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# Life cycle assessment of different biochar application scenarios in Swiss agriculture

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# Table of Contents

# Summary

Climate change poses significant challenges and risks to agriculture. However, agriculture also emits greenhouse gases (GHG). The pyrolysis of biomass and the use of the produced biochar in agriculture are approaches that can serve both climate change mitigation and adaptation. Since a large fraction of the carbon in the biochar is stable for a long time after application to the soil, biochar application to soils can serve as a negative emission technology (NET). In agriculture, biochar use can improve animal welfare and nutrient recycling as well as enhance soil properties by improving nutrient retention and soil organic carbon (SOC) built-up. The Swiss Federal Council's long-term climate strategy, which aims for net-zero greenhouse gas (GHG) emissions by 2050, emphasises the role of biomass and biochar in achieving negative emissions while addressing competition for biomass resources. Despite numerous studies demonstrating the various effects of biochar in different contexts (geography/climate, type of use, etc.), there is no comprehensive overview of the environmental effects—from production to the application of biochar—at the level of a Swiss farm.

The main objective of this study was therefore to analyse the climate change impact of biochar production and application across the entire Swiss agricultural value chain quantified by the 100-year time horizon global warming potential (GWP100), hereinafter referred to as GWP for simplicity, using life cycle assessment (LCA). In Switzerland, biochar is often not applied directly to the soil; instead, it is used in animal husbandry (feed additive, animal bedding), so that it enters the soil as part of the manure. Given the potential effects of biochar at various levels beyond its application (e.g. in animals, on the air quality in the stable, in the manure, etc.), this is also referred to as cascade use.

To quantitatively assess changes in emissions and climate change due to on-farm biochar applications, we defined eight biochar application scenarios for different entry points of biochar:

(1) Biochar mixed into animal bedding (equivalent to 1% of the feed, mass equivalent)
(2) Biochar mixed into animal bedding (10% straw volume)
(3) Biochar as a swimming layer in manure storage as an example of an innovative manure management strategy[1]
(4) Direct biochar application to soil (1000 kg/ha)
(5) Direct biochar application to soil (5000 kg/ha)
(6) Combination of scenarios 1, 3, and 4
(7) Combination of scenarios 2, 3, and 5
(8) Combination of scenarios 1 and 4

The combination Scenarios 6–8 allowed the estimation of the combined effects of biochar application at various entry points, such as animal bedding, liquid manure storage, and direct soil application. In the scenarios, we considered the following effects of biochar application based on the literature and expert judgment:
(i) animal feed and bedding: sorption of 1 g nitrogen (N) per kg of biochar,
(ii) manure (slurry): biochar as a swimming layer on uncovered manure storage. Here, we assumed a 60% reduction of $NH_3$ emissions compared to non-covered manure storage.
iii) biochar directly applied to soil, leading to two effects: (a) reduction of $NO_3$ leaching of up to 13% and (b) 13% reduction in $N_2O$ emissions once total biochar application exceeded 5 t $ha^{-1}$. It should be noted that these modelled effects remain uncertain since they are influenced by various factors.

To obtain generalisable results that could be extrapolated to the whole of Switzerland, "model farms" were defined and subjected to LCA to investigate scenarios with biochar compared to non-biochar baseline scenario. These model farms represent farms that typically apply biochar. The model farms were used to evaluate the impact of the biochar application scenarios and the upscaling to the Swiss agricultural sector. Based on the survey by Dittmann and Baumann (2023) and the 2023 census data from the farm structure survey, we defined three model farms, with a focus on dairy, pig, and vegetable production, representing 4096, 939, and 654 farms, respectively. The findings from

[1] Many options for using biochar in slurry manure management have been suggested. We selected this option based on data availability.

these three model farms were extrapolated to a national scale using the number of farms that each model farm represents.

We investigated the climate change impact separately for the (i) animal/field emissions due to biochar cascade using (ii) the carbon sequestration potential of biochar and (iii) the production of biochar. In the following, we provide the results for on-farm emissions related to the biochar cascade use, followed by the expected carbon sequestration. Note that the quantitative results from this study for the carbon sequestration potential of biochar and its production are well supported by the comprehensive literature. However, it is important to acknowledge the uncertainties associated with the animal/field emissions and the cascading use of biochar: Variability in application techniques, and climate and soil conditions can significantly influence the effects of biochar in different contexts. Therefore, we emphasise the need for caution in interpreting changes in emissions on the fields as well as in stables related to the use of biochar.

In the model, Scenarios 1 and 2 reduce the direct C and N field emissions and the direct animal emissions. The GWP is reduced for both scenarios by approximately 0.05 kg $CO_2$-eq, 0.03 kg $CO_2$-eq, and 0.04 kg $CO_2$-eq per year and per kg of biochar used on dairy, pig, and vegetable farms, respectively, when compared to baseline farms. Furthermore, as in all of the following scenarios, biochar in soil stores 2.51 kg $CO_2$-eq of carbon per kg of biochar, as detailed below. The decrease in direct animal emissions can be explained by the sorption capacity of biochar, sorbing nitrogen of animal excrements and reducing $NH_3$ volatilisation, and $N_2O$ emissions from the bedding. The decrease in direct field emissions can be explained by lower $N_2O$ emissions and $NO_3$ leaching due to the application of liquid manure mixed with biochar. The model results show that the decrease in direct C and N field emissions is markedly higher than the reduction in direct animal emissions.

Scenario 3 is the only scenario that shows for all three model farms a *higher* GWP when compared to the baseline, exhibiting an increase of 1.48, 2.07, and 0.40 kg $CO_2$-eq per year and per kg of biochar used on dairy farm, pig farm, and vegetable farm, respectively, when compared to baseline farms. The direct animal emissions decrease, but the direct field emissions increase such that it leads to an increase in GWP compared to the baseline. In the model, the decrease in direct animal emissions can be explained by the reduced $NH_3$ emissions induced by the (biochar) cover of manure storage. The increase in direct field emissions is related to the increased nitrogen content of the manure, resulting in higher $N_2O$ field emissions and $NO_3$ leaching after its application in fields. It is worth noting that the GWP per kg of biochar used changes most in Scenario 3. This is directly related to the largely reduced ammonia emissions from manure storage (and the increased nitrogen content in the manure) that are covered with a swimming biochar layer.

Scenarios 4 and 5 investigate the direct soil application of biochar in vegetable production. The application of 1000 and 5000 kg biochar $ha^{-1}$ (Scenarios 4 and 5, respectively) only affects direct C and N field emissions by a reduction in GWP of 0.05 kg $CO_2$-eq and 0.02 kg $CO_2$-eq per kg of biochar, respectively. The results per scenario barely differ among the three analysed model farms. As the model vegetable farm has, by definition, much more vegetable areas than the dairy and pig farms (12.15 ha compared to 0.24 ha and 0.30 ha, respectively), it is evident that the total applied amount of biochar and thus the induced change of the direct field emissions is by far highest for the vegetable farms modelled. The application of 5000 kg $ha^{-1}$ exceeds the maximum annual application rate according to the Fertilizer Ordinance (DüV, 2023) but was calculated here to investigate the effects of the accumulation of biochar at the permissible repeated application rate of up to 10 t $ha^{-1}$ over 20 years.

Scenarios 6–8 reveal that the effect on the GWP is not equal to the sum of its parts in the model. The main reason for this discrepancy is related to the used threshold value of 13% nitrate leaching reduction, which is assumed to be constant for biochar applications of more than 1 t $ha^{-1}$. Another reason is the sorption of N by the biochar when added in the bedding, which reduces $NH_3$ and $N_2O$ emissions from the animal bedding as well as from the manure storage, as the N sorption still occurs in the biochar containing manure. Consequently, both contribution groups “Direct field emissions of C & N” and “Direct animal emissions” are influenced by the combination of entry points and show different modelled results as the sum of the biochar effects from single entry points.

To analyse the environmental impact of biochar application from all life-cycle stages in the model, it is of interest to compare the changes in GWP induced by on-farm biochar application scenarios to that of biochar production. The GWP for biochar production in state-of-the art facilities, which produce biochar for agriculture in agreement with current regulations for air and fertiliser quality, was calculated based on available data adapted to current Swiss conditions for the following three feedstocks: forest wood chips, landscape conservation wood, and straw. Our calculations resulted in 0.153, 0.063, and 0.373 kg $CO_2$-eq emissions for the production of 1 kg biochar, which stores 2.5, 2.5, and 2.1 kg $CO_2$-eq for at least 100 years (according to IPCC (2019) method), respectively. These distinct differences in emissions can be mainly attributed to different feedstocks for the production of biochar, as well as different feedstock amounts needed to produce 1 kg of biochar. Differences in carbon storage per 1 kg of biochar arise from the different carbon content of the biochar, which is lower in straw-based biochar.

In the total change in GHG emissions from biochar usage (accounting for biochar production, biochar cascade use, and carbon sequestration), this LCA study has shown that the by far most important contribution to mitigating climate change is the potential of biochar to sequester $CO_2$ in the soil. This positive effect of carbon sequestration from biochar application on soils markedly exceeds the modelled contribution of changes in the direct field and animal emissions in the first year after application by more than a factor of 50 for all investigated scenarios, excluding Scenario 3. However, the effects of biochar in soil remain in the following years and thereby will continue to reduce the negative side effects of agriculture, such as reduction of nitrate leaching.

Our results show that the net GWP (production of biochar, emissions due to biochar cascade use, and carbon sequestration) decreases – independently of the entry point of biochar application—by 2.40 kg $CO_2$-eq per kg biochar added in all scenarios except Scenario 3.

Extrapolating our findings to the entire agricultural sector in Switzerland (which is represented here by the model farms) shows that the GWP can be reduced by up to approximately 411,000 t $CO_2$-eq, corresponding to nearly 4.9% of the total GWP ("total" refers to the GWP of the baseline of the three model farms extrapolated to the part of Switzerland they represent). Note, however, that this result is based on Scenario 7 with a 5 t $h^{-1}$ application of biochar, which is currently not allowed according to the Swiss regulation that restricts the direct application to soil to 1 t $h^{-1}$ $year^{-1}$. Scenario 2 leads to the largest reduction in GWP (3.6% corresponding to around 301,680 t $CO_2$-eq) which fulfils the current legal requirements. Again, these results need to be interpreted with caution, as animal/field emission modelling linked to biochar use is highly dependent on application techniques, animal housing system, and climate and soil conditions.

In Switzerland, biochar production and use are subject to strict regulations regarding pollutant content and application quantities, which ensures that its use is safe. Although the quantifiable benefits of biochar use beyond carbon sequestration remain limited, its use can be a tool for both climate change mitigation and adaptation in agriculture. It should be seen as a tool that should be used in conjunction with other measures wherever possible, as it is not a stand-alone solution.

# Zusammenfassung

Die Landwirtschaft steht angesichts des Klimawandels grossen Herausforderungen und Risiken gegenüber. Allerdings emittiert sie selbst auch Treibhausgase (THG). Die Pyrolyse von Biomasse und der Einsatz der dabei produzierten Pflanzenkohle in der Landwirtschaft können gleichzeitig sowohl zum Klimaschutz als auch zur Anpassung an den Klimawandel beitragen. Da ein grosser Anteil des in Pflanzenkohle enthaltenen Kohlenstoffs über lange Zeiträume im Boden stabil bleibt, lässt sich ihre Ausbringung als Negativemissionstechnologie (NET) betrachten. Pflanzenkohle kann in der Landwirtschaft Tiergesundheit und Nährstoff-Recycling fördern und die Bodeneigenschaften durch eine optimierte Nährstoffspeicherung und den Aufbau von organischem Kohlenstoff im Boden (SOC) verbessern. In der langfristigen Klimastrategie des Schweizer Bundesrats, die bis 2050 das Netto-Null-Ziel für Treibhausgase anstrebt, wird die Rolle der Biomasse und der Pflanzenkohle bei der Erzielung negativer Emissionen erwähnt, aber auch der Wettbewerb um Biomasse-Ressourcen betont. Obwohl die vielfältigen Wirkungen von Pflanzenkohle in verschiedenen Kontexten (Geografie/Klima, Nutzungsart usw.) in zahlreichen

Studien belegt wurden, fehlt bislang eine umfassende Übersicht über die Umweltauswirkungen von Pflanzenkohle – von der Produktion bis zur Anwendung – auf der Ebene der Landwirtschaftsbetriebe in der Schweiz.

Die vorliegende Studie soll daher primär die Auswirkungen der Herstellung und Anwendung von Pflanzenkohle auf den Klimawandel in der gesamten landwirtschaftlichen Wertschöpfungskette der Schweiz analysieren. Dazu wird das globale Erwärmungspotenzial über einen Zeitraum von 100 Jahren (GWP100, nachstehend vereinfachend als GWP bezeichnet) unter Verwendung der Ökobilanzen (LCA) quantifiziert. In der Schweiz wird Pflanzenkohle oft nicht direkt auf den Boden ausgebracht, sondern in der Tierhaltung (Futterzusatz, Stalleinstreu) eingesetzt, sodass sie schliesslich über den Hofdünger in den Boden gelangt. Die applizierte Pflanzenkohle wirkt sich potenziell auf verschiedenen Ebenen aus (z. B. Tiere, Luftqualität im Stall, Hofdünger usw.); deshalb ist auch von der Kaskadennutzung die Rede.

Um die Auswirkungen der Applikation von Pflanzenkohle in Landwirtschaftsbetrieben auf Emissionen und Klimawandel quantitativ zu evaluieren, wurden acht Szenarien mit verschiedenen Eintragspunkten definiert:

(1) Pflanzenkohle vermischt mit Einstreu (entspricht 1 Gewichts% des Futtermittels)
(2) Pflanzenkohle vermischt mit Einstreu (10 % des Strohvolumens)
(3) Pflanzenkohle als Schwimmschicht in Güllebehältern als Beispiel einer innovativen Strategie zur Hofdüngerbewirtschaftung[2]
(4) Direkte Applikation von Pflanzenkohle in den Boden (1000 kg/ha)
(5) Direkte Applikation von Pflanzenkohle in den Boden (5000 kg/ha)
(6) Kombination der Szenarien 1, 3 und 4
(7) Kombination der Szenarien 2, 3 und 5
(8) Kombination der Szenarien 1 und 4

Die kombinierten Szenarien 6–8 ermöglichen es, die Auswirkungen der Pflanzenkohle-Applikation an verschiedenen Eintragspunkten (z. B. Einstreu, Güllebehälter, direkte Applikation in den Boden) abzuschätzen. In den Szenarien wurden gestützt auf Fachliteratur und Expertenmeinungen die folgenden Auswirkungen der Anwendung von Pflanzenkohle untersucht:
(i) Tierfutter und Einstreu: Sorption von 1 g Stickstoff (N) pro kg Pflanzenkohle,
(ii) Dünger (Gülle): Pflanzenkohle als Schwimmschicht auf offenen Güllebehältern. Hier wurde im Vergleich zu nicht abgedeckten Güllebehältern von einer Reduktion der $NH_3$-Emissionen um 60 % ausgegangen.
iii) Direkte Applikation von Pflanzenkohle im Boden: führt zu folgenden zwei Wirkungen (a) Reduktion der $NO_3$-Auswaschung um bis zu 13 %, (b) Reduktion der $N_2O$-Emissionen um 13 %, sobald die Gesamtmenge der applizierten Pflanzenkohle 5 t $ha^{-1}$ übersteigt. Es ist zu beachten, dass aufgrund verschiedener Faktoren eine gewisse Unsicherheit in Bezug auf die modellierten Effekte besteht.

