands does not mean that they are actually sequestering carbon. To achieve this, it would be necessary to reinitiate a growth of the peatlands.

This could mean resettling native vegetation, which is assumed to take at least a few decades, and it is not clear how well this could work. For this reason, no potential for negative emissions is assumed to be associated with rewetting of peatlands until 2050 (Honegger et al., 2020) but they are seen as cheap mitigation options to reduce GHG releases.

Another option to sequester additional carbon in agriculturally used areas, is the implementation of agroforestry systems either in agricultural fields or grassland systems. This double use of the land can lead to higher yields than if either trees or agriculture would be performed separately on different areas. It also allows for additional sequestration of carbon in the woody biomass. While agroforestry systems were classically studied and applied in tropical areas, a new interest in temperate agroforestry systems seems to arise. A recent meta-analysis on agroforestry systems of Europe showed an overall positive effect of agroforestry on biodiversity, soil fertility, nutrient-cycling and erosion control, while no reduction of timber and food production compared to monoculture was found (Torralba et al., 2016). Pilot-studies of agroforestry establishment in Switzerland also found that participating farmers reported mostly positive outcomes of agroforestry (Jäger, 2019), thus agreeing with the results of the meta-analysis. The potential of agroforestry in Switzerland has thus also been recognized by policy makers and the aim to make agroforestry eligible for direct payments has been explicitly stated the Swiss long-term climate strategy (Federal Council of Switzerland, 2021).

2.2 Determining the LMT scope for national level simulation modelling

To reach its aim of net zero emissions in 2050, Switzerland will likely need to offset emissions that are difficult to avoid. Those are estimated to be around 10 Mt CO_2 per year (FOEN, 2020). In this section we discuss which set of LMTs are most promising and will be studied in detail. Table 2 summarises the main LMTs of Switzerland and indicates the inclusion into the short-list of the LMT portfolio. The rationales for inclusion in the national level scaling simulation assessment are presented thereafter.

Table 3: Long-listing of relevant land based LMTs

LMT	Subcategory	Specification	Included in national LANDMARC LMT portfolio
Biomass based LMTs	BECCS	BECCS based on domestic biomass already used today	Y
	Biochar	-	Y
Land management practices	Wetlands	Peat soil management, including rewetting, reverse drainage	N
	Cropland	Reduced tillage, conservation/ organic agriculture	Y
		Deep tillage	N
		Agroforestry and landscape elements (hedgerows etc.)	Y

	Grassland	Peat soil management	N
		Agroforestry and landscape elements (hedgerows etc.)	Y
	Forest land	Avoided deforestation	N
		Forest maintenance with biomass use (BECCS in cascade)	N

- **BECCS based on domestic biomass**

  With the largest potential of all LMTs, the use of BECCS forms an integral part of the portfolio of Swiss strategies for negative emissions and is favoured by Swiss policy. Attractive is that about 40% (2.1 Mt CO_2 per year) of the overall BECCS potential of Switzerland could be achieved by applying CCS techniques to biomass that today is already energetically used, thus BECCS will very likely be used at least to capture these carbon sources. An interesting question would be, to what extent additionally available biomass should be used for BECCS. It is likely a waste of resources to use biomass of higher value for BECCS, e.g. wood that could also be used for construction or biochar. It could be most effective to prioritize the use for permanent wooden products and biochar, butt apply BECCS when products get disposed or to capture CO_2 released from biochar production.

- **Biochar**

  The application of biochar to agricultural fields could potentially be a cheap option to sequester additional carbon in the soils, if the stability of biochar over several decades to centuries would be verified. In their recent report, the foundation "risk dialogue" prescribed a huge potential to the application of biochar in Switzerland to sequester 2.2 Mt of CO_2 per year (Beuttler et al., 2019). In addition, biochar might reduce the production of other greenhouse gases, mainly N_2O in soils where it is applied and may increase soil fertility (Beuttler et al., 2019). There is also a scepticism of farmers and the government towards a large-scale application of biochar in Swiss soils, mainly due to incomplete understanding of potentially negative side effects such as faster biochar turnover than expected, negative effects on soil microorganisms, and a higher albedo due to darker soils (Federal Council of Switzerland 2020). However, due to only certified biochar being allowed in Switzerland, the risk of soil pollution, for example through heavy metals in the biochar is considered to be low. Through the additional side benefits for soil fertility and reducing GHG emissions, using biomass for biochar may be of added value compared to pure BECCS but a coupling of biochar production to BECCS seems feasible.

- **Reduced tillage, improved crop rotations, organic farming**

  Altering agricultural management, for example reduced tillage could potentially lead to higher soil organic carbon stocks, though it is debated in the literature whether this increases carbon stocks or just prevents the redistribution of carbon along the depth profile (Beuttler et al., 2019). Yet, it was shown that with a rigorous use of the "equivalent soil mass approach" higher carbon stocks in reduced tillage systems compared to conventional tillage are detectable (Gauder et al., 2016). Apart from potentially higher carbon stocks, a lower mechanic energy requirement of reduced tillage systems could additionally contribute to lower overall GHG emissions of reduced tillage systems. Other management options that are considered feasible to increase soil organic carbon stocks in Switzerland are improved crop rotations, including a more intensive use of cover crops and leaving residues on the field (Beuttler et al., 2019). The increase of area under organic farming could be a further suitable measure to increase soil organic carbon stocks. For example, it has been shown that organic farming can lead to lower losses or the maintenance of carbon stocks compared to conventional agriculture (Fließbach et al., 2007), while being more efficient in nitrogen use (Mäder et al, 2007) which could reduce N_2O emissions. All the agricultural management techniques have the advantage that they are not competing for land or biomass with other LMTs and are considered to be relatively cheap. Thus their use fits well into the portfolio with the other selected LMTs.

- **Agroforestry**

  While an increase in forest area or wood biomass stocks in Switzerland seems difficult due to no available land and high carbon stocks already present in forests, agroforestry establishment bears the potential to increase the tree coverage in Switzerland without reducing agricultural land. Thus, agroforestry implementation was suggested as a measure to sequester additional carbon in Switzerland (Beuttler et al., 2019). Agroforestry may thus be more suitable than afforestation for reaching the goal of increasing the tree biomass in Switzerland. This and the apparent absence of severe yield depressions in agroforestry systems in Europe (Torralba et al., 2016), may make agroforestry the LMT with the highest potential to intensify the carbons sequestration potential of agricultural systems. The few innovative farmers who have already adopted agroforestry in Switzerland, seem to report mostly beneficial outcomes (Jäger, 2019). Therefore, despite not being broadly adopted at this time, the largest potential for increasing wood biomass in Switzerland may lie in agroforestry, which also offers several potential side benefits. This is also reflected in the stated political interest to support the development of more agroforestry systems in Switzerland by making it eligible to additional subsidies (Federal Council of Switzerland, 2021).

Excluded options from the shortlist

- **Peatland management**

  About 2.3% of the Swiss land area are peatland areas but only 9% of these peatlands areas are still natural peatlands (e.g. matching the definition of bog or raised bog; Klaus, 2007), while 82% of functioning peats have vanished in the last 120 years (BAFU, 2017). Due to their high emission potential, it is an integral part of the declared climate action strategy of Switzerland to maintain the carbon stocks in peatland soils (Federal Council of Switzerland, 2021). The only option to remediate disturbed peatlands would be rewetting them, as apparently there is no option to agriculturally use Swiss peat soils while maintaining their carbon stocks (BAFU, 2017; Honegger et al., 2020). A potential danger of rewetting peatlands is that rewetting will lead to increased CH_4 emissions and in formerly agricultural areas also to N_2O emissions, which in the short term might increase radiative forcing by an amount that cannot be offset by the additionally sequestered carbon (Petrescu et al., 2015). Peatlands in Switzerland are estimated to lead to emissions of 0.6

Mt CO_2 per year (Federal Council of Switzerland, 2020), yet it is considered unlikely that they will lead to significant negative emissions until 2050 (Honegger et al., 2020). Due to a scarcity of arable land and a lack of food self-sufficiency of Switzerland, there is a high pressure to keep using Swiss peatlands for agricultural production (personal communication Daniel Bretscher). Thus, despite the strategy to maintain intact peatlands, there is no plan of rewetting disturbed peatlands at the moment and even if they would be rewetted, it would take a long time for disturbed peats to become actual sinks. Therefore, peatland management was excluded from the short list of LMTs.

- **Afforestation/ Forest maintenance with biomass use (BECCS)**
  As for now, there is no additional land available for afforestation apart from the tree line moving uphill due to climate change. There seems to be some potential to make more biomass available by a more efficient extraction. This sustainable extraction of wood while maintaining the forest would have the benefit of reducing the risk of a loss of forest carbon stocks due to higher turnover at higher atmospheric temperatures or increased disruptions of the forest systems, as the carbon stocks of Swiss forests already considered to be close to saturation (Federal Council of Switzerland, 2020). However, as afforestation in Switzerland is not an option and thus a tremendous change in forest area and use are not expected. Agroforestry is considered as a more innovative option to increase the availability of wood biomass in Switzerland. Thus, active forest management is excluded from the short-list of LMTs to be studied in detail but could be indirectly included as biomass for biochar or BECCS may likely originate from forests.

- **Deep tillage**
  While deep tillage practices have been suggested as an option to sequester carbon by transferring soil material to the surface, that is not yet saturated with carbon (Beuttler et al., 2019), it is a relatively new idea. Hence, the side effects have not been studied intensively. While deep tillage has the advantage of not being in competition for biomass with the other LMTs, it is questionable if farmers would be willing to plough their fertile soil under and reduce their soil fertility for decades or longer, only to sequester carbon. Thus, due to the lack of co-benefits and instead having potential negative side-effects, the potential of deep tillage is considered too uncertain and it is therefore not included in the short list.

2.3 Discussion on short-listing LMTs

2.3.1 Competition for biomass between BECCS & biochar

The competition for biomass of several LMTs that rely on biomass has been identified as a key limitation for the national potential in Switzerland (Federal Council of Switzerland, 2020). Thus, LMTs that create additional biomass to the biomass available now, bear the largest potential. With about a third of Switzerland already covered by forest (UFAM, 2021) and a scarcity of arable land due to being a net importer of food (Federal Statistical Office of Switzerland, 2020a), an increase in forest area through afforestation is not considered feasible as it would go at the cost of agricultural production area in Switzerland. The two main objectives of Swiss forest policy were therefor specified as, firstly, the conservation of forest area, avoiding deforestation and maintaining healthy forest and, secondly, facilitating an efficient use of forest biomass (FOEN, 2013) so even with business as usual, forest are expected to be maintained and efficiently used. The promotion of agroforestry in contrast, bears the potential to provide additional woody biomass and may help to reduce the pressure on domestic biomass. The LANDMARC project offers the opportunity to not only study and compare the different alternatives which exists for the use of biomass, including use of wood for long-term products, and using forest biomass for biochar and/or BECCS, but also to determine which use is most feasible and how different uses could be efficiently combined in a cascade system.

When comparing the different uses of domestic biomass for suitability as LMTs, the duration of carbon storage and the economic feasibility are two major aspect which should be studied over longer time periods, applying methods such as lifecycle analysis. For high quality wood for example, a material use may be of higher economic value than energy generation. Yet, a cascade use may be feasible with an energetic use at the end of product lifetime. For lower quality biomass, the direct competition between biochar and BECCS raises the question of the cost and storage time for both. Additional logistics might be needed for both, for example to allow for the use of wooden products at the end of their lifetime, yet for BECCS or the combination of biochar production with BECCS there are additional constraints. A carbon capturing and storing as done for in the case of BECCS needs the large-scale facilities to be economically feasible, sufficient storage facilities in the right geological conditions and the infrastructure (trains or pipelines) to transport the compressed CO_2 to the place of storage (Beuttler et al., 2019). To date, neither the transport system nor any certified storing facilities exist in Switzerland (Federal Council of Switzerland, 2020). Thus, despite being ascribed the highest potential of all LMTs, there is tremendous uncertainty surrounding the feasibility of BECCS, which needs to be considered (e.g. with respect to expected consumer behaviour and additional energy cost of making the biomass available and for CCS). Additionally, there is the issue of CCS storage. A high theoretical potential for geologically storing captured carbon in saline aquifers of Switzerland was postulated, estimated to be about 2700 Mt of CO_2 (Swiss Federal Office of Energy, 2010) - 60 times the current yearly CO_2 emissions of Switzerland (Federal Council of Switzerland, 2020). However, this potential is a purely theoretical estimate, based on the geological knowledge about Switzerland. There is to date no practical proof of this theoretical potential. As detailed studies are currently lacking, and the actual realizable potentially is at the moment unknown. Switzerland also considers the case of transporting captured CO_2 to storage facilities outside of Switzerland to be a realistic option in case no storage inside Switzerland is possible (Federal Council of Switzerland, 2020).

2.3.2 Limited potential of cropland management but low competition and cost effectiveness

Due to the scarcity of arable land in Switzerland making major changes in land use are unfeasible, Improved management schemes are needed to sequester carbon and reduce GHG emissions while maintaining the current land use. This strategy offers a potential for negative emissions which are mostly not in competition for biomass with BECCS or biochar. Yet, it is explicitly stated that the potential to sequester additional carbon in soils by improved cropland management is limited and only possible until a new steady state of the soil organic carbon is reached, which is expected to be the case within a few decades (Federal Council of Switzerland 2020). Thus, improved management for higher soil carbon could serve as interim solution with the higher soil fertility being an important co-benefit. The extent to which individual measures of conservation agriculture are already adopted and thus, the additional available potential, depends on the exact measure. The current policy of Switzerland already rewards and drives optimized crop rotations. For example, about 81% of the farmers, which are operating year-round, are getting direct subsidies for at least one conservation agriculture measure while measures to reduce soil disturbance (e.g. reduced or zero tillage) are only practiced on 81,933 ha (FOAG, 2020a,b) corresponding to roughly 30 of arable land. A special case of management options is organic farming, which has been shown to bear the potential to increase carbon storage or with at least a better maintenance of carbon stocks compared to conventional agriculture (Fließbach et al., 2007). However, yield reductions in organic farming are observed (e.g. around 14% in wheat; Mäder et al, 2007). This potentially negative side effect could be of high relevance for Switzerland, being a net importer of food. Despite this, a continuous demand for organic products leads to a continued growth of the area of organic agriculture in Switzerland, being now already at 16% (Federal Statistical office of Switzerland, 2021).

Table 4: Agricultural land use in the Switzerland from 1999 to 2019 (in 1000 ha)

Land use category	1999		2009		2019	
Total area of Switzerland	4128.5		4128.5		4128.5	
Agricultural area	1071.9	100%	1055.6	100%	1043.7	100%
Cereals	182.3	17%	152.8	14%	141.4	14%
Potatoes, turnips	34.4	3%	32.4	3%	29.0	3%
Oil seeds	18.9	2%	25.0	2%	30.3	3%
Remaining arable land	58.3	5%	65.1	6%	71.4	7%
Temporary grassland	115.9	11%	129.8	12%	126.7	12%
Natural grassland	626.8	58%	614.6	58%	605.7	58%
Permanent cultures	23.2	2%	23.4	2%	24.0	2%
Remaining agricultural land	12.0	1%	12.4	1%	15.2	1%

Source: Federal Statistical Office of Switzerland 2020b

To get an overview on the realistic potential of additional carbon storage in Swiss soils, one could relate the numbers given in Table 1 to the agricultural area. The increase of carbon stocks by conservation measures, such as reduced tillage or improved crop rotations, could for example only be achieved in cropland and on temporary grasslands which will be transformed to cropland again. Together they make up 38% of Swiss agricultural area combined (The extent to which individual measures of conservation agriculture are already adopted and thus, the additional available potential, depends on the exact measure. The current policy of Switzerland already rewards and drives optimized crop rotations. For example, about 81% of the farmers, which are operating year-round, are getting direct subsidies for at least one conservation agriculture measure while measures to reduce soil disturbance (e.g. reduced or zero tillage) are only practiced on 81,933 ha (FOAG, 2020a,b) corresponding to roughly 30 of arable land. A special case of management options is organic farming, which has been shown to bear the potential to increase carbon storage or with at least a better maintenance of carbon stocks compared to conventional agriculture (Fließbach et al., 2007). However, yield reductions in organic farming are observed (e.g. around 14% in wheat; Mäder et al, 2007). This potentially negative side effect could be of high relevance for Switzerland, being a net importer of food. Despite this, a continuous demand for organic products leads to a continued growth of the area of organic agriculture in Switzerland, being now already at 16% (Federal Statistical office of Switzerland, 2021).

Table 4: Agricultural land use in the Switzerland from 1999 to 2019 (in 1000 ha)

In contrast, it is unclear if any management options to sequester additional carbon in natural grasslands (58% of agricultural area) exist, and thus the natural potential of grasslands to sequester carbon depends on if their carbon stocks are already at steady state. Swiss croplands and temporary grasslands combined have assumed stocks of 40 Mt of carbon in the top 100 cm of soil. The technical potential of yearly carbon sequestration in agricultural soils was assumed to be 2.7 Mt CO_2, which requires combining the best management practices for sequestering carbon on all agricultural land (e.g. zero tillage, catch crops and no straw removal on agricultural land, best grassland management and deep tillage on up to 5000 ha per year; Beuttler et al., 2019). This amount of 2.7 Mt CO_2 corresponds to 0.74 Mt of carbon. Thus, if the sequestration would be realized in the cropland and temporary grasslands alone, the 0.74 Mt would correspond to an annual growth rate of the estimated carbon stocks by 1.8%. This is almost five times the proposed aim of the 4 per 1000 initiative, whose aim to annually increase current soil carbon stocks by 0.4% (Minasny et al., 2017) is already heavily debated in the scientific community as being too ambitious (e.g. Wiesmeier et al., 2020). If permanent grasslands (including all agricultural and alpine grasslands) are included in the growth of carbon stocks (122 Mt of carbon in the top 100 cm), an increase of 0.6 % per year would be needed to achieve the annual sequestration 2.7 Mt CO_2, which would still be highly ambitious. It is therefore questionable, if this potential could really be achieved with standard practices, if novel practices will be needed or if other LMTs should be used.

Table 5: Calculated soil organic carbon stocks in Switzerland

Depth	Land-use (area)			
			Permanent grassland	
	Arable land (2893 km²)	Temporary grassland (1141 km²)	Favourable* (5045 km²)	Unfavourable* (5800 km²)
		SOC (t ha^{-1})		
0–20 cm	40.6	43.4	50.7	47.7
0–100 cm	90.4	117.4	92.3	62.9
		Soil organic carbon stock (Mt C)		
0–20 cm	11.7 ± 2.6	4.9 ± 1.2	25.6 ± 6.4	27.6 ± 6.6
0–100 cm	26.2 ± 5.8	13.4 ± 3.4	46.6 ± 11.2	36.5 ± 8.8

Source: Adapted from Leifeld et al (2005). *Due to different sources the numbers do not match perfectly to Table 3, but favourable grassland can be considered mostly equivalent to natural grassland in Table 3, wheres unfavorable grassland consits of alpine grasslands not specified in Table 3.