Um Ergebnisse zu erzielen, die verallgemeinerbar und auf die ganze Schweiz übertragbar sind, wurden «Modellbetriebe» definiert. Für diese wurden die Szenarien mit Pflanzenkohle mit dem Referenzszenario ohne Pflanzenkohle verglichen. Die Modellbetriebe repräsentieren Landwirtschaftsbetriebe, auf denen bereits heute Pflanzenkohle eingesetzt wird. Anhand der Modellbetriebe wurden die Auswirkungen der verschiedenen Szenarien, in denen Pflanzenkohle angewendet wird, evaluiert und auf die Schweizer Landwirtschaft extrapoliert. Gestützt auf die Erhebung von Dittmann und Baumann (2023) zu Betrieben, die Pflanzenkohle einsetzen und die Daten der Landwirtschaftlichen Strukturerhebung von 2023 wurden drei Modellbetriebe mit Fokus auf Milch-, Schweine- oder Gemüseproduktion definiert, die 4096, 939 bzw. 654 Betriebe repräsentieren. Die Erkenntnisse zu den drei Modellbetrieben wurden anhand der Anzahl repräsentierter Betriebe auf die nationale Ebene extrapoliert.

Die Auswirkungen des Klimawandels wurden separat untersucht: für (i) Tier-/Feldemissionen aufgrund der Kaskadennutzung von Pflanzenkohle, unter Nutzung (ii) des C-Sequestrierungspotenzials von Pflanzenkohle und (iii) für die Herstellung von Pflanzenkohle. Nachstehend werden zuerst die Ergebnisse der durch die Kaskadennutzung der Pflanzenkohle verursachten Emissionen auf dem Betrieb beschrieben, anschliessend wird auf

[2] Für den Einsatz von Pflanzenkohle in der Hofdüngerbewirtschaftung wurden viele Optionen vorgeschlagen. Die vorliegende Option wurde wegen der Verfügbarkeit der Daten ausgewählt.

die erwartete C-Sequestrierung eingegangen. Die quantitativen Studienergebnisse zum C-Sequestrierungspotenzial von Pflanzenkohle und deren Herstellung sind durch die Fachliteratur gut abgestützt. Bei den Tier-/Feldemissionen und zur Kaskadennutzung von Pflanzenkohle gibt es jedoch gewisse Unsicherheiten, die betrachtet werden sollten: Die Auswirkungen der Pflanzenkohle variieren je nach Art der Anwendung sowie Klima- und Bodenbedingungen erheblich. Die durch die Pflanzenkohle-Applikation ausgelösten Änderungen der Emissionen aus Ackerbau und Viehzucht sind deshalb mit Vorsicht zu interpretieren.

Im Modell werden in Szenario 1 und 2 die direkten C- und N-Feldmissionen sowie die direkten Tieremissionen reduziert. Das GWP wird in beiden Szenarien im Vergleich zu den Referenzbetrieben um etwa 0,05 kg $CO_2$-Äquivalent im Milchviehbetrieb, um 0,03 kg $CO_2$-Äquivalent im Schweinbetrieb und um 0,04 kg $CO_2$-Äquivalent im Gemüsebetrieb reduziert. Dies bezieht sich auf ein Jahr und 1 kg eingesetzte Pflanzenkohle. Zudem wird durch Pflanzenkohle im Boden – in allen folgenden Szenarien – 2,51 kg $CO_2$-Äquivalent Kohlenstoff pro kg Pflanzenkohle gespeichert (s. Einzelheiten unten). Die Abnahme der direkten Tieremissionen erklärt sich aus der Sorptionskapazität von Pflanzenkohle, die Stickstoff aus tierischen Ausscheidungen bindet und die Verflüchtigung von $NH_3$ sowie $N_2O$-Emissionen aus der Einstreu reduziert. Die Abnahme der direkten Feldemissionen erklärt sich daraus, dass die Ausbringung von mit Pflanzenkohle versetzter Gülle die $N_2O$-Emissionen und die $NO_3$-Auswaschung reduziert. Die Modellergebnisse zeigen, dass die direkten C- und N-Feldemissionen deutlich stärker abnehmen als die direkten Tieremissionen.

Nur Szenario 3 weist gegenüber dem Referenzszenario bei allen drei Modellbetrieben ein höheres GWP auf, nämlich (verglichen mit den Referenzszenarien) eine Zunahme von 1,48, 2,07 bzw. 0,40 kg $CO_2$-Äquivalent pro Jahr und pro kg in Milchvieh-, Schweine- bzw. Gemüsebetrieben eingesetzter Pflanzenkohle. Die direkten Tiermissionen nehmen ab, aber die direkten Feldemissionen steigen an, sodass das GWP gegenüber dem Referenzwert auch zunimmt. Im Modell erklärt sich die Abnahme der direkten Tieremissionen daraus, dass in (mit Pflanzenkohle) abgedeckten Güllebehältern weniger $NH_3$-Emissionen entstehen. Die Zunahme der direkten Feldemissionen hängt mit dem erhöhten Stickstoffgehalt des Hofdüngers zusammen; dies führt nach der Düngerausbringung auf dem Feld zu höheren $N_2O$-Feldemissionen und einer höheren $NO_3$-Auswaschung. In Szenario 3 ändert sich das GWP pro kg verwendeter Pflanzenkohle am stärksten. Dies hängt direkt mit der weitgehenden Reduktion der Ammoniakemissionen aus den mit einer Pflanzenkohle-Schwimmschicht abgedeckten Güllebehältern (und dem höheren Stickstoffgehalt der Gülle) zusammen.

In den Szenarien 4 und 5 wird die direkte Applikation von Pflanzenkohle in den Boden im Gemüseanbau untersucht. Die Applikation von 1000 und 5000 kg Pflanzenkohle $ha^{-1}$ (Szenario 4 und 5) wirkt sich nur auf die direkten C- und N-Feldemissionen aus: Das GWP wird um 0,05 kg $CO_2$-Äquivalent bzw. um 0,02 kg $CO_2$-Äquivalent pro kg Pflanzenkohle reduziert. Die Ergebnisse für die verschiedenen Szenarien unterscheiden sich in den drei analysierten Modellbetrieben nur geringfügig. Gemüse-Modellbetriebe verfügen definitionsgemäss über deutlich mehr Gemüseanbauflächen als Milchvieh- und Schweinehaltungsbetriebe (12,15 ha gegenüber 0,24 ha bzw. 0,30 ha); daher ist bei ersteren die insgesamt applizierte Menge Pflanzenkohle und die entsprechende Änderung der direkten Feldemissionen am grössten. Die Applikation von 5000 kg $ha^{-1}$ liegt zwar über der maximalen jährlichen Ausbringung gemäss Düngerverordnung (DüV, 2023), wurde aber hier berechnet, um die Auswirkungen der Anreicherung von Pflanzenkohle bei einer zulässigen wiederholten Ausbringungsmenge von bis zu 10 t $ha^{-1}$ über 20 Jahre zu untersuchen.

Die Szenarien 6 bis 8 zeigen, dass die Auswirkung der kombinierten Eintragspfade auf das GWP nicht der Summe der einzelnen Betrachtungen im Modell entspricht. Hauptgrund für die Abweichung ist der verwendete Schwellenwert von 13 % Reduktion der Nitratauswaschung, der für eine Pflanzenkohle-Applikation von über 1 t $ha^{-1}$ als konstant angenommen wird. Ein weiterer Grund ist die Sorption von N durch die der Einstreu beigemischten Pflanzenkohle. Dadurch reduzieren sich die $NH_3$- und $N_2O$-Emissionen aus der Einstreu und aus der Hofdüngerlagerung, da die N-Sorption im mit Pflanzenkohle versetzten Dünger weiterhin erfolgt. Beide Beitragsgruppen – «direkte Feldemissionen von C und N» und «direkte Tiermissionen» – werden durch die gewählte Kombination der Eintragspunkte beeinflusst. Dabei unterschiedet sich die Summe aus den Einzeleffekten vom Resultat, wenn PK gleichzeitig an mehreren Eintragspunkten eingebracht wird.

Um die Umweltauswirkungen der Ausbringung von Pflanzenkohle in allen Lebenszyklusstadien im Modell zu analysieren, ist es von Interesse, die durch die Szenarien der Ausbringung von Pflanzenkohle in landwirtschaftlichen Betrieben verursachten Änderungen des Treibhauspotenzials mit denen der Pflanzenkohleproduktion zu vergleichen. Das GWP der Herstellung von Pflanzenkohle in modernen Anlagen, die den Vorgaben für Lufthygiene und des Düngerrechts genügen, wurde mit verfügbaren Daten zu den aktuellen schweizerischen Bedingungen für die drei Ausgangsstoffe Waldholzschnitzel, Landschaftspflegeholz und Stroh berechnet. Unsere Berechnungen ergaben Emissionen von 0,153, 0,063 und 0,373 kg $CO_2$-Äquivalent für die Herstellung von 1 kg Pflanzenkohle, die mindestens 100 Jahre lang 2,5, 2,5 bzw. 2,1 kg $CO_2$-Äquivalent speichert (gemäss der Methode des IPCC (2019)). Diese deutlichen Differenzen bei den Emissionen gehen primär auf die unterschiedlichen Ausgangstoffe und die unterschiedlichen davon benötigten Mengen für die Herstellung von 1 kg Pflanzenkohle zurück. Aus Stroh gewonnene Pflanzenkohle weist einen geringeren Kohlenstoffgehalt auf, was die Differenzen bei der Kohlenstoffspeicherung pro kg Pflanzenkohle erklärt.

Diese Ökobilanzstudie zeigt, dass im gesamten Lebenszyklus der Pflanzenkohle (Produktion, Kaskaden-nutzung und C-Sequestrierung) die-Sequestrierung den bei weitem wichtigsten Klimaschutzfaktor darstellt. Der positive Effekt der C-Sequestrierung aufgrund der Applikation von Pflanzenkohle in den Boden fällt in allen untersuchten Szenarien (ausgenommen Szenario 3) über 50-mal stärker ins Gewicht als die modellierten Änderungen der direkten Feld- und Tieremissionen im ersten Jahr nach der Applikation. Die Pflanzenkohle zeigt jedoch auch in den Folgejahren noch Wirkung im Boden und trägt daher weiter zur Abmilderung der unerwünschten Nebeneffekte der Landwirtschaft bei, z. B. durch die Reduktion der Nitratauswaschung.

Unsere Ergebnisse zeigen, dass das Netto-GWP (Herstellung von Pflanzenkohle, Emissionen infolge der Kaskadennutzung und C-Sequestrierung) unabhängig vom Eintragspunkt in allen Szenarien (ausser Szenario 3) pro kg applizierte Pflanzenkohle um 2,40 kg $CO_2$-Äquivalent sinkt.

Die Extrapolation der Erkenntnisse auf die gesamte Schweizer Landwirtschaft (hier durch die Modellbetriebe repräsentiert) zeigt eine mögliche Reduktion des GWP um rund 411 000 t $CO_2$-Äquivalente. Dies entspricht beinahe 4,9 % des gesamten GWP («gesamt» bezieht sich auf das GWP des Referenzwerts der drei Modellbetriebe, extrapoliert auf den jeweils repräsentierten Teil der Schweiz). Dieses Ergebnis beruht indessen auf Szenario 7 mit einer Pflanzenkohle-Applikation von 5 t $h^{-1}$, was heute gemäss der DüV, die die direkte Applikation in den Boden auf 1 t $h^{-1}$ $Jahr^{-1}$ beschränkt, nicht zulässig ist. Szenario 2 führt zur stärksten Reduktion des GWP (3,6 %, d. h. rund 301 680 t $CO_2$-Äquivalent) bei Einhaltung der aktuellen gesetzlichen Kriterien. Auch diese Ergebnisse sind mit Vorsicht zu interpretieren, da die Modellierung der Emissionen von Tieren und Feldern im Zusammenhang mit der Verwendung von Pflanzenkohle stark von den Ausbringungsmethoden, dem Haltungssystem der Tiere sowie den Klima- und Bodenbedingungen abhängt.

In der Schweiz gelten bei Herstellung und Verwendung von Pflanzenkohle strenge Vorschriften zu Schadstoffgehalt und Anwendungsmengen. Dadurch ist eine sichere Nutzung gewährleistet. Obwohl die Verwendung von Pflanzenkohle neben der C-Sequestrierung nur begrenzte quantifizierbare Vorteile bietet, kann sie in der Landwirtschaft als Instrument für Klimaschutz und Anpassung an den Klimawandel dienen. Pflanzenkohle stellt keine Patentlösung dar, sondern sollte nach Möglichkeit als Instrument zusammen mit anderen Massnahmen eingesetzt werden.

# Résumé

L'agriculture est confrontée à des défis et à des risques majeurs liés au changement climatique, tout en étant elle-même source d’émissions de gaz à effet de serre (GES). La pyrolyse de la biomasse et l'utilisation du charbon végétal dans l'agriculture représentent des solutions pouvant à la fois contribuer à la protection du climat et permettre de s’adapter au changement climatique. Étant donné qu'une grande partie du carbone contenu dans le charbon végétal reste stable pendant longtemps après son application dans le sol, celle-ci peut donc être considérée comme une technologie à émissions négatives (NET). Le charbon végétal peut favoriser la santé animale et le recyclage des éléments nutritifs dans l'agriculture et améliorer les propriétés du sol en optimisant le stockage de ces éléments

et en favorisant la formation de carbone organique dans le sol (SOC). La stratégie climatique à long terme du Conseil fédéral suisse, qui vise la neutralité carbone d'ici 2050, mentionne le rôle de la biomasse et du charbon végétal dans la réalisation d'émissions négatives, mais souligne également la concurrence croissante pour les ressources en biomasse. Bien que les multiples effets du charbon végétal aient été démontrés dans de nombreuses études réalisées dans différents contextes (géographie/climat, type d'utilisation, etc.), il n'existe à ce jour aucune synthèse exhaustive des impacts environnementaux du charbon végétal – de la production à l'utilisation – à l'échelle des exploitations agricoles en Suisse.

La présente étude a pour principal objectif d'analyser les effets de la production et de l'utilisation du charbon végétal sur le changement climatique tout au long de la chaîne de valeur agricole en Suisse. A cet effet, le potentiel de réchauffement global sur 100 ans (PRG100, ci-après simplifié en PRG) est quantifié à l'aide d'analyses du cycle de vie (ACV). En Suisse, le charbon végétal n'est souvent pas épandu directement sur les sols, mais utilisé dans l'élevage (complément alimentaire, litière) avant de se retrouver dans le sol via les engrais de ferme. L'application du charbon végétal impacte ainsi plusieurs niveaux (animaux, qualité de l'air dans les étables, engrais de ferme, etc.), d'où l'utilisation du terme «utilisation en cascade»

Afin d'évaluer les effets de l'application de charbon végétal dans les exploitations agricoles sur les GES et le changement climatique d'un point de vue quantitatif, huit scénarios avec différents points d'entrée ont été définis:

(1) Charbon végétal mélangé à de la litière (correspond à 1 % du poids de la ration alimentaire animale)
(2) Charbon végétal mélangé à de la litière (10 % du volume de paille)
(3) Charbon végétal formant une couche flottante dans des réservoirs à lisier, exemple d'une stratégie innovante de gestion des engrais de ferme[3]
(4) Application directe de charbon végétal dans le sol (1000 kg/ha)
(5) Application directe de charbon végétal dans le sol (5000 kg/ha)
(6) Combinaison des scénarios 1, 3 et 4
(7) Combinaison des scénarios 2, 3 et 5
(8) Combinaison des scénarios 1 et 4

Les scénarios combinés 6 à 8 permettent d'estimer les effets cumulés de l'application de charbon végétal à différents points d'entrée (p. ex. litière, réservoir à lisier et application directe dans le sol). Sur la base de la littérature spécialisée et des avis d'experts, les impacts suivants de l'utilisation du charbon végétal ont été pris en compte dans ces scénarios:
(i) Alimentation animale et litière: adsorption de 1 g d'azote (N) par kg de charbon végétal,
(ii) Engrais (lisier): charbon végétal formant une couche flottante dans les réservoirs de lisier non couverts. Dans ce cas, une réduction des émissions de $NH_3$ de 60 % par rapport à des réservoirs de lisier non couverts a été prise comme hypothèse.
iii) Application directe de charbon végétal dans le sol: entraîne les deux effets suivants (a) réduction du lessivage de $NO_3$ jusqu'à 13 %, (b) réduction des émissions de $N_2O$ de 13 % dès que la quantité totale de charbon végétal appliquée dépasse 5 t $ha^{-1}$. Il convient de noter qu'en raison de différents facteurs, il existe une certaine incertitude quant aux effets modélisés.