2.3.3 Biochar and Agroforestry as innovative options with potential co-benefits but adoption barriers

While at this stage not largely accepted and applied in Switzerland, both biochar and agroforestry show potential as future LMTs for Switzerland (personal communication Sonja Keel and Daniel Bretscher). Both technologies have co-benefits, such as increased soil fertility (biochar) a higher land-use efficiency (agroforestry) and a long time-frame (permanence) of carbon storage (both). Depending on how the additional woody biomass is used, agroforestry may add the highest carbon sequestration potential, as it allows for an additional long-term sink in the woody biomass, which was previously not present. It is thus a special kind of afforestation that does not compete with arable land. However, for agroforestry on arable land, the shading induced by the trees may cause yield losses. For example, yield losses between 25 and 45% were observed due to shading of wheat Belgium (Artru et al., 2017), mainly due to light competition. Yet, with a proper planning of the systems tree orientation, tree spacing and crops to include significant yield losses can be avoided (Carrier et al., 2019). Especially attractive could be the implementation into permanent grasslands because most forages can tolerate or oven benefit from shading (Pang et al., 2019). The potential additional labour requirements or mechanization costs should also be considered when analysing economic feasibility of agroforestry.

While agroforestry mostly increases carbon stocks in biomass, biochar application increases soil carbon stocks. Biochar application can also reduce N_2O emissions (Dong et al., 2020), increase soil fertility by improving nutrient storage capacity and it may even carry the potential to reduce the turnover of carbon already present in the soil (Beuttler et al., 2019). Even if biochar does not slow down the turnover of the carbon already present in the soil the turnover of biochar itself is very slow and it is estimated to stay in the soil between 270 and 5400 years (Beuttler et al., 2019), thus providing a significant period of sequestration. Yet, due to the slow turnover of biochar in the soil, it is difficult to estimate the exact retention time and a conservative estimate should be used to assess its potential as LMT. An additional adoption barrier for biochar could be the price of the biochar itself, which depends on the origin and quality and due to certification standards in Switzerland may be higher than in other parts of the world. For example, Struhs et al. (2020) reported prices between 200 and 700 US $ per t of biochar. Yet prices may come down in the future as the technology matures and economies of scale come to play. Overall, biochar and agroforestry may add to the portfolio of Swiss LMTs, offer real long-term potential to use agricultural systems to sequester additional carbon and have both promising additional benefits.

3. Co-design of LMT narratives

3.1 Introduction

We developed the narratives based on the short-listed LMTs that were selected based on Swiss policy documents and a first round of stakeholder interviews. The further trajectory of the selected LMTs was then delineated in a two-step process. First, an in-depth literature research was conducted in 2021 and a first version of the narratives written based on that. Second, further interviews throughout 2022 were conducted within LANDMARC tasks 4.1, 4.2 and 5.2 in which we also included questions that arose from the first version of the narratives and feedback from modelers (i.e. LANDSHIFT). The final version of this report was then enriched with key insights gained through the stakeholder interviews, to complete the picture.

As demonstrated by several official government documents, Switzerland aims to be at the forefront on negative emission technologies. However, the focus of Swiss policy seems to be technical solutions, such as DACCS, BECCS and to a lesser extent, biochar. The interest here seems to be to become and exporter of these technologies in the future once they are applied at large scale. Land-based technologies, such as improved agricultural management and agroforestry, are seen as interim technologies until technical solutions can be deployed, but Swiss policy has concerns about their permanence. An important limitation that LMTs face in Switzerland is the scarcity of available land, hence afforestation projects are for example not feasible, and it is aimed to apply LMTs with minimal land competition.

3.2 BECCS based on domestic biomass

3.2.1 Introduction

The energetic use of available biomass in Switzerland is a common practice, including the use of biogas, burning of organic waste from waste treatment plants and the use of timber for heating. However, estimations are, that to date the amount of biomass available in Switzerland is underutilized by about 30% in wood and by more than 70% in other organic wastes (SFOE, 2017). The CO_2 released during the energetic use of biomass was sourced by plant photosynthesis from the atmosphere. Thus, capturing this CO_2 from the combustion process and storing it thereafter, would be an effective way to achieve negative emissions. While BECCS has never been applied in Switzerland, there is, in the context of the need to compensate remaining emissions by 2050, an increased focus on BECCS as a negative emission technology in the Swiss policy. Yet, there is, to date, no single bioenergy plant in Switzerland that captures the CO_2 from the combustion of biomass and stores it geologically. While the process of CO_2 capturing is not a technical problem, the lack of any BECCS facilities in Switzerland is due to a lack of geological storage. There is a theoretically estimated potential for storing CO_2 in saline aquifers in Switzerland, but this is only based on knowledge about the geological formations and has not been proven. Hence, Switzerland is also looking into the possibility to store captured CO2 in aquifers abroad.

3.2.2 Policy context

Due to the novelty of the BECCS technique, no policy which addresses BECCS directly has been established to date. However, BECCS has been mentioned as a key LMT in several national policy documents, most recently in the long-term climate strategy of Switzerland (Schweizer Bundesrat 2021). If negative emissions by BECCS could be accounted for, it would be possible to finance BECCS via carbon credits. However, while Switzerland already established a CO_2 price for fossil fuels for private consumers (currently around 90 CHF per ton of CO_2, with 1 CHF roughly equivalent 1 € at the time of writing Oct 2022) and some private sectors, the heavily emitting sectors such as cement industry are currently not included in the CO_2 tax. Yet, while not taxed for emissions those sectors are part of the cap and trade EU emission certificates trading system that also allows for negative emissions such as BECCS to be accounted (Schweizer Bundesrat 2021), which however has a much lower price than the CO_2 tax. Increased prices for CO_2 could therefore favour the deployment of BECCS and be a way to compensate for hard to avoid emissions through market mechanisms. Another development that could benefit the deployment of BECCS is the aim of the Swiss forest policy to exhaust the sustainably extractable harvest potential of tree biomass, which is currently underutilized by about 20 – 30 % (FOEN, 2013). Harvesting this additionally available potential would increase the available biomass and be a driving factor for any biomass-based LMT.

While no actors are currently applying BECCS in Switzerland, many currently existing users of bioenergy could potentially be coupled to CCS. Waste incineration plants, for example have an estimated share of 50% of their emitted CO_2 being of biological origin (Schweizer Bundesrat 2021). Further actors that could potentially be coupled to CCS are biogas plants, which sometimes have already installed CO_2 capturing technology to remove CO_2 from the biogas before feeding it into the gas grid. Also, larger scale central district heating plants applying various forms of bioenergy seem feasible for BECCS. As BECCS, compared to other LMTs, provides no additional benefit apart from removing CO_2 from the atmosphere, the most feasible financing option for BECCS are likely the carbon emission trading systems or direct payments for CO_2 removal. Already now, fossil fuel importers in Switzerland have compensate for a percentage of the emissions from the fuel they import (at the moment only for 10% of emissions but the legal framework foresees that this percentage increased to be up to 90% in the future; Schweizer Bundesrat 2021). These funds are then redistributed to GHG compensation projects through the foundation KLIK (Home – Foundation for Climate Protectionand Carbon Offset (klik.ch)) and could also become available for BECCS projects.

3.2.3 Current land use and potential land-use competition

The application of BECCS does not directly require land. However, the biomass which is required for BECCS is obviously sourced from land and this land for the generation of biomass for bioenergy is therefore in competition with other land-uses. Due to a scarcity of agricultural land, transforming agricultural land to land that is only used to produce biomass for BECCS is mostly out of the question for Switzerland. This scarcity of agricultural land in Switzerland is further amplified by increases in organic farming area, and by landscape biodiversity measures, which both reduce the intensity of Swiss agriculture. However, a potential to extract more biomass from Swiss forests than what is used today, has been identified. While not applied yet, the implementation of BECCS is an explicitly stated goal within the Swiss long-term climate strategy. On the other hand, it is recognized that an energetic use is the lowest possible value use of biomass. Applying BECCS is therefore primarily foreseen for the lowest values biomass, for example waste incineration plants that make use of biomass, and for additionally available biomass (e.g. from forest) that is not suitable for a material use. Several important Swiss documents (e.g. Beuttler et al., 2019; Federal Council of Switzerland 2020) state that a material use of wood, for example in construction, is to be preferred. Hence BECCS should be applied within a cascade use system, where an energetic use of biomass coupled to BECCS occurs only at the end of product lifetime, for example when construction wood cannot be recycled anymore. This affects the scalability of BECCS and limits the use to the left-over low value biomass and biomass already energetically used today. On the other hand, in contrast to coniferous trees, the demand for wood from deciduous trees for a material use seems to be lower than the natural supply by Swiss forests and most of it is used as firewood anyway (personal communication with WSL expert). This might favour an energetic use of the additionally available potential or using this wood for biochar with BECCS capturing the generated CO_2 during pyrolysis.

While there is no explicit projection on the extent to which BECCS will be applied in the future in Switzerland, it was estimated that about 5 mln ton CO_2 per year could be removed if all available biomass of Switzerland would be used, whereas applying BECCS to bioenergy already in use today would already remove 2.1 mln ton CO_2 per year (Federal Council of Switzerland 2020). Even if most emissions are avoided by 2050, about 6.8 mln ton CO_2 per year are expected to remain to be compensated, so the potential of BECCS suggests that it will likely be one of the key technologies for compensating remaining emissions (Schweizer Bundesrat 2021), because CCS application in other sectors, such as in the cement industry and for non-biogenic waste treatments are already a fix part of the Swiss plan to reduce CO_2 emissions.