Afin d'obtenir des résultats généralisables et transposables à l'ensemble du territoire suisse, des «exploitation-types» ont été définies. Pour chacune d'elles, les scénarios intégrant l'usage du charbon végétal ont été comparés au scénario de référence sans charbon végétal. Les exploitations-types représentent les exploitations agricoles qui utilisent généralement du charbon végétal. À partir de ces modèles, les effets des différents scénarios d'utilisation du charbon végétal ont été évalués, puis extrapolés à l'échelle de l'agriculture suisse. Sur la base de l'enquête de Dittmann et Baumann (2023) auprès des exploitations utilisant du charbon végétal et du relevé des données structurelles de 2023, trois exploitations-types axées sur la production laitière, porcine ou maraîchère ont été définies,

[3] De nombreuses options ont été proposées pour l'utilisation du charbon végétal dans la gestion des engrais de ferme. L'option présentée ici a été retenue en raison de la disponibilité des données.

représentant respectivement 4096, 939 et 654 exploitations. Les résultats obtenus pour les trois exploitations-types ont ensuite été extrapolés à l'échelle nationale en fonction du nombre d'exploitations représentées par chaque type.

Les effets du changement climatique ont été étudiés selon trois volets distincts: (i) les émissions animales/au champ liées à l'utilisation en cascade du charbon végétal, (ii) le potentiel de séquestration du carbone contenu dans le charbon végétal et (iii) la production de charbon végétal. Les résultats relatifs aux émissions générées par l'utilisation en cascade du charbon végétal dans les exploitations sont décrits ci-après, suivis de l'estimation sur la séquestration de carbone attendue. Les résultats quantitatifs de l'étude concernant le potentiel de séquestration du carbone contenu dans le charbon végétal et la production de celui-ci reposent sur une solide base bibliographique. Toutefois, des incertitudes subsistent en ce qui concerne les émissions animales/au champ et l'utilisation en cascade, car les effets du charbon végétal varient considérablement en fonction du type d'application et des conditions climatiques et pédologiques. Par conséquent, les variations d'émissions observées, qu'elles interviennent au champ ou dans les étables, à la suite de l'application de charbon végétal, doivent être interprétées avec prudence.

Dans les scénarios 1 et 2, on observe une réduction des émissions directes de C et de N, tant au niveau des champs que des animaux. Dans les deux scénarios, le PRG diminue d'environ 0,05 kg d'équivalent $CO_2$ dans l'exploitation laitière, de 0,03 kg d'équivalent $CO_2$ dans l'exploitation porcine et de 0,04 kg d'équivalent $CO_2$ dans l'exploitation maraîchère par rapport aux exploitations de référence. Ces chiffres se rapportent à une année et à 1 kg de charbon végétal utilisé. De plus, dans l'ensemble des scénarios suivants, le charbon végétal incorporé au sol permet de stocker 2,51 kg d'équivalent $CO_2$ sous forme de carbone par kg de charbon végétal (voir détails ci-dessous). La diminution des émissions directes des animaux s'explique par la capacité d'adsorption du charbon végétal, qui fixe l'azote contenu dans les excréments animaux et réduit la volatilisation du $NH_3$ et les émissions de $N_2O$ provenant de la litière. Quant à la diminution des émissions directes sur les champs, elle s'explique par l'épandage de lisier enrichi en charbon végétal qui limite à la fois les émissions de $N_2O$ et le lessivage du $NO_3$. Les résultats du modèle montrent que les émissions directes de C et de N sur les parcelles diminuent nettement plus que celles provenant des animaux.

Seul le scénario 3 présente un PRG supérieur à celui du scénario de référence pour les trois exploitations-types, avec une augmentation respective de 1,48, 2,07 et 0,40 kg d'équivalent $CO_2$ par an et par kg de charbon végétal utilisé dans les exploitations laitières, porcines et maraîchères (par rapport aux scénarios de référence). Dans ce scénario, bien que les émissions directes des animaux diminuent, les émissions directes sur les champs augmentent, de sorte que le PRG augmente également par rapport à la valeur de référence. Dans le modèle, la diminution des émissions directes provenant des animaux s'explique par le fait que les réservoirs de lisier couverts (avec du charbon végétal) produisent moins d'émissions de $NH_3$. L'augmentation des émissions directes sur les champs est liée à la teneur accrue en azote des engrais de ferme, qui, une fois épandus, provoquent une hausse des émissions de $N_2O$ et un lessivage plus important du $NO_3$. Le scénario 3 est celui où le PRG par kg de charbon végétal utilisé varie le plus, ce qui s'explique directement par la réduction importante des émissions de $NH_3$ (combinée à la concentration plus élevée en azote du lisier) provenant des réservoirs à lisier recouverts d'une couche flottante de charbon végétal.

Les scénarios 4 et 5 examinent l'application directe de charbon végétal dans le sol des cultures maraîchères. L'application de 1000 et 5000 kg de charbon végétal $ha^{-1}$ (scénarios 4 et 5) n'a d'effet que sur les émissions directes de C et de N dans les champs: le PRG est réduit respectivement de 0,05 kg d'équivalent $CO_2$ et de 0,02 kg d'équivalent $CO_2$ par kg de charbon végétal. Les résultats des différents scénarios ne diffèrent que légèrement dans les trois exploitations-types analysées. Par définition, les exploitations maraîchères types disposent de surfaces cultivées nettement plus vastes que les exploitations laitières et porcines (12,15 ha contre respectivement 0,24 ha et 0,30 ha); c'est pourquoi la quantité totale de charbon végétal appliquée et son impact sur les émissions directes dans les champs y sont plus significatives. Bien que l'application de 5000 kg $ha^{-1}$ dépasse la limite annuelle autorisée par l'ordonnance sur les engrais (OEng, 2023), elle a été retenue ici afin de simuler les effets d'un enrichissement en charbon végétal correspondant à un apport cumulé autorisé allant jusqu'à 10 t $ha^{-1}$ sur 20 ans.

Les scénarios 6 à 8 montrent que l'impact sur le PRG de l'utilisation combinée de charbon végétal dans plusieurs points d'entrée ne correspond pas à la somme des impacts des scénarios avec un seul point d'entrée. Cet écart s'explique principalement par la valeur seuil de 13 % de réduction du lessivage des nitrates, supposée constante dès lors que l'apport de charbon végétal dépasse 1 t $ha^{-1}$. Une autre explication réside dans la capacité d'adsorption de N par le charbon végétal lorsqu'il est mélangé à la litière. Ce phénomène réduit les émissions de $NH_3$ et de $N_2O$ provenant de la litière et du stockage des engrais de ferme, car l'adsorption de N se poursuit dans l'engrais enrichi en charbon végétal. Les deux catégories d'émissions – «émissions directes de C et N dans les champs» et «émissions directes des animaux» – sont toutes deux influencées par la combinaison des points d'entrée choisis. La somme des effets individuels diffère du résultat lorsque le charbon végétal est introduit simultanément à plusieurs points d'entrée.

Afin d'analyser dans le modèle l'impact environnemental de l'épandage de charbon végétal à tous les stades de son cycle de vie, il est intéressant de comparer les variations du potentiel de réchauffement global induits par les scénarios d'épandage de charbon végétal dans les exploitations agricoles avec ceux générés lors de sa production. Le PRG de la production de charbon végétal dans des installations modernes, conformes aux exigences en matière de qualité de l'air et à la législation sur les engrais, a été calculé sur la base de données actuelles pour trois types de matières premières: les copeaux de bois forestier, le bois issu de l'entretien du paysage et la paille. Nos calculs ont révélé des émissions de 0,153, 0,063 et 0,373 kg d'équivalent $CO_2$ pour la production d'1 kg de charbon végétal et un stockage de carbone organique dans le sol de respectivement 2,5, 2,5 et 2,1 kg d'équivalent $CO_2$ pendant au moins 100 ans (selon la méthode du GIEC, 2019). Ces différences significatives dans les émissions s'expliquent principalement par la nature des matières premières utilisées et par les quantités nécessaires à la production d'un kilogramme de charbon végétal. La paille, en particulier, donne un charbon végétal à plus faible teneur en carbone, ce qui explique les différences dans le stockage du carbone par kg de charbon végétal.

Cette analyse de cycle de vie montre que, sur l'ensemble du cycle de vie du charbon végétal (production, utilisation en cascade et séquestration du carbone), la séquestration est de loin le levier le plus efficace pour la protection du climat. Dans tous les scénarios étudiés (à l'exception du scénario 3), l'effet positif de la séquestration du carbone liée à l'incorporation de charbon végétal dans le sol est plus de 50 fois supérieur aux variations modélisées des émissions directes sur les champs et celles liées aux animaux au cours de la première année suivant l'application. De plus, le charbon végétal continue d'agir dans le sol au fil des années et contribue ainsi à atténuer certains impacts environnementaux de l'agriculture, notamment en réduisant le lessivage des nitrates.

Nos résultats montrent que le PRG net (production de charbon végétal, émissions résultant de l'utilisation en cascade et séquestration du carbone) diminue de 2,40 kg d'équivalent $CO_2$ par kg de charbon végétal appliqué, et ce, quel que soit le point d'entrée ou le scénario considéré (à l'exception du scénario 3).

L'extrapolation des résultats à l'ensemble de l'agriculture suisse (représentée ici par les exploitations-types) indique une réduction potentielle du PRG jusqu'à environ 411 000 tonnes d'équivalent $CO_2$. Cela correspond à près de 4,9 % du PRG total (ce dernier étant basé sur la valeur de référence des trois exploitations-types, extrapolée à la partie de la Suisse représentée). Ce résultat repose toutefois sur le scénario 7, qui prévoit une application de charbon végétal de 5 t $ha^{-1}$. Une telle dose n'est pas autorisée à ce jour selon l'ordonnance sur les engrais, qui limite l'application directe dans le sol à 1 t $ha^{-1}$ $an^{-1}$. Le scénario 2 conduit à la plus forte réduction du PRG (3,6 %, soit environ 301 680 tonnes d'équivalent $CO_2$) dans le respect des normes légales en vigueur. Là encore, ces résultats doivent être interprétés avec prudence, car la modélisation des émissions animales/au champ liées à l'utilisation du charbon végétal dépend fortement des techniques d'application, du système de détention des animaux, ainsi que des conditions climatiques et pédologiques.

En Suisse, la production et l'utilisation du charbon végétal sont encadrées par des exigences strictes concernant la teneur en polluants et les quantités utilisées. Ces règles garantissent une utilisation sûre. Bien que les bénéfices mesurables de l'utilisation du charbon végétal soient limités en dehors de la séquestration du carbone, il peut être utile à la protection du climat et à l'adaptation au changement climatique en agriculture. Le charbon végétal n'est pas une solution miracle, mais un levier complémentaire qui gagne à être combiné avec d'autres mesures.

# Riassunto

Il cambiamento climatico pone l'agricoltura di fronte a notevoli sfide e rischi. Tuttavia, la stessa agricoltura contribuisce alle emissioni di gas a effetto serra (GES). La pirolisi della biomassa e l'impiego in agricoltura del carbone vegetale prodotto attraverso di essa possono contribuire al contempo sia alla protezione del clima sia all'adattamento ai cambiamenti climatici. Poiché una grande parte del carbonio contenuto nel carbone vegetale resta stabile nel suolo per lunghi periodi, il suo impiego può essere considerato una tecnologia a emissioni negative (NET). In agricoltura, il carbone vegetale può favorire la salute degli animali e il riciclo delle sostanze nutritive, oltre a migliorare le proprietà del suolo grazie a una ritenzione dei nutrienti ottimizzata e all'accumulo di carbonio organico nel suolo (SOC). La strategia climatica a lungo termine del Consiglio federale, che punta a raggiungere un saldo netto delle emissioni di gas serra pari a zero entro il 2050, riconosce il ruolo della biomassa e del carbone vegetale per il raggiungimento delle emissioni negative, tuttavia sottolinea anche la concorrenza per le risorse di biomassa. Anche se numerosi studi hanno documentato i molteplici effetti del carbone vegetale in diversi contesti (geografici/climatici, tipo di utilizzo ecc.), finora manca una panoramica complessiva degli impatti ambientali del carbone vegetale, dalla produzione all'impiego, a livello delle aziende agricole in Svizzera.

L'obiettivo principale del presente studio è quindi analizzare gli effetti della produzione e dell'impiego del carbone vegetale sul cambiamento climatico lungo l'intera catena del valore dell'agricoltura svizzera. A tal fine, è stato quantificato il potenziale di riscaldamento globale su un orizzonte temporale di 100 anni (GWP100, indicato di seguito semplicemente come GWP, Global Warming Potential), mediante l'utilizzo di ecobilanci (Life Cycle Assessment LCA). In Svizzera, spesso il carbone vegetale non viene applicato direttamente al suolo, bensì trova impiego nel settore della detenzione animale (come additivo agli alimenti per animali o come materiale per lettiera), per poi giungere nel suolo attraverso i concimi aziendali. Il carbone vegetale utilizzato genera effetti potenziali a più livelli (p. es. animali, qualità dell'aria nelle stalle, concimi aziendali ecc.), pertanto si parla di anche di «utilizzo a cascata».

Per valutare in modo quantitativo gli effetti dell'applicazione di carbone vegetale nelle aziende agricole sulle emissioni e sul cambiamento climatico sono stati definiti otto scenari basati su differenti punti di introduzione:

(1) carbone vegetale miscelato alla lettiera (corrispondente all'1 % del peso dell'alimento per animali);
(2) carbone vegetale miscelato alla lettiera (corrispondente al 10 % del volume della paglia);
(3) carbone vegetale utilizzato come strato flottante nei serbatoi del colaticcio, come esempio di strategia innovativa per la gestione dei concimi aziendali[4];
(4) applicazione diretta del carbone vegetale nel suolo (1000 kg/ha);
(5) applicazione diretta del carbone vegetale nel suolo (5000 kg/ha);
(6) combinazione degli scenari 1, 3 e 4;
(7) combinazione degli scenari 2, 3 e 5;
(8) combinazione degli scenari 1 e 4.

Gli scenari combinati 6–8 permettono di valutare gli effetti dell'applicazione del carbone vegetale in diversi punti di introduzione (p. es. lettiera, serbatoi del colaticcio, applicazione diretta nel suolo). Sulla base della letteratura scientifica e dei pareri degli esperti, nei diversi scenari sono stati analizzati i seguenti effetti dell'applicazione del carbone vegetale:
(i) Alimentazione animale e lettiera: assorbimento di 1 g di azoto (N) per kg di carbone vegetale.
(ii) Concime (colaticcio): carbone vegetale come strato flottante sui serbatoi del colaticcio aperti. Per questo caso si è ipotizzata una riduzione del 60 per cento delle emissioni di $NH_3$ rispetto ai contenitori non coperti.
(iii) Applicazione diretta del carbone vegetale nel suolo: comporta i due seguenti effetti (a) riduzione del dilavamento di $NO_3$ fino al 13 per cento, e (b) diminuzione delle emissioni di $N_2O$ del 13 per cento, se il quantitativo applicato supera 5 t $ha^{-1}$. Va notato che esiste, per vari motivi, una certa incertezza riguardo agli effetti modellizzati.

[4] Per l'impiego del carbone vegetale nella gestione dei concimi aziendali sono state proposte numerose opzioni; quella qui considerata è stata selezionata sulla base della disponibilità dei dati.

Per ottenere risultati di validità generale e rappresentativi dell'intero contesto svizzero sono stati definiti dei «modelli aziendali» per i quali gli scenari con carbone vegetale sono stati confrontati con scenari di riferimento privi di quest'ultimo. Tali modelli rappresentano realtà agricole che già impiegano il carbone vegetale. Sulla base di essi sono stati valutati gli effetti dei diversi scenari di applicazione del carbone vegetale ed estrapolati a livello nazionale. A partire dai dati raccolti da Dittmann e Baumann (2023) relativi alle aziende che impiegano carbone vegetale e dai dati del censimento delle aziende agricole 2023, sono stati definiti tre modelli aziendali con focus sulla produzione lattiera, suinicola e orticola, che rappresentano rispettivamente 4096, 939 e 654 aziende. I risultati ottenuti per i tre modelli aziendali sono stati poi riportati a livello nazionale in funzione del numero di aziende rappresentate.

Gli effetti sul cambiamento climatico sono stati analizzati separatamente per (i) le emissioni provenienti dagli animali e dal campo e dovute all'utilizzo a cascata del carbone vegetale utilizzando (ii) il potenziale di sequestro di C del carbone vegetale e (iii) per la produzione di quest'ultimo. Di seguito vengono presentati dapprima i risultati delle emissioni aziendali riconducibili all'utilizzo a cascata del carbone vegetale, seguiti dal sequestro di C atteso. I risultati quantitativi degli studi sul potenziale di sequestro del carbonio da carbone vegetale e dalla sua produzione trovano un solido riscontro nella letteratura specializzata. Per le emissioni provenienti dagli animali e dal campo e l'utilizzo a cascata vi sono invece alcune incertezze che devono essere prese in considerazione: gli effetti del carbone vegetale variano in misura significativa in funzione del tipo di applicazione, delle condizioni del clima e del suolo. Le variazioni delle emissioni provenienti dalla campicoltura e dall'allevamento di bestiame innescate dall'applicazione del carbone vegetale devono quindi essere interpretate con cautela.

Nel modello, negli scenari 1 e 2 si osserva una riduzione delle emissioni dirette di C ed N a livello del campo e anche delle emissioni animali dirette. In entrambi gli scenari, il GWP si riduce di circa 0,05 kg $CO_2$-eq nell'azienda lattiera, di 0,03 kg $CO_2$-eq nell'azienda suinicola e di 0,04 kg $CO_2$-eq nell'azienda orticola rispetto alle aziende di riferimento. Queste stime si riferiscono a un periodo di un anno e a 1 kg di carbone vegetale utilizzato. Inoltre, in tutti gli scenari seguenti, il carbone vegetale applicato nel suolo immagazzina 2,51 kg di $CO_2$-eq sotto forma di carbonio per ogni kg di carbone vegetale (si vedano in dettagli più avanti). La diminuzione delle emissioni animali dirette è attribuibile alla capacità di assorbimento del carbone vegetale, in grado di legare l'azoto contenuto negli escrementi animali e di ridurre la volatilizzazione di $NH_3$ e le emissioni di $N_2O$ dalla lettiera. La riduzione delle emissioni dirette dal campo si spiega con il fatto che l'applicazione di colaticcio arricchito con carbone vegetale riduce le emissioni di $N_2O$ e il dilavamento di $NO_3$. I risultati del modello indicano che le emissioni di C ed N dirette dal campo si riducono in misura significativamente maggiore rispetto alle emissioni dirette provenienti dagli animali.

Rispetto allo scenario di riferimento, soltanto nello scenario 3 si osserva un aumento del GWP per tutti e tre i modelli aziendali, nello specifico (nel confronto con gli scenari di riferimento) pari a 1,48 kg $CO_2$-eq nelle aziende lattiere, a 2,07 $CO_2$-eq nelle aziende suinicole e a 0,40 $Co_2$-eq nelle aziende orticole, in tutti e tre i casi su base annuale e per ogni kg di carbone vegetale utilizzato. Le emissioni animali dirette diminuiscono, ma le emissioni dirette provenienti dal campo aumentano: in questo modo aumenta anche il GWP rispetto al valore di riferimento. Nel modello, la riduzione delle emissioni animali dirette è spiegata dal fatto che nei serbatoi del colaticcio coperti (con carbone vegetale) si sviluppano meno emissioni di $NH_3$. L'aumento delle emissioni dirette provenienti dal campo è dovuto all'incremento del tenore di azoto nel concime aziendale; ciò comporta, una volta applicato il concime sul campo, maggiori emissioni di $N_2O$ dal campo e un aumento del dilavamento di $NO_3$. Lo scenario 3 evidenzia la maggior variazione di GWP per kg di carbone vegetale utilizzato. Ciò è direttamente correlato alla notevole riduzione delle emissioni di ammoniaca dai serbatoi del colaticcio coperti con uno strato flottante di carbone vegetale (e al maggiore tenore di azoto del colaticcio).

Negli scenari 4 e 5 si analizza l'applicazione diretta del carbone vegetale nel suolo in orticoltura. L'applicazione di 1000 e 5000 kg di carbone vegetale per $ha^{-1}$ (scenario 4 e 5) incide esclusivamente sulle emissioni dirette di C ed N dal campo: il GWP si riduce rispettivamente di 0,05 e 0,02 kg di $CO_2$-eq per ogni kg di carbone vegetale. I risultati dei diversi scenari presentano solo lievi differenze tra i tre modelli aziendali analizzati. Per definizione, le aziende orticole dispongono di superfici coltivate a ortaggi significativamente più estese rispetto alle aziende lattiere e a quelle suinicole (12,15 ha contro rispettivamente 0,24 ha e 0,30 ha); di conseguenza, nelle prime la quantità complessiva di carbone vegetale applicata e la corrispondente variazione delle emissioni dirette dal suolo risultano essere le più elevate. Anche se l'applicazione di 5000 kg $ha^{-1}$ supera il limite annuo previsto dall'ordinanza sui concimi (OCon, 2023), in questa sede è stata calcolata per analizzare l'effetto dell'arricchimento del carbone vegetale con un'applicazione ripetuta consentita fino a un massimo di 10 t $ha^{-1}$ distribuita su un arco di 20 anni.

Gli scenari da 6 a 8 mostrano che l'effetto sul GWP dei percorsi di applicazione combinati non corrisponde alla somma degli effetti delle singole valutazioni nel modello. Il motivo principale della discrepanza è l'uso di un valore soglia del 13 % di riduzione del dilavamento di nitrati, che si presume costante per un'applicazione di carbone vegetale superiore a 1 t $ha^{-1}$. Un altro motivo è l'assorbimento di N da parte del carbone vegetale miscelato alla lettiera, che comporta una riduzione delle emissioni di $NH_3$ e $N_2O$ provenienti sia dalla lettiera sia dallo stoccaggio dei concimi aziendali, poiché l'assorbimento di N continua ad avvenire anche nel concime arricchito con carbone vegetale. Entrambe le categorie, «emissioni dirette di C e di N dal campo» e «emissioni animali dirette», vengono influenzate dalla combinazione dei punti di introduzione scelti. In questo caso, la somma degli effetti singoli differisce dal risultato che si ottiene quando il carbone vegetale viene applicato contemporaneamente in più punti di introduzione.

Per analizzare nel modello gli impatti ambientali associati all'impiego di carbone vegetale in tutte le fasi del ciclo di vita, è di interesse confrontare le variazioni del potenziale di effetto serra causato dagli scenari di applicazione del carbone vegetale nelle aziende agricole con quelle derivanti dalla sua produzione. Il GWP della produzione di carbone vegetale in impianti moderni, conformi alle prescrizioni in materia di igiene dell'aria e alla legislazione sui concimi, è stato calcolato sulla base dei dati disponibili relativi alle condizioni attuali in Svizzera per tre materie prime: cippato di legno forestale, legname proveniente dalla cura del paesaggio e paglia. Dai nostri calcoli risultano emissioni rispettivamente pari a 0,153, 0,063 e 0,373 kg di $CO_2$-eq per la produzione di 1 kg di carbone vegetale, che immagazzina rispettivamente 2,5, 2,5 e 2,1 kg di $CO_2$ equivalente per almeno 100 anni (secondo il metodo IPCC, 2019). Le marcate differenze tra le emissioni sono riconducibili principalmente alle diverse materie prime e alle differenti quantità necessarie per produrre 1 kg di carbone vegetale. Il carbone vegetale ottenuto dalla paglia presenta un tenore di carbonio inferiore, il che spiega le differenze di capacità di sequestro di questa sostanza per kg di carbone vegetale.

Questo studio sull'ecobilancio mostra che, considerando l'intero ciclo di vita del carbone vegetale (produzione, utilizzo a cascata e sequestro di C), il sequestro rappresenta di gran lunga il fattore principale in termini di protezione del clima. Nel primo anno dopo l'applicazione, l'effetto positivo dovuto al sequestro di C derivante dall'applicazione del carbone vegetale nel suolo risulta, in tutti gli scenari analizzati (ad eccezione dello scenario 3), oltre 50 volte più rilevante rispetto alle variazioni modellate delle emissioni dirette dal suolo e dagli animali. Tuttavia, il carbone vegetale continua ad avere effetti nel suolo anche negli anni successivi, contribuendo all'ulteriore riduzione degli effetti collaterali indesiderati dell'agricoltura, ad esempio tramite la diminuzione del dilavamento dei nitrati.

I nostri risultati mostrano che il GWP netto (produzione di carbone vegetale, emissioni derivanti dall'utilizzo a cascata e sequestro di C) si riduce, indipendentemente dal punto di applicazione, in tutti gli scenari (ad eccezione dello scenario 3) di 2,40 kg di $CO_2$-eq per ogni kg di carbone vegetale applicato.

L'estrapolazione di questi risultati all'intero contesto dell'agricoltura svizzera (rappresentato in questo studio dai modelli aziendali) indica un potenziale di riduzione del GWP di circa 411 000 tonnellate di $CO_2$-eq. Ciò corrisponde a circa il 4,9 per cento del GWP complessivo (laddove «complessivo» si riferisce al GWP del valore di riferimento dei tre modelli aziendali, estrapolato sulle rispettive quote rappresentative della Svizzera). Questo risultato si basa sullo scenario 7, che prevede un'applicazione di carbone vegetale pari a 5 t $h^{-1}$, quantitativo che attualmente non è ammesso ai sensi dell'OCon, la quale limita l'applicazione diretta al suolo a 1 t $h^{-1}$ $anno^{-1}$. Lo scenario 2 comporta la maggiore riduzione del GWP (3,6 %, vale da dire circa 301 680 t di $CO_2$-eq) nel rispetto dei criteri normativi attualmente in vigore. Anche questi risultati devono essere interpretati con cautela, poiché la modellizzazione delle emissioni degli animali e dei campi in relazione all'uso del carbone vegetale dipende fortemente dai metodi di applicazione, dal sistema di allevamento degli animali e dalle condizioni climatiche e del suolo.

In Svizzera, per la produzione e l'utilizzo di carbone vegetale vigono prescrizioni severe in riferimento al contenuto di sostanze dannose alle quantità di applicazione, garantendo così un impiego più sicuro. Pur offrendo benefici quantificabili limitati oltre al sequestro di C, l'utilizzo del carbone vegetale in agricoltura può essere considerato uno strumento per la mitigazione e l'adattamento ai cambiamenti climatici. Esso non costituisce una soluzione unica, ma dovrebbe essere impiegato, ove possibile, in modo combinato con altre misure.

# 1 Introduction

## 1.1 Scientific Background

Global warming (climate change) is driven by the human-induced greenhouse effect, with $CO_2$ being a major contributor. Reducing emissions of fossil $CO_2$ and other greenhouse gases (GHG) is crucial, but we also need negative emissions technologies (NET) to reach the 2°C target of the Paris Agreement (IPCC, 2022). The production and non-oxidative use of biochar is a NET that is already being deployed today (Schmidt et al., 2019a). Through photosynthesis, plants remove $CO_2$ from the atmosphere. Biomass pyrolysis (e.g. plant residues, wood chips) converts this carbon into solid, liquid, and gaseous forms by heating it at 400–900°C in the absence of molecular oxygen. The liquid (pyrolysis oil) and gases (including $H_2$, CO, $CO_2$, and $CH_4$) are typically used to generate energy, power the process, and provide heat, for example, for district heating or industrial processes. Thus, pyrolysis can also help reduce emissions by replacing fossil fuels. The solid product, biochar, can become a long-term storage of carbon outside the atmosphere when used in a non-oxidative manner, for example, in soil (Hagemann et al., 2018; Schmidt et al., 2019a).
During biomass pyrolysis, organic pollutants, such as polycyclic aromatic hydrocarbons, are formed that may condensate and contaminate biochar. However, the condensation of contaminants can be avoided by proper process control. This risk is well understood and mitigated by good practice in biomass pyrolysis (Bucheli et al., 2015; Buss et al., 2022; Grafmüller et al., 2024b). Biochar application in Switzerland is considered safe under the established industrial standards of biochar quality management and the regulations in the Fertilizer Ordinance (DüV, 2023, EBC, 2024) and ORRChem (SR, 2005), which include regular biochar analysis. Interestingly, biochar also has the potential to sorb pesticides, reducing their availability and limiting unwanted uptake by soil organisms and plants (Das et al., 2021). However, this interaction might diminish the effectiveness of some soil-applied pesticides, possibly leading to the need for higher pesticide doses. Additionally, the presence of biochar can slow the degradation of some pesticides, leading to their accumulation in the soil (BAFU, 2023).

Biochar used in agricultural soils reduces nutrient losses and can reduce GHG emissions (especially nitrous oxide - $N_2O$, Borchard et al., 2019), promote the formation of soil organic matter (Blanco-Canqui et al., 2020), and improve water retention, thereby supporting agriculture's adaptation to climate change (Edeh et al., 2020). While these effects are generally supported by scientific research, their duration and magnitude can vary significantly depending on the properties of the biochar, its application method, and local soil and climatic conditions. More long-term field trials are needed to improve our understanding. There is no statistical evidence indicating increased crop yields in Switzerland's climate or in well-developed soils (i.e. soils that are neither highly degraded nor underdeveloped), as shown in studies by Jeffery et al. (2017) and Melo et al. (2022). While yield improvements may be possible with optimised biochar applications (e.g. Grafmüller et al., 2024a), consistent results have yet to be demonstrated in the field. Additionally, biochar can reduce the efficacy of soil-active herbicides through sorption (Wang et al., 2015), but there are currently no established application guidelines to mitigate these potential negative effects. Adverse impacts on earthworms and other soil macrofauna have also been reported when biochar of unknown quality (without pollutant analysis) was applied directly to the soil at high rates (>10 t $ha^{-1}$) (Briones et al., 2020). By contrast, biochar used in Swiss agriculture has proven to be low in contaminants. The limit values for heavy metals in biochar laid down in the Chemical Risk Reduction Ordinance are stricter than those for compost. The limit values for organic pollutants are the similar. In addition, the application to soil is restricted to 1 t $h^{-1}$ $year^{-1}$ and a total of 10 t $ha^{-1}$ within 20 years.

Thus, the effects of agricultural biochar application in Switzerland remain uncertain due to the lack of data on specific data and mechanistic understanding of biochar effects in well-developed soil under temperate climates. Biochar is currently an expensive raw material (approx. 1000 CHF/t of biochar dry matter equivalent). The so-called cascading use is one way to optimise its economic use by accumulating the effects of biochar at several stages in the agricultural value chain after its application at one entry point. The starting point of the "classic" cascade is the livestock's feed. After its effect on the animal, the biochar is excreted and contained in the farmyard manure. Through the field application of farmyard manure, biochar enters the soil. Biochar can also be used as a stable bedding or as an additive when composting manure and other materials. Several studies have demonstrated the beneficial effects of using biochar at various levels.

- Fertiliser additive: Biochar enhances nutrient retention and reduces soil-borne $N_2O$ emissions and nutrient leaching, particularly nitrate. It also increases water retention and biological activity in the soil (Borchard et al., 2019; Haider et al., 2020; Kammann et al., 2015).
- Compost additive: Biochar reduces nutrient losses and GHG emissions, especially $N_2O$ emissions (Vieira Firmino & Trémier, 2023).
- Silage additive: Biochar stabilises fermentation, binds pesticide residues, and reduces mycotoxins (Schmidt et al., 2019b).
- Feed additive: Biochar contributes to improved animal welfare and health (Schmidt et al., 2019b).
- Additive to animal bedding: Biochar improves conditions in the stable by reducing odours and binding volatile carbon compounds, leading to lower ammonia emissions. It also helps prevent bale and hoof inflammation and retains nutrients, such as nitrogen, in animal excreta (Graves et al., 2022).