3.2.4 Climate risks & sensitivities

The application of BECCS is not directly sensitive to climate changes. Yet the production of the biomass that is needed for BECCS will obviously be influenced by climate change. However, since almost any biomass could be used for BECCS, it is difficult to tell what the final effect of climate change in Switzerland may be. Diverse effects could cancel each other out. For example, while biomass production Switzerland may be impacted by dryer summers, an increase in temperature in Switzerland could prolong the vegetation period, move up the tree line in the alps. Yet, as for BECCS basically all biomass, even of the lowest quality, could be used, it is likely that BECCS is less sensitive to summer droughts than for example crop yields. It is likely that the climatic risk to BECCS feedstock of the biomass already used today is lower than for newly sourced biomass. Especially forests are expected to suffer from climate change, so the additional feedstock from there may be at higher risk.

3.2.5 Economic implications

A main challenge of BECCS may be, that the capturing of CO_2 and the transport infrastructure may only be economically feasible, when applied at sufficiently large scale. Furthermore, since BECCS is not yet applied in Switzerland the estimations of costs are subject to much uncertainty. They depend on the cost for capturing CO_2 from the combustion processes, the scale at which this can be done, the distance and how the captured CO_2 will be transported to its final location (e.g. trains vs. pipelines) and the ease to access the location (e.g. in the north sea vs within Switzerland). All these components are not yet clear, thus the relatively wide price span of 50 – 250 CHF (1 CHF is about 1 € at time of writing) per ton of CO_2 stored was estimated (Federal Council of Switzerland 2020). The competitiveness of BECCS will then strongly depend on the price per ton of CO_2 emissions or the price assigned to negative emissions. At the moment there is a CO_2 tax on fossil fuels in Switzerland equivalent to 90 CHF per ton of CO_2 (CO2-Gesetz - UVEK (admin.ch)), which depending on how well Switzerland will be on track with its climate goals may rise to 210 CHF in 2030 (Schweizer Bundesrat 2021). However, the current system is a cap and trade system while negative emissions can, at the moment, not be sold. Furthermore, there are several exceptions from the CO_2 tax for heavy emission industries to keep them competitive, so it is mostly a consumer tax. Yet, if the CO_2 price would become generally applicable to all industries and negative emissions could be accounted, it is very likely that BECCS will become feasible, though Switzerland has also stated that negative emissions that are realized in other countries while being paid by the Swiss could be a way to achieve negative emissions in a cheaper fashion.

3.2.6 Co-benefits and trade-offs

While, due to a clear prioritization of the Swiss government, BECCS will not be directly in competition for land with food production, there is a competition for the biomass also with other LMTs. For example, straw biomass could either be incorporated into fields, used for biochar, or BECCS. As reduced input of biomass into fields would lower soil carbon stock and thus fertility, there could thus be a very indirect risk to agricultural production. Also, an increased pressure to use biomass for BECCS could change the landscape if a shift towards more intensive fast-growing biomass-plants or trees is favoured. If the production of biomass would be the only goal, it is likely that more intensive production systems would be needed, also threatening biodiversity. However, as biodiversity and landscape conservation are a strong focus of Swiss agricultural policies, including subsidies that are paid for a measured biodiversity, it is unlikely that biomass production for BECCS will be prioritized to have strong effects. It is more likely and already stated, that BECCS should be focused on biomass already used today, or on biomass which is underutilized such as forest biomass (FOEN 2013).

3.2.7 Risks associated with scaling up

The main risks associated with scaling up the use of BECCS is likely the competition for biomass with other uses and the fact that Switzerland has no confirmed geological storage capacity. Yet, Switzerland has clearly positioned itself in a way that BECCS shall only be used with lowest quality biomass. However, BECCS can likely only be applied at larger scales, as the infrastructure to enable BECCS (such as pipelines for the CO_2) will probably only make sense at large scales. Hence, there may be a challenge to transition from small scale utilization of biomass (e.g. firewood) to large scale BECCS plants. Another main risk is likely the lack of practical experience with BECCS up to this point, which is in stark contrast with the clear plan to incorporate CCS technologies into the mitigation technologies portfolio. Thus, it is hard to foresee what kind of unforeseen difficulties could come up when trying to deploy BECCS at national scale.

3.2.8 Research gaps

While the long-term climate strategy of Switzerland already plans with CCS technologies storing significant amounts of CO_2, e.g. half of remaining emissions in 2050, in their ZERO-Base emission scenario (Schweizer Bundesrat 2021), there are many open questions. To date, it is not even established, whether there is any storage potential in Switzerland (Federal Council of Switzerland, 2020). The lack of this clear potential assessment is thus the largest research gap. If there is no storage potential within Switzerland, there is the idea to build CO_2 pipelines towards the north-sea, which however could significantly increase the cost. One could thus summarize that the research should mostly focus on delineating the technical feasibility of CCS, especially the storage potential. Estimates on the amount of available biomass are on the other hand much better resolved.

3.3 Biochar

3.3.1 Introduction

Biochar is charcoal produced from biomass, such as wood or harvest residues, applying a pyrolysis at high temperatures (400-650°C) in the absence of oxygen (Beuttler et al., 2019), a process that also produces thermal energy that could be used for heating. During biochar production, part of the carbon stored in the biomass is released, and thus the potential exists to combine biochar production facilities with BECCS. As a potential LMT, the biochar is applied to soils with the aim of improving soil properties and to be a long-term storage of carbon. Prior to application, biochar is usually mixed with other organic residues or manure so it soaks up nutrients which it can then slowly release. A growing popularity of biochar application in the recent years has to do with the discovery of highly fertile man-made soils of more than 2000 years of age in recent decades in Brazil, called the “Terra Preta” soils. These are found in areas where soils are commonly degraded and they contain up to 70 times more black carbon than surrounding soils (Glaser et al., 2001). What classifies the application of biochar to the soil as an LMT, is the long turnover times of biochar in the soil, expected to be in the range of many decades to several centuries. Thus, biochar will remain in soils for much longer than normal organic material and constitute a significant sink of carbon. An interesting point, raised by a biochar expert, is that it is the currently the only available LMT that is really considered long-term, and thus favoured on voluntary carbon markets. It is therefore sometimes also referred to as Pyrogenic Carbon Capture and Storage (PyCCS). Adding to the attractiveness of biochar is that the addition of biochar to soils is associated with additional co-benefits, such as increased nutrient or water-holding capacity (Hüppi et al., 2015) thus increasing the fertility of especially lower fertile soils. The application of biochar to soils has also been associated to reduced N_2O emissions in several studies (e.g. Hüppi et al, 2015, 2016).

Different forms of biomass, ranging from forest wood, plantation wood to crop residues, can be used to create biochar, which results in different biochar properties and likely affects biochar stability in soil. While biochar in "Terra Preta" soil of millennial age was found, the stability of biochar in temperate regions is hypothesized to be rather in the range of decades to centuries (Beuttler et al., 2019). Yet, char of old age is also naturally found in many temperate fertile soils such as the steppe soils of Ukraine and Russia (Beuttler et al., 2019).

3.3.2 Policy context

The application of biochar to soils in Switzerland is legal since the year 2013 but each application needs to be approved by the local office of the Swiss Federal Office for Agriculture. The Biochar quality standards in Switzerland are the same as for the European Union and are formulated in the European Biochar Certificate (EBC, 2012). It regulates that biochar is only produced from domestic biomass, free of any additives, and does not contain any organic contaminants. Apart from the regulation, which is assuring the quality of biochar, there is until now, no legal framework that addresses the deployment of biochar, for example through subsidies. Yet such schemes could be developed in the future, as biochar is mentioned in several government reports about LMTs (Federal Council of Switzerland, 2020) and climate change mitigation (Schweizer Bundesrat 2021). Additionally, producing biochar could be one way to make full use of the currently underutilized available biomass of Swiss forests, a declared goal of Swiss forest policy (FOEN 2013). The application of biochar in Switzerland is limited to agricultural soils. Research on biochar is currently conducted by Agroscope (Pflanzenkohle (admin.ch)) and by the Ökozentrum Langenbruck (CharNet.ch). A large-scale application of biochar is to date not practiced in Switzerland, partly because there are concerns about unwanted side effects, such as introducing toxic substances (though mostly being prejudice, as the biochar quality standards are high in Switzerland), but also due to the current high market prices of biochar (around 800 CHF per ton). Thus, at the moment the application of biochar is mainly done by a few innovative farmers. However, it was postulated that an average annual application of biochar of 0.5 ton ha^{-1} would lead to many beneficial side effects and that therefore the reasonable demand to achieve these benefits could be up to 600,000 ton per year for whole Switzerland (Beuttler et al., 2019). At the moment, there are no special funds available for biochar in Switzerland, but if biochar application would be classified as a negative emission, it could receive additional funds. Another option is funds through the foundation KLIK (Home – Foundation for Climate Protectionand Carbon Offset (klik.ch)), which distributes import taxes for fossil fuel import to GHG mitigation projects could be a source of funds for biochar in the future. However, a stakeholder highlighted, that as an indicator of a high future potential, biochar is among the most requested C sequestration technologies on the voluntary carbon market.