Life cycle assessment (LCA) studies have already been carried out on various aspects of the cascading use of biochar (Furrer et al., 2021). Hoeskuldsdottir (2022) conducted a parametric analysis to study the potential of biochar use in Europe to reduce $CO_2$ emissions as a function of various input parameters (e.g. pyrolysis temperature or feedstocks for biochar production). The calculations showed a reduction in $CO_2$ emissions of between 1.77 and 6.66 kg $CO_2$-eq per kg of biochar compared to the reference scenario without the use of biochar. A distinction is made between avoided emissions and permanent $CO_2$ storage (negative emissions). Matuštík et al. (2020) presented a meta-analysis of LCA analyses of biochar as a soil conditioner. The authors proposed a method to facilitate the comparison of the results from various LCA studies.

However, a study that comprehensively analyses the environmental effects of biochar at the whole-farm level using an LCA approach and that takes the Swiss context into account is missing. This study aims to close some of the existing gaps based on a full LCA, calculating the environmental impacts (with a clear focus on GWP) over the entire life cycle of biochar used in different application scenarios. We focus on quantifiable aspects, including the production of biochar, change of on-farm emissions due to the application of biochar and carbon sequestration. Among other aspects, biochar impact on animal health and potential interaction with pesticides are not considered.

## 1.2 Policy Framework

In 2019, the Federal Council decided that Switzerland should not emit more GHG by 2050 than natural and technical sinks can sorb (net zero target). On 27 January 2021, the Federal Council adopted its “Long-Term Climate Strategy”. The long-term climate strategy shows that Switzerland can greatly reduce its GHG emissions from transport, buildings, and industry by 2050 by moving away from fossil fuels. In 2050, the remaining emissions of approximately 12–14 million tonnes of $CO_2$ equivalents per year from industry (especially cement production), waste incineration, agriculture, and international aviation are difficult to avoid. These emissions should be compensated for according to the Long-Term Climate Strategy with $CO_2$ capture and storage technologies (approx. 5 million tonnes of $CO_2$ of fossil or geogenic origin) and NET (approx. 7 million tonnes of $CO_2$ of atmospheric origin). Various plant-based and technical approaches are known to achieve negative emissions. However, these techniques are currently only deployed on a very small scale.

The pyrolysis of biomass into biochar and its subsequent and repeated application to soil and resulting carbon storage offer an opportunity to achieve negative emissions in Switzerland. According to the Federal Council’s report of 2 September 2020, in fulfilment of Postulate 18.4211, negative $CO_2$ emissions of up to 2.2 million tonnes of $CO_2$ could be generated if nearly all sustainably usable biomass in Switzerland were used. However, biomass can be used in many different ways and plays a central role in the decarbonisation of various sectors of the economy, which poses certain competition for raw materials. Novel approaches to accessing other biomass sources to produce biochar and the use of the raw material in a circular economy or cascade are therefore of great interest.

## 1.3 Goal of the Project

The main objective of the project was to assess the GWP associated with emissions from (i) biochar production, (ii) cascade use of biochar, and (iii) carbon sequestration from field-applied biochar. This goal was achieved by developing scenarios for biochar use at the farm level and comparing them to a reference scenario without biochar application. Furthermore, the study aimed to upscale the results from individual model farms to the entire Swiss agricultural sector.

## 1.4 Target Stakeholders

This report provides interesting findings for the following stakeholder groups:

- Scientific community
- Extension services
- Authorities and policymakers
- Farm managers.

Researchers and academic institutions can deepen scientific knowledge of the environmental impacts of biochar applications. Extension services (e.g. government agencies), aiming at improving agricultural practices, enhancing productivity, and supporting sustainable development in the agricultural sector may also profit from the present analysis. Based on the findings of the study, policymakers can evaluate the contribution of a biochar project to reach net-zero GHG emissions. Farmers are focused on management practices and the biochar's potential to enhance soil fertility and reduce GHG emissions.

# 2 Life Cycle Assessment Method

## 2.1 Method LCA: Principles

LCA is a comprehensive and standardised methodology used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle—from raw material extraction, production, use to disposal or recycling (from cradle-to-grave). LCA is based on ISO 14040 and is defined as "*the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (i.e. consecutive and interlinked stages of a product system, from raw materials acquisition or generation from natural resources to final disposal*)" (ISO, 2006a). The main purpose of using LCA within the present project is to quantify various environmental impacts of the application of biochar on Swiss agricultural farms, as well as to identify hotspots and give insight into the impacts of different processes along the value chain. This especially applies to the production of biochar and the effects of biochar applied at different entry points on farms.

The LCA process can be broken down into four essential steps (Figure 1).

I. Goal and scope definition (see Sections 2.2)
II. Life cycle inventory analysis (see Section 2.3)
III. Life cycle impact assessment (see Section 2.5)
IV. Life cycle interpretation (see Sections 4 and 5).

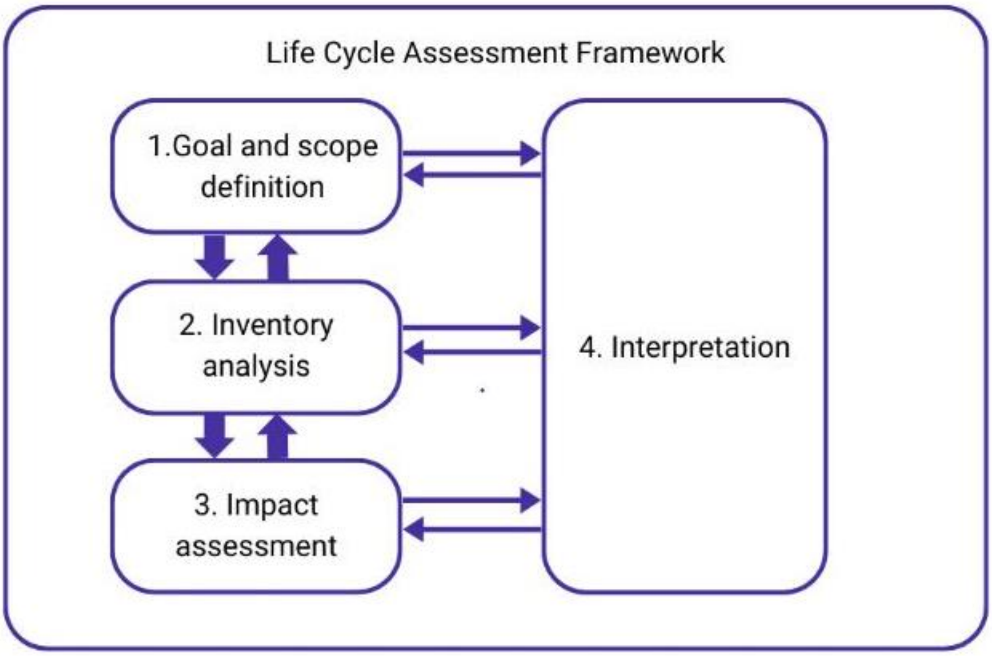


*Figure 1: Stages of the LCA framework according to ISO 14040.*

It is important to stress that LCA is an iterative process, meaning that previous phases may need to be revisited based on the results of later phases. For example, new data or findings from current studies may lead to adjustments to the assumptions used in the previous step.

## 2.2 Goal and Scope Definition

The first step of LCA is crucial to properly developing and describing the framework. It defines the main goal of the study and describes the system boundary, the target audience, and the assumptions made. This includes the definition of the functional unit used as a reference to normalise all emissions and environmental impacts. The goal of the project is detailed in Section 1.3; for the targeted stakeholders, the reader is referred to Section 1.4.

### 2.2.1 System Boundary

The system boundary determines which processes are included in the LCA study. This must be chosen so that the objectives of the study are achieved in the best possible way. The system boundary for this project comprises the production of biochar, including all involved background processes and on-farm processes of biochar application (on-farm emissions) up to the farm gate. All relevant material flows across the system boundary are considered. In the case of GHG emissions, this means accounting for $CO_2$ uptake by plants, all climate-relevant emissions from livestock buildings, croplands, meadows, and pastures, all emissions from land use and land-use changes, and carbon storage in the soil ( using LCA.

Figure 2). The resulting balance of these flows is then evaluated in the impact assessment using LCA.

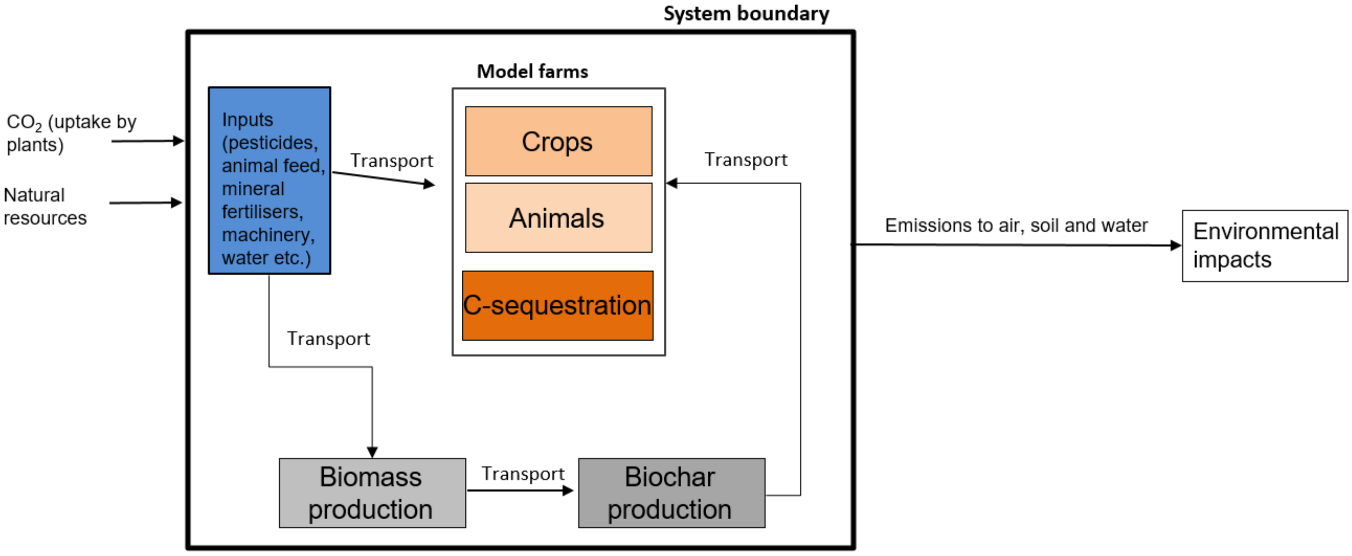


*Figure 2: System boundary and included processes (detailed description of the individual steps in Sections 2.2.3 and 2.3).*

### 2.2.2 Function and Functional Unit

The focus of this study is on the farm level (model farm), with subsequent extrapolation to the entire Swiss agricultural system. The environmental impacts are initially expressed for all farms and then for the entire agricultural sector. In addition, the environmental impacts of biochar production are expressed per kg of biochar applied on the model farm.

### 2.2.3 Scenarios for biochar application

#### *2.2.3.1 Theory*

The effects of biochar on the environment, including those on soil-borne GHG emissions, have been researched for about two decades. In addition to systematic reviews, meta-analyses that provide a quantitative evaluation of many similar studies are increasingly providing insights into this topic. Nevertheless, evaluating the environmental impacts and GHG emissions of the agricultural application of biochar in Switzerland remains a major challenge for many reasons.

- Both soils and biochars show a wide range of properties that influence the effects in individual cases. The literature must be narrowed down to the relevant parameters when evaluating the application of a defined biochar in a certain soil.
- Many studies have been conducted in the laboratory or in greenhouses. If no data from field trials or direct environmental observations are available, the findings must be critically examined to determine whether the data can be used to evaluate real-world biochar applications.
- In biochar research, dosages in the range of 10–100 t of biochar per hectare are often investigated. In Switzerland, the Fertiliser Ordinance limits biochar application to 1 t $ha^{-1}$ and year, which may be repeated until a total of 10 t $ha^{-1}$ have been applied. In practice, the total quantities applied today and in the near future are even lower. Here, whether and to what extent individual effects also occur at these lower dosages must be examined.

Compared to the wide range of biochar types used in global research, the properties of Swiss biochar can be defined quite narrowly. Swiss biochars are currently made from wood, as this was a legal requirement until the end of 2023. They are produced by pyrolysis at 600–750°C. In line with the suggestions of the IPCC (2019), we assume a biochar carbon content of 77% and that a fraction of 89% of the carbon is persistent. Thus, 11% of the biochar carbon is assumed to be released as $CO_2$ for 100 years following soil application. This results in 2.51 t $CO_2$ sequestered per 1 t of biochar (dry matter) being applied to soil for biochar made from wood chips or landscape conservation wood. For straw biochar, a carbon content of 65% and a fraction of 89% of persistent carbon lead to 2.12 t $CO_2$ sequestered per 1 t of biochar.

The special feature of the present study is the consideration of multiple applications of biochar in contrast to its exclusive direct soil application. Here, the possibility of modelling different types of application of biochar, in silage, in animal feeding, in bedding, and in compost, is reviewed. Table 1 covers the information on the entry points considered in this project.

- **Silage**: Biochar is spread in corn or other shredded whole plants prior to compression to achieve an effect during the subsequent ensiling in the silage bales or silo. The main motivation is to improve ensiling and to reduce the formation and/or bio-availability of mycotoxins (Appell et al., 2023; Schmidt et al. 2019). During ensiling, the GHG $CH_4$ and $N_2O$ can be produced and, under certain circumstances, emitted. To the best of our knowledge, there are no usable studies on the effects of biochar on these processes. Therefore, the use of biochar prior to ensiling will not be considered further. Biochar in silage enters the soil through animal feeding via manure field applications. The biochar used in the silage can later take effect in the animal's digestion, in the farmyard manure, and in the soil. The amounts of biochar that could be applied via the silage equal those used in feed and were considered in this study via the point of entry of animal bedding.
- **Feed**: Biochar can be administered as an ingredient of mixed feed or offered as an additional feed ad libitum. Its use in feed is quite popular among biochar-affine farmers, who report multiple benefits on ruminants (e.g. lower cell counts in milk), pigs (e.g. reduction of weaning diarrhoea in piglets), and (laying) hens (e.g. fewer irregularly shaped eggs, reduction of feet disease). Improved air quality in stables and lower veterinary costs are generally reported. In addition to reports from farmers, there are numerous scientific publications on the mechanisms of action and individual effects of biochar on feeding (Schmidt et al., 2019). However, very few studies are practice-oriented or conducted under Swiss conditions. A recent study conducted at AgroVet Strickhof showed that "none of the variables related to animal performance […], animal health […], methane emission and N excretion […] showed any significant differences between the control and the BC treatment" (Dittmann et al., 2024). Therefore, biochar administered as an ingredient of the mixed feed or as additional feed does not have any direct effects on GHG emissions but will later have effects on animal bedding, manure, and soil. The amount of biochar used in feed can be approximated with 1% feed by mass.
- **Bedding**: Biochar is sprinkled on the slatted floor or in the usual bedding (typically straw). Farmers report improved air quality and reduced odours in the barn and aim to bind urine-borne nitrogen to reduce ammonia emissions. To the best of our knowledge, no usable study has examined the possible effects of biochar in bedding in barns. Therefore, we limit the consideration in the LCA to the sorption capacity of biochar with regard to ammonium nitrogen. Based on Fidel et al. (2018) and Weldon et al. (2022), we assumed 1 g N sorption per 1 kg of biochar, as Swiss biochars are typically produced from wood at 600–700°C. Higher nitrogen sorption (average of 4 g $kg^{-1}$ across the scientific literature (Weldon et al. 2022)) is achieved with biochar from non-woody biomass and/or biomass amended with minerals. The biochar used in bedding can later take effect in manure and soil. The possible dosages range from the same order of magnitude as in feeding (approx. 100–200 g per livestock unit) to 10% by volume of the straw bedding (approx. 40% by mass). The latter is of interest for compost-bedded pack barns and similar systems (Eberl et al., 2024).
- **Composting:** Composting is an important way of refining biochar for use in the soil, and composting is a source of GHG emissions that can be reduced by biochar addition (Vieira Firmino and Trémier 2023). The biochar used in the composting later takes effect in the soil. The amount of biochar that could be applied via composting equals the higher dosages assumed for its use in bedding. However, any effects of composting are strongly dependent on specific compost management and are thus hard to model. Therefore, composting was not considered here.
- **Manure (slurry) management:** Biochar can be mixed into slurry. Similar to its use in bedding, farmers report fewer odours when spreading the slurry and a reduction of ammonia volatilisation. Some farmers see application in the slurry pit as an easier route compared to use in bedding. However, while the biochar in animal bedding comes into contact with fresh urine that still contains urea, the nitrogen in the slurry is already present as ammonium. Biochar can have diverse effects on ammonia emissions, which also depend on overall manure management, especially the resulting pH of the slurry. Accordingly, scientific studies have shown different results (no effect vs. reduction) regarding the effects of biochar on ammonia emissions, depending on the exact experimental conditions. The available studies are too few to derive generalisable

findings. Thus, for biochar application in general, we did not consider any effect beyond ammonia sorption (1 g N sorption per 1 kg of biochar), as described for the entry point bedding. However, many farmers do not use biochar/biochar mixing into slurry as a stand-alone solution but combine biochar application to slurry with other amendments, such as leonardite or spraying of lactic fermenting microorganisms in the barn to lower slurry pH and shape the microbiota in the slurry. However, the effect of such combined approaches is difficult to assess scientifically, as the definition of the control group is already challenging. Here, we considered biochar application as a floating layer in manure storage, resulting in a 60% reduction of $NH_3$ emission compared to non-covered storage (Chen et al., 2021). The floating layer will be applied to manure storage without cover, but no biochar will be applied to already covered manure storage. Our motivation is not to promote this specific application of biochar but to represent innovative manure management strategies that include biochar use. Thus, the floating layers of biochar serve only as an example.

- **Soil**: All biochar uses mentioned above result in biochar entering the soil and taking effect there, including the nitrogen stored in it. No difference in effect was assumed between biochar that has been used in one of the cases mentioned above and fresh biochar or biochar that has been externally processed (e.g. purchased biochar compost, biochar-based fertiliser) and applied directly to the soil. Impacts in soil relevant to this LCA include effects on soil-borne GHG emissions ($CH_4$, $N_2O$, and $CO_2$) and the fate of nitrogen. No effect was assumed on $CH_4$ emissions. We evaluated meta-analyses (Borchard et al., 2019; Huang et al., 2023) in terms of the effects applicable to Switzerland. This includes the following conditions:
    - Neutral to alkaline soils
    - Dryland soils (in contrast to paddy)
    - Cold humid to temperate humid climate
    - Biochar from wood with moderate pH (pH 8–10)
    - Low biochar application rate (<10 t ha$^{-1}$)

  Priority was given to meta-analysis and data from field experiments and experiments with longer durations. Conservative values (lower effect size) were given preference. The following effects were implemented in this study:

- There is no effect on soil-borne $CH_4$ emissions, which are already low under Swiss conditions.
- $N_2O$ emissions are reduced by 13% only if at least 5 t ha$^{-1}$ biochar is applied. Grafmüller et al., *in prep*., showed no effect at an approximately 1 t ha$^{-1}$ biochar application rate, whereas 10 t ha$^{-1}$ still reduced overall $N_2O$ emissions by 7% in a greenhouse trial. Global meta-analyses suggest a reduction of 23% (Huang et al., 2023) to 38% (Borchard et al., 2019) across all data-sets available. Huang et al. (2023) further derived a 7% reduction of application rates of <10 t ha$^{-1}$ across all types of biochar, while Swiss biochars generally show a higher potential to reduce $N_2O$ emissions than the average biochars used in scientific studies (e.g. biochars produced at 550–700°C 28% reduction (range 6–29% for <400°C–>700°C), biochars from wood 27% reduction (range 19-33% for “biosolids”, “herbaceous”, “manure”, and “wood”)). There have been doubts about the persistence of the $N_2O$ emission reduction effect of biochar; however, Huang et al. included 145 data pairs acquired from experiments lasting at least 2 years. Nevertheless, the effect size decreases over time, from 37% emission reduction in experiments shorter than 1 year to 12% emission reduction in experiments conducted for 5 years or longer.
- Nitrate leaching is reduced by 13% reduction of $NO_3$ leaching for soil biochar content of 1 t ha$^{-1}$ or higher with linear increase of the effect for 0 to 1 t ha$^{-1}$. This value is taken from Borchard et al.’s (2019) meta-analysis, which was calculated across all studies. For experiments lasting longer than 30 days, greater reductions were derived (26%). However, most studies in meta-analysis were conducted with >10 t ha$^{-1}$, thus a very conservative assumption for low biochar dosages. Still, Grafmüller et al. (2024a) observed the reduction of nitrogen leaching by 26-35% already at 1.1 t ha$^{-1}$;
- No effect on soil organic carbon (SOC) is assumed. In fact, the available studies on the long-term effect on SO that explicitly consider only non-biochar carbon are very few, and their results are contradictory. A study from Germany showed no effect, while a study from the USA showed a 2 t ha$^{-1}$ increase in SOC per year

against a non-biochar amended control. Both studies applied >10 t $ha^{-1}$ biochar (Blanco-Canqui et al., 2020, Gross et al., 2024).

Table 1: Entry points of biochar for cascading use and their implementation in this project.

| Entry point | Implementation in the project | Background |
|---|---|---|
| Silage | - | No studies known with regard to GHG emissions. Interaction with nitrogen with effects on downstream emissions is covered with the entry point "bedding". |
| Feed | - | No effect on enteric $CH_4$ emissions. Interaction with nitrogen with effects on downstream emissions is covered with the entry point "bedding". |
| Bedding | Yes | No impact on GHG emission. Sorption/immobilisation nitrogen (plant available in soil): 1 g N $kg^{-1}$ biochar (Fidel et al., 2018, Weldon et al., 2022). |
| Composting | - | SALCAfuture cannot model composting; no sufficient data, and emissions strongly depend on compost management. |
| Manure (slurry) | Yes | Mixing biochar into manure can have diverse effects on ammonia emissions, which also depends on the overall manure management. Specifically, we consider biochar application as a floating layer in manure storage, resulting in a 60% reduction of $NH_3$ emission compared to non-covered storage (Chen et al., 2021). No biochar application on already covered manure storage. |
| Soil | Yes | 13% reduction of $NO_3$- leaching for soil biochar content of 1 t $ha^{-1}$ or higher with linear increase of the effect for 0 to 1 t $ha^{-1}$ (Borchard et al., 2019, Grafmüller et al. 2024a)<br><br>13% reduction of $N_2O$ emissions for soil biochar content of 1 t $ha^{-1}$ or higher; no effect for lower concentrations (Huang et al., 2023, Grafmüller et al., in prep)<br><br>No accumulation of soil organic SOC beyond biochar carbon.<br><br>Biochar degradation (11% for 100 years, assuming linear degradation, that is, 1% of total degradation per year). |

It is interesting to note that Dittmann and Baumann (2023) mention in their survey for Switzerland that biochar is currently primarily used for bedding, as a feed additive, and for the storage and treatment of farm manure.

#### *2.2.3.2 Evaluated biochar application scenarios*

As mentioned in the previous subsection, Swiss biochars are currently made from wood. Therefore, further calculations are made only with the wood chips biochar. This biochar is assumed to sequester 2.51 kg $CO_2$-eq in all its applications in soil. In addition, we evaluated the GWP reduction potential of specific biochar uses compared to no biochar usage. Feedstock selection shapes the properties and, thus, the potential effects of biochar. It is likely that the application of biochars from wood, landscaping wood, and straw would result in slightly different effects at the experimental level. However, given the high level of abstraction and generalisation of the data that had to be made for this study, it can be assumed that all biochars would have a similar effect. To comprehensively assess the impact of biochar on GHG emissions of the model farms, eight different scenarios were considered: five scenarios with a single entry point, and three scenarios with a combination of two or three entry points. The implication of these scenarios on emissions, as shown in Table 2, represents the best of current knowledge found in literature.

Table 2: Scenarios of biochar application on model farms.

| Scenario | Entry points | | | Effects modelled[1] | Compliance with current regulations[2] |
|---|---|---|---|---|---|
| | Animal bedding | Manure storage | Direct soil application | | |
| 1 | Quantity of biochar = 1% animal feed (mass equivalent) | | | a), c) | Yes (0.03–0.12 t $ha^{-1}$)[3] |
| 2 | Quantity of biochar = 10% straw volume | | | a), c) | Partly for dairy farm: 0.69 t $ha^{-1}$ applied annually[3], limit of 10 t $ha^{-1}$ would be reached after 14 years.<br><br>Yes for pig (0.10 t $ha^{-1}$) and vegetable farms (0.19 t $ha^{-1}$) |
| 3 | | Biochar as a swimming layer on liquid manure storage | | b), c) | Yes (<0.01 kg $ha^{-1}$) |
| 4 | | | 1000 kg/ha on surfaces with annual vegetables | d) | Yes, as vegetable production is part of a crop rotation, biochar is not applied on the same field every (e.g. 0.44 t $ha^{-1}$ average biochar application at the farm level on the vegetable farm) |
| 5 | | | 5000 kg/ha on surfaces with annual vegetables | d) | No.[4] |
| 6 | Quantity of biochar = 1% animal feed (mass equivalent) | Biochar as a swimming layer on liquid manure storage | 1000 kg/ha on surfaces with annual vegetables | a), b), c), d), | 0.48 t $ha^{-1}$ applied on average on the vegetable farm; 10 t $ha^{-1}$ limit would not be reached within 20 years |
| 7 | Quantity of biochar = 10% straw volume | Biochar as a swimming layer on liquid manure storage | 5000 kg/ha on surfaces with annual vegetables | a), b), c), d), | No |
| 8 | Quantity of biochar = 1% animal feed (mass equivalent) | | 1000 kg/ha on surfaces with annual vegetables | a), c), d) | Yes (0.06–0.47 t $ha^{-1}$) |

[1]Effects modelled (for more details, see Table 1)

a. N sorption in animal bedding (1 g N per kg biochar) (Fidel et al., 2018, Weldon et al., 2022)
b. Reduced $NH_3$ emissions by 60% during manure storage when storage is covered with a floating layer of biochar (Chen et al., 2021)
c. Effect on $NO_3$ leaching, $N_2O$ emissions, and C sequestration when manure containing biochar is applied to soils (Borchard et al., 2019, Grafmüller et al. 2024a, Huang et al., 2023)
d. Effect on $NO_3$ leaching, $N_2O$ emissions, and C sequestration when biochar is directly applied to soils (Borchard et al., 2019, Grafmüller et al. 2024a, Huang et al., 2023)

[2]Section 3.2.4 of Appendix 2.6 of the Ordinance of risk reduction from chemicals (Chemikalien-Risikoreduktions-Verordnung - ChemRRV) limits biochar application to 1 t $ha^{-1}$ per year and a total of 10 t $ha^{-1}$ in 20 years.

[3]Total amount of biochar applied per year divided by farm area.

[4]However, for dairy and pig farms, this scenario results in 0.03 and 0.02 t $ha^{-1}$, respectively, annual average biochar application at the farm level.

All scenarios were evaluated using SALCAfuture, a software developed by Agroscope for agricultural LCA. It is based on the Swiss Agricultural Life Cycle Assessment (SALCA) method and comprises data collection, emission calculation, and impact assessment (Douziech et al., 2024; Nemecek et al., 2024).

**Application of biochar as a swimming layer to slurry storage (Scenario 3)**: This was implemented in SALCAfuture as an additional option of slurry storage cover with an associated emission reduction of 60% of $NH_3$ emissions from slurry storage. Only one covering option could be selected per slurry storage; however, multiple storages with different covers were modelled per model farm. Table 3 presents the available options for slurry storage covers in SALCAfuture. The amount of biochar applied as a swimming layer onto the slurry was calculated as a 6-mm biochar layer with a bulk density of 250 kg/m$^3$ for the biochar and an assumed average height of 3 m for the slurry storage, resulting in a value of 0.5 kg biochar/m$^3$ slurry storage. The emission reduction during slurry storage reduces the nitrogen content in the slurry at the moment of spreading in the field, which leads to increased direct field emissions from slurry spreading. Net emissions therefore depend on the relationship between reduced emissions during storage and increased emissions during slurry application.

Table 3: Reduction of $NH_3$ emissions through different slurry storage covers (Kupper et al., 2021).

| Choices for slurry storage cover | $NH_3$ emission reduction |
|---|---|
| no cover or unspecified | 0% |
| natural crust | -40% |
| floating foil | -80% |
| foil tent | -60% |
| perforated cover | -40% |
| solid cover | -90% |
| biochar layer | -60% |

**Application of biochar in animal bedding:** This was the earliest entry point to the cascade considered in this study. As adding biochar to silage or feed does not cause any specific effect that could be considered within the scope of LCA, it does not matter if biochar is added to silage, feed, or bedding for the biochar to be able to sorb 1 g of nitrogen per kg of biochar. Similarly, the dependence on the animal housing system was not considered with the modelling of the model farms. Biochar applied to silage or feed is also excreted into the litter or onto stable surfaces, and will therefore remove nitrogen from potential emission pathways in the same way as for its direct application to animal bedding. This was implemented in this study as a reduction of the nitrogen amount on which the emissions in housing and the nitrogen amount entering manure storage were calculated. This led to a cascade effect in the model, as less nitrogen became available for all emissions that occurred after the emissions in housing (storage emissions and direct field emissions during application).

Regarding the quantity of biochar applied to animal bedding, the scientific literature does not provide any guidance, and recommendations from, for example, farmers and vendors vary greatly. The biochar amount was calculated as a 1% mass equivalent based on the total feed quantity (kg) determined from the model farm, as 1% biochar in feed is generally perceived as the upper limit. Dittmann et al. (2024), for example, used 1% based on dry matter, that is, slightly less biochar. Thus, Scenario 1 covers both a biochar application in feed and biochar sprinkling on a slatted floor. In Scenario 2, the total straw quantity (kg) was determined from the model farm. Its volume was calculated assuming a straw density of 60 kg/m$^3$, and the biochar quantity (kg) was calculated as a 10% volume equivalent, assuming a biochar density of 250 kg/m$^3$. In practice, this scenario is relevant to farmers who focus on solid manure for composting or direct application from the dung heap.

**Transfer of biochar from bedding and slurry storage onto the field and direct field application of biochar:** The amount of biochar applied in animal bedding and as a swimming layer is later transferred onto the fields by manure spreading. This process was implemented in SALCAfuture. SALCAfuture was also extended to model the effect of biochar applied directly onto the fields. Therefore, the amount of biochar arriving in the fields was summed up over all possible sources. Importantly, this sum only includes the biochar application of one year, specifically the first year of biochar application. The accumulation of biochar in the soil as a result of continuous use in animal husbandry was not considered. Once in the field, the effects of biochar on $NO_3^-$ leaching and $N_2O$ emissions were modelled. The reduction of nitrate leaching by 13% was achieved when 1000 kg ha$^{-1}$ (or more) biochar was applied (Scenario 4). For smaller amounts, the reduction increased linearly from 0% to 13%. For nitrous oxide emissions, the emission reduction requires a minimum amount of 5000 kg biochar applied per hectare (Scenario 5). For lower biochar amounts, no effect was assumed. A nitrous oxide emissions reduction of 13% was modelled for the application of 5000 kg/ha or more biochar on the field.

## 2.3 Life Cycle Inventory

The life cycle inventory (LCI) includes the data collection and analysis of all relevant input and output flows. This includes a description of the data quality and the sources, allowing correct interpretation of the results. Since the pyrolysis process leads to more than one product, allocation is required to distribute the emissions and the environmental impacts to individual products, such as biochar and pyrolysis gas.