3.3.3 Current land use and potential land-use competition

The application of biochar in Swiss agriculture is currently only a niche, with a use of less than 1,600 ton in 2018, corresponding to less than 10% of the overall Swiss consumption of biochar-like products including uses such as active char or char for barbecue (Beuttler et al., 2019). However, it is projected that if the interest increases and prejudice barriers are overcome, there is a market potential of 600,000 ton per year (assuming an average input of half a ton per year in all agricultural fields), a quantity which would not exhaust available biomass in Switzerland (Beuttler et al., 2019). Since the application of biochar is to date still a niche and no policies subsidize it, it is difficult to project the development of biochar application in the coming decades. Additionally, there seems to be a common perception among Swiss cantonal soil protection agencies that the application of biochar is connected to risks for soil life, for reduction of pesticide effectiveness and for introduction of pollutants (Federal Council of Switzerland, 2020). However, perceived risks may be greater than actual risks, none of the above stated concern was found a significant concern in recent literature on biochar application. Due to the scarcity of agricultural land in Switzerland, it is highly unlikely that suitable land for food production will be used to produce biomass for biochar. Food production is and will remain a priority in Switzerland, as import dependence is high and maintaining or increasing food self-sufficiency is a declared goal of Swiss policy. It is therefore likely that the competition of biochar for land and biomass, will only be on the land not used for food production. Thus, the competition would be between biochar, BECCS, and the material use of biomass. Such a competition can exist for biomass, which is already used today, including harvest residues, as well as for the currently underutilized biomass (such as underutilized deciduous tree wood from forests). While BECCS and biochar production could be coupled and biochar will likely not be in direct competition with a material use of high-quality wood, there could be a competition between the direct application of harvest residues in the field and the use of those residues to produce biochar (Federal Council of Switzerland, 2020). This could mean that increasing incorporation of harvest residues into soils would be in competition with scaling up the use of biochar. However, since most harvest residues are turned over in a relatively short time of one or a few years, the use of at least some of this biomass for biochar creation could have a higher CO_2 sequestration potential than returning residues.

3.3.4 Climate risks & sensitivities

Due to the long-term stability of biochar even in tropical soils (Glaser et al., 2001), the sensitivity of biochar application as LMT to climate related changes should be relatively low. However, as biochar production depends on biomass availability, the amount of biomass available for biochar production could be negatively influenced by drought, or by a decrease in forest productivity in a changing climate.

3.3.5 Economic implications

The current price of biochar is around 800 CHF per ton (Schmidt et al., 2021). Thus, if 62% of the CO_2 captured within the biochar would be counted as stable and thus a negative emission (the value assumed by Beuttler et al., 2019), the cost would be roughly 350 CHF per ton of CO_2 sequestration (800 x 3.66 tCO2/t C /.62). Thus, if only the CO_2 sequestration is considered, biochar appears to be a very expensive LMT at the current price level. Yet, other benefits such as reduced N_2O emissions and increased yields have been identified across a broad range of studies in a recent meta-analysis which showed that the strength of the effects also depended on the rate of biochar application and initial soil properties (Zhang et al., 2020). It is, however, recognized that the yield increase due to biochar application is strongest in unfertile soils with a low pH and that Swiss soils have mostly alkaline pH and are fertile, so large yield increases are not expected in Switzerland (Schmidt et al., 2021). Yet the combination of positive side effects of biochar with a compensation for negative emissions could, depending on the CO_2 price make biochar a competitive negative emission technology and it is expected that the future cost per avoided ton of CO_2 could be between 135 and 10 CHF (Federal Council of Switzerland, 2020).

3.3.6 Co-benefits and trade-offs

While in theory, there could be competition for land of biomass production area with agricultural production, this is not expected to occur in Switzerland (Beuttler et al., 2019) due to a clear priority on producing food and most subsidies being paid for food production only. In general, the application of biochar to soils is associated with benefits to crop production, due to higher nutrient and water storage capacities of biochar amended soils. Yield increases in the range of +20% are commonly reported after biochar application to soils with limited soil fertility (Zhang et al., 2020). While such strong increases are not expected in Switzerland, due to most soils being already high in fertility (Schmidt et al., 2021), the application of biochar is still expected to benefit rather than decrease agricultural production. Also, a stakeholder pointed out that biochar provides several benefits to the soil, such as increasing water holding capacity and it may also be beneficial in capturing and binding soil pollutants, due to its high surface area. As a soil amendment, biochar will likely not have a strong influence on landscape composition or biodiversity, whereas there is a strong potential to reduce N_2O emissions in Switzerland (15-50 %; Hüppi et al. 2015, 2016), which is also in alignment with a recent global meta-analysis (Zhang et al., 2020). An additional risk that has been mentioned is that the application of biochar in larger quantities could increase the albedo of the soil, leading to higher absorbance of sunlight and thus contributing to warming (Federal Council of Switzerland, 2020). However, this effect is only expected if the biochar is not properly incorporated (e.g. ploughed) into the soil (Schmidt et al., 2021) and if the soil is left bare, so with good practice this risk should be negligible. Overall, the summarized literature suggests, that the application of biochar, if done correctly, will be associated with many co-benefits, such as increased soil fertility and reduced N_2O emissions. While there is in theory the risk of creating a competition for biomass with for example harvest residues, it was estimated that the sustainably available biomass in Switzerland is sufficient to satisfy the demand for biochar, even if applied at national level. Yet there seem to be several negative perceptions about biochar, such as that it will negatively impact soil life or introduce pollutants to the soil. As for certified biochar application these risks are found to be negligible in the literature (Schmidt et al., 2021), it seems as if the application of biochar would benefit from campaigns aiming at improving the public perception of biochar.

3.3.7 Risks associated with scaling up

As mentioned before, the main risk for scaling up the use of biochar to the national level is an increased demand and competition for biomass with other LMTs. However, as the expected demand of a maximum of 600,000 ton of biochar annually does not exceed the national availability of biomass (Beuttler et al., 2019), the overall risk seems relatively low. While biomass cannot be simultaneously used for a material use, biochar and BECCS, there is a clear hierarchy of value and cascade use is possible. Material use is of highest value, but is only feasible for high quality biomass, while the pure energetic use for BECCS is the lowest value use. However, there is the potential to synergistically combine BECCS and biochar production, storing the CO_2 which is emitted during the production of biochar via CCS technologies. Thus, with a solid planning practice it should be possible to manage the risk of scaling up well.

3.3.8 Research gaps

One of the largest research gaps about biochar application is the persistence of human introduced biochar in temperate soils. This has to do with the generally long persistence of biochar, and the long-term experiments thus required to analyse the turnover time in detail. However, in a condensation of various studies it was postulated that turnover of biochar in the soil would take at minimum 270 times longer than biomass normally introduced and that biochar could be almost inert at maximum (Beuttler et al., 2019). A similar conclusion was made by the literature analysis of Schmidt et al. (2021), showing that with the most conservative estimate about 0.3% of biochar turnover is possible, corresponding to a half-life in the soil of at least 230 years. Another open question is how the presence of biochar could affect the functionality of pesticides intended to affect the soil, for example nematicides (Schmidt et al., 2021). It could thus be that agricultural systems that highly depend on this special class of pesticides should refrain from applying biochar.

3.4 Reduced tillage, conservation/organic agriculture

3.4.1 Introduction

Soils are the largest terrestrial carbon pool in active exchange with the atmosphere and store more than double the amount of carbon than biomass (Lal, 2004). Any soil management options that enhance the amount of carbon in soils are thus effective LMT. Soil carbon is in constant turnover, new carbon formation and turnover of present carbon happen simultaneously, and thus enhancing soil carbon stocks in contrast to other LMTs has an element of impermanence. On the other hand, the increase of soil carbon stocks has also several co-benefits, as it improves water holding- and nutrient storage capacities, soil structure and soil aeration (Bashir et al., 2021). It should thus not come as a surprise that the global increase of soil carbon stocks is a topic of high political interest. For example, it was postulated that increasing global soil carbon stocks by 4 permille annually would compensate all man-made GHG emissions (Minasny et al., 2017). While it needs to be clearly stated that the 4 permille are only a numeric example and in fact not an achievable technical potential, it is still useful to illustrate the importance of global soil carbon stocks. The two ways to alter soil carbon stocks are either slowing down the decomposition of soil carbon or increasing the input of new carbon into the soil. Reduced tillage addresses the first way, as tillage breaks up soil aggregates protecting some of the soil carbon, thereby effectively increasing the speed of carbon cycling in the soil (Six et al., 1999). Other measures such as conservation agriculture, for example using cover crops to produce more biomass, or organic agriculture, often increase the amount of carbon input into the soil. Additionally, through either reduced application of nitrogen fertilization or improved recycling of nitrogen, nitrogen losses can be reduced. This is especially relevant with regard to the amount of N_2O emitted from soils, which is comprising a large part of agricultural GHG emissions.

3.4.2 Policy context

Swiss agricultural policy has implemented several regulations addressing conservation agriculture. For example, there are subsidies for measures that are stated to increase resource use efficiency, which includes no-till and reduced tillage practices in the Swiss subsidy system (Ressourceneffizienzbeiträge (admin.ch)). For example, there is a subsidy of 150 CHF for mulch seeding and 250 CHF per ha for direct seeding. There are also additional subsidies for practitioners of organic agriculture (Beitrag für biologische Landwirtschaft (admin.ch)). There is no additional subsidy for the application of cover crops in Switzerland, but instead it is mandatory to assure a crop cover in winter months to receive subsidies at all (Direktzahlungen (admin.ch)). Thus, it is very commonly applied as the Swiss agricultural subsidies usually make up a significant share of farm income. Further subsidies are available for practitioners of organic agriculture apart from the price premium. However, there has been concerns the recent past that the increase of food prices in general, following the current Ukraine conflict, have relatively decreased the importance of this price premium. On top of the usual agricultural subsidies, farmers applying organic agriculture in Switzerland get additional yearly subsidies of 200 CHF per ha or up to 1,600 CHF per ha for horticulture. Of the different agricultural management practices discussed as LMT, organic farming is the most widely applied. Currently, 16% of Swiss farmers are already practicing organic farming (Federal Statistical office of Switzerland, 2021) and the number has been constantly growing in the last years. Additionally, according to official statistics, reduced tillage subsidies have been paid for about 82,000 ha in 2019, which is about 7.5 % of agricultural area in Switzerland.