### 2.3.1 Biochar Production

#### *2.3.1.1 Life cycle inventories to model biochar production*

This chapter presents LCIs related to biochar production using information from the literature (Kumar, 2024; Sistek, 2021), calculations, and data from the ecoinvent v3.10 database. The functional unit is 1 kg biochar at farm. All LCIs were modelled for Switzerland and the current technological level in 2024. New inventories were developed when Swiss-specific data were not available in the ecoinvent database. When possible, processes labelled as {CH} were chosen. If no appropriate data or inventory was available, processes provided on the European market {RER} or global process {GLO} were selected. The inventories were modelled in SimaPro 9.6.01. Figure 3 provides an overview that includes all the processes for biochar production.

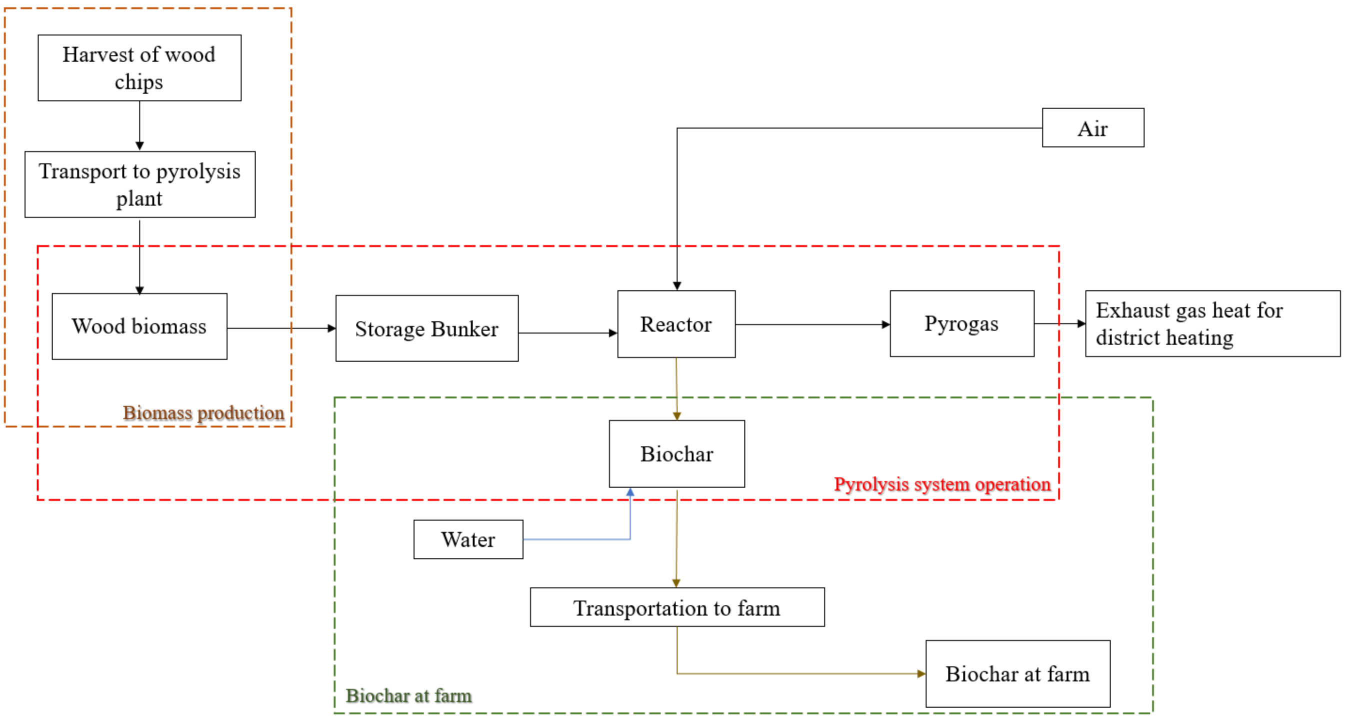


*Figure 3: Overview of the core and main processes for the biochar production in the pyrolysis plant.*

The production of biochar was modelled by the following four main LCIs: (i) wood biomass production, (ii) pyrolysis system operation with the two outputs biochar and pyrolysis gas (pyrogas), (iii) exhaust gas heat for district heating, and (iv) biochar at farm. Biochar at farm is the LCI used on the model farms. An overview of the entire system showing the single LCIs is displayed in Figure 4. The wood biomass enters the reactor where “Biochar” and “Pyrogas” are produced. The biochar product is then transported to the farm (“Biochar at farm”) to be used for the $CO_2$ capture, while the produced pyrogas is led to a combustion chamber. “Exhaust gas heat for district heating” describes the production of heat from the combustion of pyrogas.

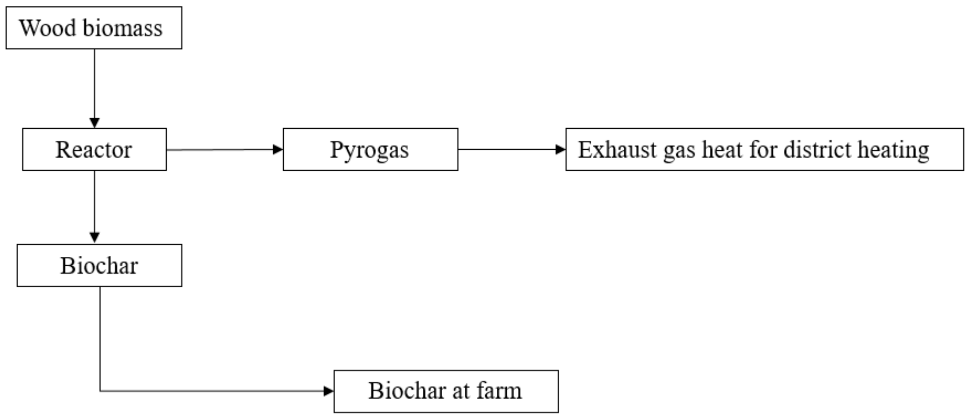


*Figure 4: Biochar production in a pyrolysis plant.*

Table 4 summarises the LCI modelling design for biochar production. We modelled the initial biomass feedstock wood and two other alternative biomasses (straw and landscape conservation wood). The second column of the table shows all the LCIs modelled for each of the three biomass feedstocks. The third column shows the environmental impacts analysed for the LCIs for each biomass feedstock. The "Ecological scarcity method" was computed for all three feedstocks but only for the final stage, that is, "Biochar at farm". The environmental impacts of biochar production are presented in Chapter 3.1, as well as in Appendix A.

Table 4: LCI modelling design for the biochar production: (i) modelled biomass feedstocks, (ii) LCIs used to model biochar production and (iii) the analysed environmental impacts.

| Biomass feedstock | LCIs used to model biochar production | Environmental impacts |
|---|---|---|
| Wood<br>Straw<br>Landscape conservation wood | Biomass feedstock<br>Storage bunker<br>Reactor<br>Pyrogas<br>Biochar<br>Exhaust gas heat for district heating<br>Biochar at farm | Global warming potential<br>Terrestrial acidification<br>Terrestrial eutrophication<br>Freshwater eutrophication<br>Marine eutrophication<br>Ecological scarcity method |

**LCI for wood biomass production**

This LCI describes the production of the wood biomass used to produce biochar. Wood chips were the main material input flow. It is assumed that the wood chips were harvested within a 25-km radius of the pyrolysis plant and were then transported to the pyrolysis plant by lorry. Thus, the "Transport, freight, lorry 3.5–7.5 metric ton, EURO4 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Cut-off, U" was selected as the second input from the technosphere. The LCI was modelled for 1 kg of wood biomass. The activity starts with harvesting wood chips and ends with their transportation to the pyrolysis plant. All the LCI data for this inventory are shown in Table A1 (Appendix A1).

**Pyrolysis system operation**

Following wood biomass production, the next step in the biochar production is the operation of the pyrolysis system. The pyrolysis system consists of several processes, including wood chip storage and pyrolysis in the reactor (Figure 5). The LCIs of the storage bunker and reactor are described in the following subchapters. Based on PYREG (2024), the pyrolysis system has a lifespan of 20 years, with 7500 working hours per year and an input feed rate of 311 kg of biomass per hour. Firstly, the wood biomass is stored in the storage bunker before entering the reactor. In the storage bunker, there are fans for air circulation, and this operation relies on electricity consumption (Sistek, 2021). When the wood biomass enters the reactor, biochar and pyrolysis gas are produced. The produced biochar is then transported to the farm, while the produced pyrolysis gas enters the combustion chamber. Air is needed for the operation of the combustion chamber. Therefore, “Air” from the atmosphere was selected as an input from nature from the ecoinvent database.

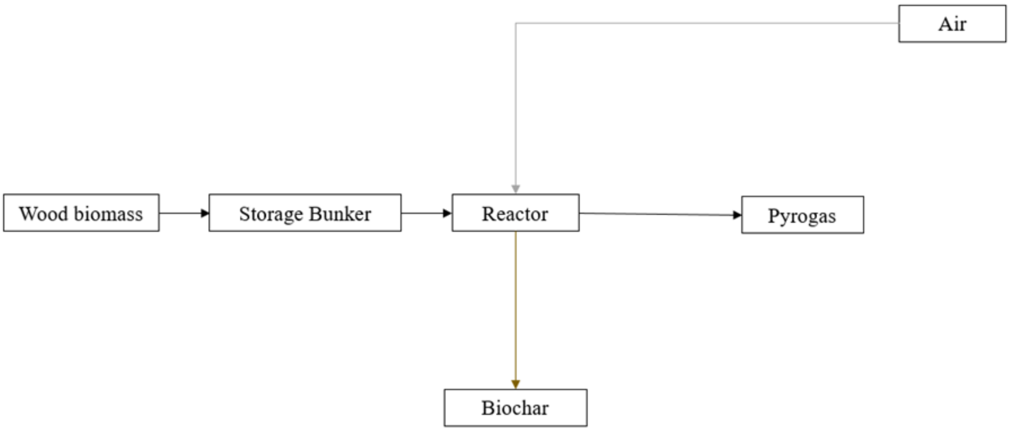


*Figure 5: Processes in the pyrolysis system operation of biochar production.*

An allocation of products between the “Biochar” and “Pyrogas” products was applied. Regarding this allocation, different percentages of the aforementioned products were applied, according to the following equation:

$$f_{biochar} = H_{i,biochar}/(H_{i,biochar} + E_{Strom} + E_{W})$$

$H_{i,biochar}$ is the gross calorific value of biochar produced, $E_{Strom}$ is the amount of electricity sold from a pyrolysis unit, and $E_{W}$ is the amount heat that is used/sold from the pyrolysis unit, for example, to a district heating given in kWh (or MWh) per year. We assumed $H_{i,biochar}$ to be equal to 33’000 kJ/kg (9.2MWh/ton) for biochar. $E_{Strom}$ was set to 0, as for the pyrolysis unit considered here does not produce electricity (the biochar obtained from production facilities in Switzerland co-producing electricity is currently not used in agriculture). The thermal energy from the combustion of pyrolysis gas used in district heating or industrial processes ($E_{W}$) was set to 1.40 MWh/per ton of biomass treated (which can be converted into biochar). According to the calculation (see Appendix A3), the allocation was 69% for biochar and 31% for pyrogas. The LCI was modelled for the annual production of biochar and pyrogas, as well as the annual operation of the pyrolysis plant. The input and output data for the LCI pyrolysis system are provided in Table A2 (Appendix A1).

**Storage bunker**

The storage bunker LCI describes the building where the wood chips are temporarily stored. It contains data on how this building is constructed, which are the inputs from nature (e.g. occupation grassland), the inputs from the technosphere (e.g. concrete, sole plate, and foundation), as well as outputs to the technosphere (e.g. waste concrete) from deconstruction after the use phase. Concrete 25–30 MPA was chosen for the construction of the storage bunker, since this is the normal strength of concrete in this type of buildings. Then, the transition of woodchips in the storage bunker follows the pyrolysis system and biochar production. Inventories for Switzerland were chosen when possible. The LCI data of the storage bunker are shown in Table A3 (Appendix A1).

**Reactor**

This inventory contains as input from the technosphere all the materials required for the construction of the reactor, and as output to the technosphere the waste from the deconstruction of the reactor. The quantities of products, materials, and wastes are based on the literature (Kumar, 2024). This activity comprises the reactor’s construction and deconstruction after its use phase. Table A4 (Appendix A1) provides the LCI data for the reactor.

***Concrete, 25–30 MPa {CH}| market for concrete, 25–30 MPa | Cut-off, U***

This LCI was created for use as an input for the storage bunker inventory. It includes data from two other concrete inventories that can be found in the ecoinvent database: "Concrete, 25MPA {CH}| market for concrete, 25 MPA| Cut-off, U" and "Concrete, 30 MPA {CH}| market for concrete, 30 MPA| Cut-off, U". Based on a literature review, the strength values for normal-strength concrete buildings range between 25 and 30 MPA. There are no 25 or 30 MPA concrete inventories for Switzerland in the ecoinvent database and SimaPro. Therefore, data for the aforementioned inventories related to the concrete type and their transportations were exported to be used as inputs from the technosphere. Table A5 (Appendix A1) shows all LCI data for "Concrete 25–30 MPA {CH}".

**Exhaust gas heat for district heating**

The "Exhaust gas heat for district heating" LCI describes the production of heat from the combustion of pyrogas. The pyrogas produced from the pyrolysis plant flows to a combustion chamber (Figure 5). Before entering the combustion chamber, the pyrogas passes through a gas filter to remove any biochar particles from the gas and to avoid ash formation in the burning chamber. This filter must be backwashed with nitrogen gas to remove particles from its surface. As no inventory for nitrogen gas or on-site small-scale production of nitrogen was available, liquid nitrogen was used. The pyrogas then enters the combustion chamber, where it is ignited with air. During the startup phase, liquefied petroleum gas is used. After combustion, 32,941,120 MJ of exhaust gas heat generated from the combustion chamber is transferred to a heat exchanger. The amount of 18,460,960 MJ "Exhaust gas heat for district heating" is produced from the heat exchanger, while 4,428,640 MJ return to the combustion chamber to aid the combustion of pyrolysis gas. The rest of the energy is lost to the surroundings and to the atmosphere through the chimney during the emission of exhaust gas, or used to dry the biomass. Electricity is used for the operation of the combustion chamber. Various exhaust gases from combustion are released into the atmosphere through a chimney. This LCI was modelled for the annual operation of the pyrolysis plant.

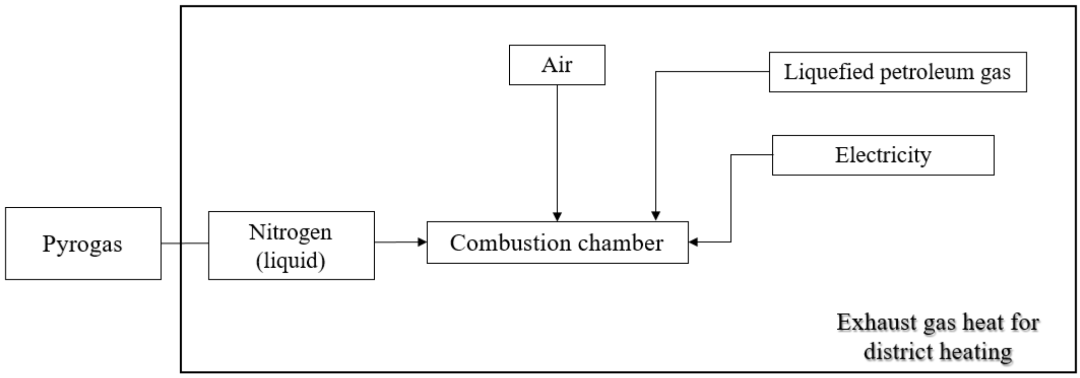


*Figure 6: Description of the processes of the life cycle inventory "Exhaust gas heat for district heating".*

**Biochar at farm**

The biochar is obtained from the pyrolysis operation process and sprayed with water to avoid self-ignition and dust formation. This happens right after the pyrolysis and is an integral part of the pyrolysis unit. Following this process, the biochar is collected in large bags and then transported to the farm by a small lorry. Based on the literature data (Kumar, 2024), the amount of biochar obtained per reference flow of 1 kg of woodchips is equal to 0.302 kg, the tap water added to the biochar is equal to 0.061 kg, and the transport to the farm is 0.00605 tkm for 1 kg of biochar. This results in a total of 0.363 kg “Biochar at farm”. Table 5 includes all the LCI data for the annual production of biochar from the pyrolysis plant.