3.4.3 Current land use and potential land-use competition

As priorly stated, about 16% of farmers in Switzerland are currently practicing organic agriculture. The area they cover is in the same magnitude and has been growing from about 120,000 ha in 2010 to about 170,000 ha in 2020 (biz20_dt_web.pdf (bio-suisse.ch)) and is expected to further increase in the future. The current extent of reduced tillage practices is about 7.5 % of Swiss agricultural area, but this is not further differentiated into reduced and no-till in the official statistics. As cover cropping is already a precondition for receiving subsidies, it is likely not in competition with other land uses. For reduced tillage systems and organic cropping systems, it is however likely that they are mutually exclusive. This is because in reduced tillage systems, herbicides such as glyphosate are often applied to reduce the competition for the crop by killing of the established weed cover prior seeding. On the other hand, synthetic herbicides are excluded in organic agriculture and to manage weed pressure, ploughing is usually the best option. An expert stakeholder stated that no-till and organic agriculture can be combined with highly sophisticated crop rotations, but this is difficult and not commonly practiced in no-till. Another critical point when it comes to organic agriculture is the reduced yields per area, compared to conventional agriculture. This could be a relevant factor in Switzerland, as about 40% of consumed food is imported. For example, compared to conventional agriculture, organic farming requires between 20 (cereals, pulses) and 80% (vegetables, animal products) more land on a per calories basis (Clark and Tilman, 2017). Yet, several stakeholders stated that in tendency, the yields in Swiss conventional agriculture are declining, due to losses of soil fertility, while organic yields due to improvements in management and cultivars increase yield – so in the long-term the yield may become similar. Another point is that GHG emissions of organic agriculture can be significantly lower and the strongest difference is found between plant and animal products, organic agriculture could be applied at larger scales if the consumption of animal products would be reduced at the same time.

3.4.4 Climate risks & sensitivities

While there is no particular vulnerability of increased levels of carbon in the soil to heat waves, it is generally agreed upon that soil organic carbon (SOC) turnover increase with temperature, all else being constant. This leads to the concern that there could be a feedback loop between increased global temperatures and increased SOC turnover (Davidson and Janssens, 2006) which is a strong argument for limiting global warming as much as possible. However, as increased summer temperatures could also be linked to increased drought, which likely reduces SOC turnover due to lack soil microbes becoming dormant, it is not entirely clear how the combination of heat and drought could affect SOC turnover. In general, increased levels of SOC benefit the water storage capacity and could reduce the drought stress that plants are subject to. Also, it improves soil structure which improves water infiltration and thus reduces the erosion potential. Hence, organic fields are generally more resilient to droughts than conventional fields. Reduced tillage and especially no-till could play an important role in mitigating erosion, as they maintain an intact soil cover throughout most of the year, while ploughing leads to open soil cover and destroys the soil cover, leaving the soil more prone to erosion until a new plant cover is established.

3.4.5 Economic implications

In contrast to technical LMTs, such as BECCS, the introduction of conservation agriculture practices such as reduced tillage or organic agriculture is expected to be a relatively cheap LMT (expected costs are in the range of 0 – 80 CHF per ton of CO_2). On the other hand, higher SOC is associated with higher turnover rates (turnover usually proportional to stocks and simulated by 1st order decay). The consequences are twofold. First, after some time of higher inputs, the system reaches a new steady state at a higher SOC stock. Second, this means that practices applied to increase SOC stocks have to be continued indefinitely to maintain the increased SOC stocks at the new steady state. This is probably the reason, why LMT that increase soil carbon stocks are considered as an interim solution available for only a few decades (Federal Council of Switzerland, 2020). It is also worth to note that, as turnover and stocks are proportional, the cost of increasing stocks increases, the more carbon is to be stored in soils. On the other hand, the many co-benefits for agriculture could make increase in SOC attractive, even if there is no direct price paid for it. Also, reduced N_2O emissions due to tighter nutrient cycles, while not being a negative emission, can be seen as a permanent reduction in GHG emissions. To address the impermanence of SOC stock enhancements, Sierra et al. (2021) recently proposed to compute the economic benefit of carbon sequestration within different pools, calculating the economic benefit as a function of residence time of carbon in a specific pool.

3.4.6 Co-benefits and trade-offs

For reduced tillage practices, there exists the risk of an increased pest pressure from either higher pressure from weeds in the field, or from higher fungal growth on crop residues remaining on the soil surface. This could thus lead to an increased need to apply pesticides, which could both negatively affect biodiversity and water quality. As already mentioned, the main risk for the practicing of organic agriculture is a generally lower yield production on a per area base. This trade-off would be especially relevant if the Swiss food consumption patterns would not change, as the land use for organic animal products is almost double compared to only about 20% increased land need for cereal production (Clark and Tilman, 2017). The higher soil fertility through higher SOC stocks from both organic agriculture and reduced tillage on the other hand could benefit agricultural production especially in dry summers. Especially the use of cover crops to enhance nutrient recycling and carbon inputs into the soils has little to no negative side-effects. On the other hand, as it is a requirement for subsidies most farmers already use cover crops and the potential for it is limited. Several positive side effects are expected at the landscape level for organic farming, for example an improved biodiversity due to more diverse crop rotations used in organic agriculture, and this could be the opposite in reduced tillage systems. Also, a lower load of nutrients, as no synthetic fertilizers are used and livestock units are coupled to land in organic agriculture, would likely lead to reduced N_2O emissions and reduced nitrate leaching, also improving the water quality. As organic agriculture is bound to local animal feed, a larger scale adoption or organic agriculture in Switzerland could also reduce GHG emissions in other parts of the world, such as GHG emissions from land clearing for soy production in Southern America. However, if animal production was coupled to available land area in Switzerland, significantly less animal products would be produced. If this would only be compensated by an increased import, the net effects would probably be negligible, as GHG emissions would just be shifted to other countries. If, however, a dietary shift towards more plant-based nutrition would be possible, shifting to organic agriculture could be an important step to closing local nutrient cycles.

3.4.7 Risks associated with scaling up

The main risk for large scales of organic farming introduction are, as stated before, risks associated with lower yields leading to an import dependence, if not accompanied by a dietary shift of the Swiss population at the same time. For reduced tillage the risk could be that there is an increased need to apply herbicides such as glyphosate to kill of the competition by present weeds at the time of seeding.

3.4.8 Research gaps

The turnover of carbon in the soil, especially in combination with climate change has been subject to controverse discussions for decades. However, this is not likely to be easily resolved. In general, while it is agreed upon, that higher inputs of plant materials into soil lead to an increase accumulation of soil carbon, it has in practice been very difficult to measure the exact increase of SOC stocks, mainly due to the heterogeneity of soils even at small scales, making changes of carbon difficult to distinguish from natural variation. This is of special relevance if carbon credits shall be substantiated by field measurements and payments are only made based on measured increases. In general, the composition of soils has been identified as one of the main predictors for the storage potential of carbon in the soil, with the amount of fine particle (silt and clay) being correlated to the storage capacity for carbon (Hassink, 1997) and this is also considered in models such as CENTURY where the decomposition of soil carbon decreases with increased soil silt and clay content (Parton et al., 1987). Thus, a main research question would be how to utilize available biomass to bring into the soil most effectively, based on soil properties. A very relevant question would be how subsidies or similar mechanisms may be used to specifically target the most responsive soils and get the highest amount of carbon sequestration with the least amount of biomass.

3.5 Agroforestry and landscape elements

3.5.1 Introduction

Agroforestry is the implementation of trees on agricultural land, leading to a dual use of the land. This includes a large variety of systems, from traditional fruit orchards, Silvopastoral systems, which are meadows with trees that provide shade for the animals, to modern alley cropping systems with trees between agricultural field rows. Many agroforestry systems are established with the general aim of achieving a higher land use efficiency than each system alone, which could be in terms of yield but could also aim at providing other ecosystem services such as increased biodiversity and additional habitat for mammals and insects, erosion control or reduced nitrate leaching trough a better recycling of nutrients from deep rooting trees. If trees of significant economic value from timber or fruits are used, agroforestry systems also allow for an economic diversification. Traditional agroforestry systems, such as meadow orchards or forest meadows were very common in Switzerland (Kay et al., 2019b). Also, landscape elements such as shrubs and trees between fields, which were also of smaller patch size in the pasts, comprised a more diverse landscape in the mid-20th century, which has been partly lost in many parts of Europe as a by-product of agricultural intensification. In a way, the establishment of agroforestry systems can thus be seen as a transformation of agricultural systems back to their roots. Despite being much less present than in the pasts, traditional agroforestry systems are still found in many areas of Switzerland. An example are the silvopastoral meadows ("Wytweiden") in the Swiss Jura. These traditional agroforestry systems are usually used very extensively. Modern agroforestry systems in contrasts facilitate a higher intensity and are planned in a way that mechanization is allowed (e.g. alley cropping systems with distances of 20 m or greater between tree rows). Agroforestry systems can directly contribute to climate change mitigation by sequestering additional carbon in the tree biomass, the vegetation below the trees and additionally in the soil. Quantifying the additional carbon stored in the tree biomass is relatively simple at the field level, as it is easy to measure and can be derived from tree density and annual growth rates (Kay et al., 2019c), but due to the diversity of systems may still be difficult at the national level. Belowground carbon, especially soil carbon, are more difficult to access. There is a general understanding that agroforestry systems in tendency enhance soil carbon compared to sole arable cropping systems (Cardinael et al. 2020) but while in the mean there is soil carbon increase many studies also reported losses of soil carbon, especially when there was a change from high carbon systems such as grassland to agroforestry (Feliciano et al, 2018).

3.5.2 Policy context

While the use of Agroforestry systems as LMT for Switzerland has been briefly mentioned in the official Swiss report about promising LMT, there is no direct policy that supports the deployment of agroforestry as an LMT. However, agroforestry systems are still eligible to agricultural subsidies, and fruit trees are receiving special biodiversity-subsidies. However, timber tree agroforestry on the other hand are not subsidized, which is a disincentive to establish any agroforestry that are not fruit trees: The part of the field that they cover is not eligible to subsidies and their establishment could lead to the risk for farmers of losing subsidies. In some cantons in Switzerland (e.g. Solothurn, Heckenrichtlinie.pdf (so.ch)) there are laws to protect landscape elements such hedges and shrubs. In practice, some farmers report that these laws impede the re-implementation of agroforestry resembling landscape elements, as once planted, their removal will be prohibited by canton law. Employees of the Swiss Federal Office for the Environment and Federal Office for Agriculture reported in personal communication that there is the intent to include Agroforestry into the agricultural legislation, making it explicitly eligible for additional subsidies and maybe carbon credits, not limited to fruit trees. Yet this only in development, and recently the amendment of the law has been postponed until at least the year 2023. Nevertheless, different projects to study and promote agroforestry in Switzerland are going on at the moment, with several innovative farmers already implementing different agroforestry systems. Several networks exist including the Project Agro4esterie (Projet ressource Agro4esterie – Agroforst) and the AGRIDEA Agroforestry network (Agroforstsysteme - AGRIDEA (abacuscity.ch)). Also, the Swiss Confederation's centre of excellence for agricultural research, Agroscope, is interested in agroforestry and involved in several projects on the topic (Kontakt – Agroforst & AGROMIX | Coventry University). According to several actors involved in these projects the current interest of farmers in agroforestry is high, and finding enough farmers to implement agroforestry within the projects was easy. On the other hand, there are no research experiments in Switzerland with long-term agroforestry systems.

3.5.3 Current land use and potential land-use competition

Historically, the agricultural landscape was more fragmented than today and landscape elements as well as agroforestry systems were very common. Though there has been a decline due to agricultural intensification, traditional agroforestry systems still are common and make up 12 % of the Swiss farmland (Herzog et al, 2018). Of those systems, the most common systems, covering more than half of the area, are forest pastures, mostly located in the pre-alps and Jura mountains. Hedgerow agroforestry systems cover about a fourth of the agroforestry systems, traditional fruit orchards cover about a fifth of the area, while chestnut selva are a rare form of agroforestry system covering less than two percent of the area (Herzog et al, 2018). Though there is no clear projection how the development of modern agroforestry systems will change the area under agroforestry, it has been suggested that the adoption of agroforestry on an additional 13 % of the agricultural area could help to reduce simultaneously occurring deficits in the ecosystem service categories of biodiversity, climate change mitigation, air and water quality, as well as soil quality (Kay et al., 2019b). This is in general in alignment with a study across Europe, where 10 % of the area was identified as agroforestry priority area, facing deficits in at least five of the aforementioned ecosystem service categories (Kay et al. 2019c). In general agroforestry does not directly compete with other LMTs for land in Switzerland as, due to high pressure on land, major land-use changes are not feasible in Switzerland and it would only be established on land that is already of agricultural use. However, in some cases agroforestry systems provide lower crop yields on the same land area than arable systems (Kay et al., 2019c), in which case they may partly be in competition with food production. For example, Kay et al. (2018b) found that modelled crop yield of agroforestry systems in Switzerland was about a third less than in arable systems, while many other ecosystem services increased. Yet, the yield reduction is most pronounced in temperate agroforestry systems while in Mediterranean systems, where light and temperature are less limiting and shading may at times benefit the crops, higher yields were observed in agroforestry systems (Kay et al., 2018b). It may thus be, that with the inevitable climate change agroforestry systems may prove the more resilient agricultural systems. Another political question in Switzerland is, that whether agroforestry can be accounted as biodiversity area. At the moment Swiss farmers need to maintain 7% of their area as biodiversity area, and if regulations would be changed to include the tree growing areas from agroforestry into the definition of biodiversity area, the competition with agricultural food production land would be reduced.

3.5.4 Climate risks & sensitivities

Many of the climate risks and sensitivities such as heat waves, drought, heavy rains or forest fires are more pronounced in warmer climates. It is therefore an interesting finding that both in terms of yield and other ecosystems services the benefit of agroforestry systems is usually more pronounced in warmer climates (e.g. Feliciano et al., 2018; Kay et al., 2018b). Many ecosystem services are enhanced in agroforestry systems, with a very clear improvement in erosion control, biodiversity and soil fertility (Torralba et al., 2016). Under increased pressure from climate change these ecosystem services provided by agroforestry may increase in relevance. For example, the trees within the system often have the capacity to buffer heat waves and drought through a better microclimate and tapping into deeper water resources, which is beneficial to animals in grazing systems (Paris et al., 2019.) They also can reduce the effect of heavy rainfall by providing a canopy to protect soils from splash erosion and runoff erosion through root systems. In tropical systems, subject to high amounts of rainfall within short periods of time, for example, agroforestry systems reduce erosion by on average 50% (Muchane et al., 2020). One of the most pronounced benefits of agroforestry in Europe is the provisioning of biodiversity ecosystem services such as habitat for birds and pollinators or providing flowers to pollinators in the case of fruit trees (Kay et al., 2020).

3.5.5 Economic implications

The diversity of agroforestry systems is also represented in the economic feasibility. While hedgerows may slightly reduce the area available, with no further side-effects, other agroforestry systems such as alley cropping systems may increase the amount of labour required per land because they require pruning. In tropical agricultural systems, where agroforestry adoption has been studied in more detail, the labour costs are often limiting the adoption of improved agricultural management techniques such as agroforestry (Cavanagh et al., 2017). The same could be the case in Switzerland, where labour costs are very high, making pruning of agroforestry trees a very expensive matter, especially if the trees are only suitable for timber and do not provide any high value fruits. Yet, the Swiss agricultural policy provides many subsidies based on ecosystem services, e.g. for biodiversity areas, which include traditional fruit orchards (bff-spb.ch : Biodiversitätsförderflächen). If modern agroforestry systems such as alley cropping systems would be included in the subsidy schemes, providing payment for the additional ecosystem services that they provide, their implementation could well become profitable. Additional payments for carbon sequestration could further increase the economic feasibility of agroforestry systems. The cost of establishing an agroforestry system with about 50 trees ha^{-1} was estimated to be in the around 10.000 CHF but could be higher depending on special requirements by the canton (personal communication with Agroscope experts). The yearly sequestration of a typical AF system with 50 trees ha^{-1} given as 1.6 ton C ha^{-1} yr^{-1} (Kay et al., 2019b) which is roughly equal to 6 ton CO_2. Thus, with an expected lifetime of 20 years or more, one could estimate the cost per ton CO_2 to be below 100 CHF, not considering additional maintenance cost, but also not considering benefits such as additional fruit yields and ecosystem services. In fact, Kay et al. (2019a) estimated that when also considering the value of other ecosystem services, agroforestry in continental Europe would already become profitable starting at already 10 € ton^{-1} C (less than 3 € ton CO_2).

3.5.6 Co-benefits and trade-offs

In the worst case, the adoption of alley cropping agroforestry in Switzerland could lead to cereal yield reductions of up to 30% (Kay et al., 2018b), but this depends largely on the system, the row spacing and if the trees also provide a harvestable yield. However, it could be a relevant trade-off, especially since Switzerland is scarce in agricultural land and already importing larger portions of its food requirements. On the other hand, it is likely that a larger scale adoption of agroforestry would lead to a more diverse landscape providing many other ecosystem services apart from food production, including erosion control, increased biodiversity, habitat and food for pollinators and birds and enhanced soil fertility (Torralba et al., 2016). In addition, the inclusion of trees often makes landscapes more attractive as recreational areas. There have not been many studies of N_2O emissions in temperate agroforestry systems, but a general tendency of reduced N_2O emissions was reported (Acheamfour et al., 2017). For example, Moore et al. (2017) reported significantly lower cumulative N_2O emissions in agroforestry systems compared to agricultural systems. The same was reported by Wolz et al. (2018) with reductions in the N_2O emissions of alley cropping compared to normal agriculture between 25 and 83%. The trees in the system thus seem to have a very significant impact on the nitrogen cycle, which is even more profound with regard to leaching of nitrogen. For example, nitrate leaching was reduced between 82 and 91% in the study by Wolz et al. (2018). This is due to the safety net function of tree roots, which reach deeper than crop roots and can take up nutrients lost for the main crop (Allen et al., 2004). It has therefore been suggested to establish agroforestry primarily in areas that are subject to environmental issues such as reduced drinking water quality due to nitrate concentrations (Kay et al., 2019a). Apart from the mentioned risks and benefits, the additional provision of wood from agroforestry systems could be another benefit. If both the tree fruits and the crops are in demand and would alternatively have to be produced on separate areas, the agroforestry can lead to overall efficiency benefit, displaying in a land equivalent ratio (LER) >1. This seems to be the case in Mediterranean climates. For example, Arenas-Corraliza et al. (2018) reported a LER between 1.3 and 2 for a walnut cereal alley cropping system in central Spain. However, for temperate regions, such as Switzerland it is expected that the LER is rather around 1.2. As the establishment of an agroforestry system can be between 10.000 to 20.000 CHF, the question whether to establish agroforestry systems is mostly an economic one. The consideration includes economic value of the trees (e.g. from fruits), if there are already marketing structures for new tree products, additional labour requirements, and also the expected lifetime of the system compared to for example how long a farmer will still be active. While there are little environmentally negative side effects of agroforestry the trade-offs may rather be economical ones, especially if the length that additional subsidies are available, is unknown.

3.5.7 Risks associated with scaling up

The main risk of large agroforestry application is in the lack of systematic assessments of agroforestry systems in Switzerland. To date all agroforestry trials are established on farms and while they are academically accompanied, no design experiments are established in Switzerland, yet, which will likely start in the coming years. A risk could thus be that if agroforestry is scaled up too fast, there may, due to the lack of regional knowledge, be an establishment of unsuitable trees or systems. In the worst case, the trees of such systems could be removed quite easily, so the risk is mostly an economic risk of capital lost through establishment and clearing.

3.5.8 Research gaps

The largest research gaps in agroforestry in Switzerland is the about the application of modern alley cropping agroforestry systems. So far there have been scientific followings of on-farm establishments of agroforestry systems but controlled scientific design experiments including control treatments without trees yet need to be established. There is a need to better understand field-crop tree interactions to optimize alley-cropping agroforestry to Swiss conditions. Another major uncertainty is how climate change may affect both the modern and traditional Swiss agroforestry systems. The studies from Mediterranean areas suggest that with warmer temperatures and increased summer droughts, the benefits agroforestry systems increase, which make it especially attractive with regard to climate change. Yet, as soils in Switzerland are different from Mediterranean soils, such space-for-time predictions need to be treated with caution.

4. Conclusions

In general, Switzerland takes a pioneer role in negative emission technologies and LMTs. At the same time, land is scarce in Switzerland, so all LMTs are at least to some extent in competition with each other and with food production. The key stakeholders and policy makers in Switzerland seem to be aware of this and already think about how LMT portfolios could be designed to minimize potential trade-offs and apply each LMT where it leads to the least competition. For example, BECCS shall primarily use of waste materials. One the other hand, there is the awareness of the limitations of each LMT. BECCS, for example, which is already planned to play a key role in the Swiss LMT portfolio, lacks CO_2 storage facilities in Switzerland and Swiss policy makers are exploring storage options outside Switzerland. Biochar is identified as the only technology with a high permanence that is already available today, but it is too expensive to be competitive under current CO_2 prices and there are some societal prejudices to overcome for large-scale application. The short-term potential, co-benefits and low cost of agricultural management practices, such as reduced tillage and organic farming, are recognized. At the same time their non-permanence is seen as an issue, especially under future climate change. Finally, modern agroforestry systems are seen to have a significant potential and under a changing climate they may even enhance crop system resilience compared to monocrops. Yet, it is recognized that there is a lack of research on agroforestry in Switzerland and no long-term trials exist. As a result of the strengths and weaknesses of the different LMTs, a sequential adoption seems feasible to the authors of this report: We think that a Swiss LMT portfolio could start with a focus on LMTs that are based on agricultural management practices combined with an experimental implementation of modern agroforestry systems on a smaller scale. If modern agroforestry systems prove successful, they may be scaled up to larger agricultural areas. With time and increasing CO_2 prices, a larger scale application of biochar may then also become feasible and BECCS could come online as the last LMT, once technological readiness is reached and feasible storage facilities are found.

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ANNEX III

OVERVIEW OF INPUT TABLES FOR SIMULATION MODELLING PER COUNTRY

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6. Switzerland

6.1. Qualitative storylines by identifying measures and actions from interviews for each LMT scenario

Switzerland Organic Agriculture:

	1. Wishes of the future for the LMT: include timing	2. How to achieve the wishes • Who pays? • Who implements?	3. Target/Actions • Policies, strategies, projects
Scenario 1: "Max growth" **Stakeholder representations:** - FiBL - BioSuisse - IP-Suisse - TerraABC	• 30, 35 and 40% of arable land under organic agriculture by 2030,40 and 50	• Paying for pollution (polluter pays principle). Currently indirectly subsidized (e.g. Interview TerraABC) • Increase awareness for positive effects of OA increasing the demand for OA products in public canteens (e.g. Interview Regenerative CH) • Implementation by farmers to satisfy the demand by policy and society	• Higher subsidies for OA, financed via increasing CO2 prices. Full payments for companies in transition. • Loosening strictness of permanence for CO2 certification --> each t CO2 sequestered is positive (e.g. SH workshop J. Leifeld) • Reducing animal numbers in conventional livestock, consumption of animal products --> less area needed for livestock (summary of SH of various interviews)
Scenario 2: "Delayed growth " **Stakeholder representations:** - IP-Suisse	• 20, 25 and 30% of arable land under organic	• Consumer-only driven increase of OA (increased	• Awareness campaigns of environmental co-benefits (and health concerns)

- BioSuisse	agriculture by 2030,40 and 50	awareness) (e.g. Interview IP-Suisse; demand-driven)	• Local actions are main driver (e.g. “Community-supported agriculture)
Scenario 3: “Stagnating at current area “	• Area remains at about 20% of arable land	• No new resources directed	• No additional policies (e.g. SH workshop SBV, no additional money, not attractive to farmers)

Switzerland Reduced/ No-Tillage:

	1. What are the wishes of the future for the LMT: include timing	2. How to achieve the wishes • How much does it cost? • Who pays for the cost? • Who implements?	3. Actions • policies, strategies, projects
Scenario 1: “Focus on RT and NT expansion” **Stakeholder representations:** - Swiss NT - Regenerativ CH - T. Friedrich - SBV (see highest potential)	• By 2050, almost no areas with normal tillage remain. • 60% of area is RT, 20% NT by 2050 (relative % of NT increases), only 20% conventional tillage remain as exception areas • RT/NT in %: 2030, 40,6; 2040, 50, 12; 2050, 60, 20	• Subsidized through “Ressourceneffizienzbeiträge (up to 250 CHF ha-1 yr-1)“ • Implemented by farmers	• Subsidies further increased • More awareness campaigns on co-benefits of NT/RT (e.g., SNT-guides, paid by BAFU https://no-till.ch/publikationen/)
Scenario 2: ”RT increase but little NT ” **Stakeholder representations**: - SBV (want fair compensation)	• RT and NT are scaled slower, NT remains at niche (10% of NT and RT area combined, as current, Agrarbericht 2022 - Ressourceneffizienzbeiträge)	• Subsidized through “Ressourceneffizienzbeiträge (up to 250 CHF ha-1 yr-1)“ • Implemented by farmers	• No further increase in subsidies • A little additional money through CO2 market • Awareness raising only by private initiatives

	• RT/NT in 2030, 36/4%, 2040, 41/4.5%, 2050, 45/5% of arable land		
Scenario 3: "No change"	• RT remains at about 30% of arable land, also no increase in NT	• No new resources directed	• No additional policies (e.g. SH workshop SBV, no additional money, not attractive to farmers)

Switzerland Agroforestry:

	4. What are the wishes of the future for the LMT • include timing	5. How to achieve the wishes • How much does it cost? • Who pays for the cost? • Who implements?	6. Actions • policies, strategies, projects
Scenario 1: "Silvoarable and silvopasture" **Stakeholder representations:** - Agroscope interview (AF has highest additionality) - First climate	• Half of permanent grassland becomes silvopasture land. 2030: 10%, 2040, 25% 2050, 50% • Experimental application of silvoarable on 10% of arable land. 2030: 2%, 2040, 4% 2050, 10%	• Paid through Swiss government: Biodiversitätsbeiträge (admin.ch) • Implemented by farmers and owners of land • Additional payments through CO2 certificates for trees	• Subsidies for silvopasture and silvoarable • Subsidies further increased • Awareness campaigns of agroforestry co-benefits • Additional research for most suitable silvoarable systems in Switzerland
Scenario 2: "Only silvopasture" **Stakeholder representations**: - Agroscope interview (AF has highest additionality) - SBV interview (limited potential)	• 30% of permanent grassland becomes silvopasture land. 2030: 5%, 2040, 15% 2050, 30%	• Paid through Swiss government: Biodiversitätsbeiträge (admin.ch)	• Subsidies only for silvopasture • Awareness campaigns of agroforestry co-benefits

	• No expansion to arable land due to land pressure	• Implemented by farmers and owners of land • Additional payments through CO2 certificates for trees	
Scenario 3: "No agroforestry " -	• No relevant increase in agroforestry area (stagnates at ~2% of agriculture area (arable + pasture land)).	• No new resources directed	• No additional policies (e.g. SH workshop SBV, no additional money, not attractive to farmers)

6.2. Quantitative storylines: pace of implementation for each LMT

	Current situation (baseline)	**SCEN-"Max out all" SH perspective:**		**SCEN-"Medium ambition" SH perspective:**		**SCEN-" Low hanging fruits" SH perspective**	
Year	Now (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 (change relative to the current situation) (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 (change relative to the current situation) (provide sources)	2030 (change relative to the current situation) (provide sources)	2050 (change relative to the current situation) (provide sources)
LMT 1: OA	18% Agrarbericht 2022 - Produktionssystembeiträge	24% of area is organic	30% of area is organic (area is limited by RT/NT)	20% of area is organic	25% of area is organic	20% of area is organic	22% of area is organic
LMT 2: RT/NT	RT~18% of arable land NT~2% Agrarbericht 2022 - Ressourceneffizienzbeiträge	30% RT 6% NT	50% RT 20% NT	25% RT 4% NT	40% RT 10% NT	25% RT 3% NT	40% RT 4% NT
LMT 3: Agroforestry	~2% Biodiversitätsbeiträge (admin.ch)	10% silvopasture 2% silvoarable	50% silvopasture 10% silvoarable	5% silvopasture 1% silvoarable	35% silvopasture 5% silvoarable	5% silvopasture 0% silvoarable	20% silvopasture 0% silvoarable