Regarding the modelling of this inventory, as an input from the technosphere, the “Biochar” product from the pyrolysis system operation process and the “Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U” were selected. In addition, the “Tap water {CH}| market for tap water | Cut-off, U” was selected as input from the ecoinvent database, as it contained data for the tap water in Switzerland and local data were required for the project. This activity starts when biochar is in the freight lorry for transport to the farm and ends when it arrives at the farm. Figure 7 schematically describes this inventory.

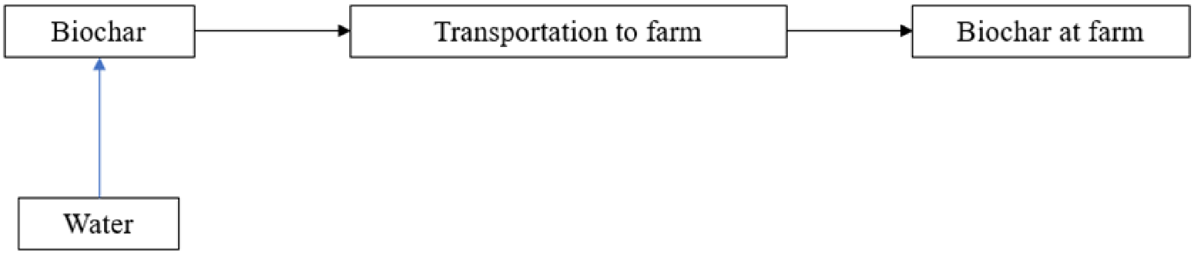


*Figure 7: Flow chart of the processes of the life cycle inventory biochar at farm.*

Table 5: LCI data for “Biochar at farm”.

| | Amount | Unit | Alloction |
|---|---|---|---|
| **Outputs: Products** | | | |
| Biochar at farm | 895,680 | kg | 100% |
| **Inputs from the technosphere: Materials/fuels** | | | |
| Biochar | 746,400 | kg | |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 \| Cut-off, U | 4,515.72 | tkm | |
| Tap water {CH}\| market for tap water \| Cut-off, U | 149,280 | kg | |

#### *2.3.1.2 Alternative biomass feedstock for biochar production*

Today, biochar in Switzerland is still produced only from wood, although the wood has different origins (forest wood, landscape conservation wood), as Swiss regulations have limited biochar production to this type of feedstock. The new Fertilizer Ordinance allows the use of biochar produced from virtually all types of plant biomass. Therefore, we modelled the biochar production from straw and landscape conservation wood following the same procedure as for the biochar production from forest wood chips. For the production of 1 kg straw biochar, 5 kg of straw biomass is needed, whereas for the production of 1 kg landscape conservation wood biochar, 3 kg of landscape conservation wood biomass is needed (pers. communication of IWB). We assumed that these feedstocks are transported to the pyrolysis plant with a freight, lorry 3.5–7.5 tonne with 0.025 tkm for the straw biomass and 0.045 tkm for the landscape conservation wood biomass (personal communication IWB). We applied energy allocation for all biochar feedstocks; that is, the allocation factors are the same as for wood biomass production.

The procedure used to model the above-mentioned feedstocks closely followed the production of wood biochar. More specifically, an LCI for each biomass feedstock was modelled, followed by the LCI for the pyrolysis system operations, the exhaust gas heat for district heating, and, lastly, the biochar at farm. The LCI for straw and landscape conservation wood can be found in Table A5 (Appendix A1) and Table A9 (Appendix A2), respectively.

## 2.4 Model Farms

A model farm represents a large sample of farms that typically use biochar. Model farms enable the quantification of percentage changes in emissions and environmental impacts between no use and use of biochar. To represent a broad range of existing Swiss agricultural farms, we selected the following three different farm types: (i) dairy farms, (ii) pig farms, and (iii) vegetable farms. The selection of these three model farms is supported by both experts and a 2023 survey of Swiss farmers, which identified the farms that are already using or would be willing to use biochar and for which application purposes (Dittmann and Baumann, 2023). The procedure for the construction of the model farms was based on the following considerations:

(i) The model farms should represent a typical farm for the given farm type.
(ii) The calculated emissions and environmental impacts for the model farms should allow a reasonable projection at the national level.

For this analysis, we used census data from the farm structure survey conducted by the Swiss Federal Office of Agriculture (FOAG) and the Swiss Federal Statistical Office (FSO). This survey conducted annually is perfectly tailored to our purposes, as it includes detailed information on livestock (in numbers and livestock units [LU]) and the area of different landscape elements (arable land, grassland) of all Swiss farms. We used the 2023 census data.

Each model farm was constructed from the average of the livestock units and land categories of the utilised agricultural area (UAA) in the sample. This allowed simple subsequent extrapolation to the Swiss level by multiplying the model farm’s results (of emissions and environmental impacts) by the number of farms in the sample (also called “represented farms”). From visual inspection of appropriate figures based on farm census data and the fact that typical dairy, pig, and vegetable farms should have a strong focus on cattle, pig, and vegetable, respectively, we formulated a short list of conditions that defines the sample the model farm is constructed from. The conditions for constructing the three model farms were set as shown in Table 6 and require that we:

(i) Exclude very small farms (regarding UAA), except for pig farms, as there is a significant number of this farm type without own cultivated land areas. This was achieved by the restriction $UAA > 1$ ha.
(ii) Focus on farms with considerable livestock in the relevant animal category. This was achieved by requiring that cattle and pigs account for more than 80% and 70% of the total livestock for dairy and pig farms, respectively.
(iii) Select the thresholds that allow the inclusion of a substantial percentage of the total cattle and the total UAA in the plain region in the sample (see Figure 8).

Table 6: Conditions (threshold values for sampled farms to build the three model farms (dairy, pig, and vegetable). UAA: used agricultural area; LU: livestock units; $a_{veg}$: vegetable-growing area.

| Model farm (type) | Region | Constraint UAA | Constraints Livestock | Constraint vegetable area |
|---|---|---|---|---|
| Dairy farm | Plain | $UAA > 1$ ha | $LU_{cattle} > 30$<br>$LU_{cattle} > 80\%$ of $LU_{tot}$ | - |
| Pig farm | Plain | - | $LU_{pig} > 5$<br>$LU_{pig} > 70\%$ of $LU_{tot}$ | - |
| Vegetable farm | Plain | $UAA > 1$ ha | - | $a_{veg} > 0.5$ ha<br>$a_{veg} > 20\%$ of UAA |

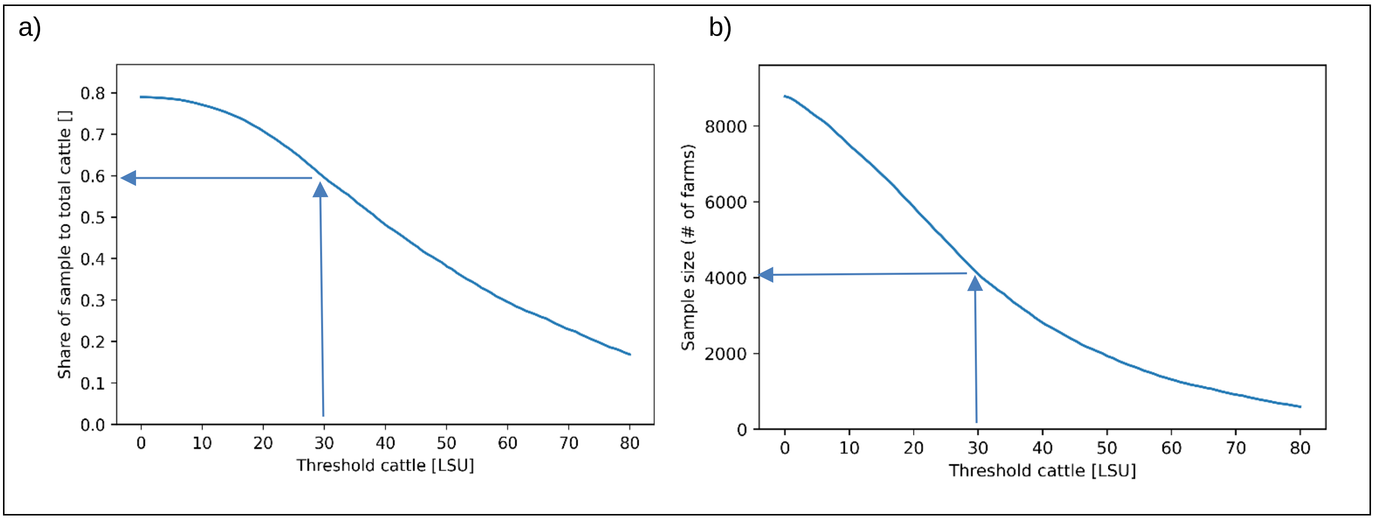


*Figure 8: (a) Share of cattle in the sample to the total cattle (in the plains). (b) Number of farms in the sample, depending on the selected threshold (minimal livestock required).*

Figure 8 reveals that the sample comprising all farms with more than 30 LU cattle covered approximately 60% of the total cattle population in the plain region (panel a) and a sample size of about 4000 farms (panel b). Note that the share in panel (a) does not reach 100% when setting the threshold to 0 LU, as the other conditions provided in Table 6 excludes certain farms with cattle husbandry, thus reducing the sample size. All farms fulfilling the conditions described in Table 6 were selected from the 2023 FSO farm census. The average of the selected farms was taken to create a model farm. One model farm therefore contained all possible livestock categories, and all land categories found on the selected farms, with the number of livestock or hectares as average among the selected farms.

As Swiss farms are quite diverse, the model farms also cover a high number of different land and livestock categories. All three model farms had 122 different land categories and 51 different livestock categories. The land categories were given in hectares and the livestock in number of animals as well as in LU. The inventories recently developed by the LCA research group at Agroscope for various land and livestock categories using the SALCA method were used for the model farms. For the livestock categories, there were 15 SALCA inventories available for the 51 FSO farm census livestock categories. Therefore, the livestock categories assigned to the same inventory were summed up together as a "revised" livestock category (Table B2, Appendix B2). For each model farm, we decided to consider the land categories accounting for more than 0.1% of the total UAA of the farm and the livestock categories accounting for more than 0.1% of the total livestock (unit: LU) of the farm (Table 7).

Table 7: Land and livestock categories accounted for in the model farms. UAA: used agricultural area. LU: livestock unit

| Model farm | Dairy farm | Pig farm | Vegetable farm |
|---|---|---|---|
| Nb of land categories ≥ 0.1% total UAA / Nb of total agricultural land elements | 29/122 | 36/122 | 45/122 |
| Percent of model farm UAA accounted | 98.45% | 98.70% | 98.67% |
| Nb of "revised" livestock categories ≥ 0.1% total LU/Total nb of "revised" livestock categories | 12/17 | 11/17 | 12/17 |
| Percent of livestock accounted (given in LU) | 99.90% | 99.85% | 96.95% |

Initially, the SALCA inventories were created for individual land category or livestock category. However, when multiple inventories were assembled to create a model farm, the following adaptations of those inventories were necessary to consider the farm as a system:

i. Adaptation of animal feed import: In the initial inventory for livestock, all types of animal feed are considered 100% imported. In the model farms, some of this feed is produced on-farm (e.g. the feed "Silage maize" comes from silage maize produced on the farm). Therefore, the percentage of feed imports had to be adapted according to the animal feed requirements of the farm and the yield of the relevant land categories.

ii. Adaptation of organic manure usage: In the initial inventories, some of the land categories are fertilised with liquid and solid manure with a Swiss average nutrient composition. All three model farms have livestock that produces manure. The SALCA inventories for land categories were therefore adapted so that the liquid and solid manure applied to the fields was the manure produced on farm rather than the standard Swiss average manure. In addition, the export of liquid and solid farm manure was added if the nutrient supply from farm manure exceeded the UAA requirements. Similarly, an import of average liquid and solid manure was added if the nutrient supply from farm manure did not meet the UAA requirements.

iii. Adaptation of purchased and sold animals: In the SALCA inventories for livestock, the number of animals that are exported (e.g. dead, slaughtered, re-categorisation due to animal age) and imported (to equilibrate the exports) is indicated. For the three model farms, the export or import sometimes corresponds to a transfer from one SALCA inventory to another (e.g. calves going to beef cattle husbandry, cattle raising going to dairy cows) and therefore should not be considered as an import from outside the farm. The livestock numbers were therefore adapted accordingly.

We assumed that the whole biochar applied to animal bedding or as a swimming layer on the manure storage (slurry pit) stayed entirely on the farm and was spread to the fields with the manure. However, in reality, the biochar from animal bedding or from manure storage cannot be separated from the manure, and part of it is exported with the exported manure on dairy and pig farms. We decided to ignore the exported 10% of the manure produced on the dairy farm (74 $m^3$ out of 699 $m^3$). However, 89% of the liquid manure produced on pig farms is exported (1386 $m^3$ out of 1556 $m^3$). This is explained by the fact that the pig farm has many animals but a limited UAA (see Table 8). We accounted for this by system expansion. With the assumption that all exported manure stays inside Switzerland, we decided to add agricultural land to the pig farm to account for the additional surfaces fertilised with the exported liquid and solid manure containing biochar. To use all liquid manure produced on the farm, 70.8 ha was added to the initial 19.1 ha of the pig farm. The additional land categories making up these 70.8 ha were determined based on the Swiss average. This means that all land categories fertilised with liquid manure in Switzerland were aggregated per land category, and their total hectares were proportionally adapted for the liquid manure quantity to correspond to the quantity exported by the pig farm.

The total GHG emissions from the pig farm (enhanced by additional land to apply the on-farm produced farm manure) therefore increased, but the difference in GWP between scenarios with biochar application and the baseline were closer to reality, as the concentration of biochar in farm manure was corrected (instead of having the entire biochar mixed in 11% of farm manure), and the effects of field application of manure containing biochar included the land fertilised with exported manure. Upscaling to the Swiss agricultural sector was then performed with the modified pig farm. Even with this extension of the system boundaries, the total UAA represented by the dairy farm, the modified pig farm, and the vegetable farm still accounted for only 54% of the total UAA of the plain region in Switzerland (see Section 3.6).

### 2.4.1 Description of the Model Farms

Table 8 below summarises the agricultural area and the livestock per model farm. Arable land includes cropland and temporary leys. Grassland includes natural meadows and pastures.

Table 8: Agricultural area and livestock per model farm. UAA = utilised agricultural area; LU = livestock units.

| | Total UAA (ha) | Arable land (ha) | Grassland (ha) | Livestock number | Total livestock (LU) |
|---|---|---|---|---|---|
| Dairy farm | 39.9 | 23.3 | 17.7 | 140.0 | 58.7 |
| Pig farm | 89.9 | 45.3 | 44.1 | 757.8 | 91.7 |
| Vegetable farm | 27.4 | 21.9 | 4.0 | 553.8 | 10.8 |

Regarding the total UAA per model farm, Figure 9 illustrates the different land categories. Tables B3, B5, and B7 in Appendix B give a complete list of land categories and their respective areas in ha for the dairy, pig, and vegetable farms, respectively. For dairy farms, 58% of their total UAA is arable land, and 39% is grassland. For the pig farm, 50% of its total UAA is arable land, and 49% is grassland. For the vegetable farm, 80% of its total UAA is arable land, and 15% is grassland.

Figure 10 displays the livestock categories per model farm. Tables B4, B6, and B8 in Appendix B give a complete list of livestock categories, the number of animals, and LU per category for the dairy, pig, and vegetable farms, respectively. Figure 11 and Figure 12 visualise the quantity of liquid and solid manure per usage type and per model farm. Figure 13 shows the volume of liquid manure storage per cover type and per model farm.

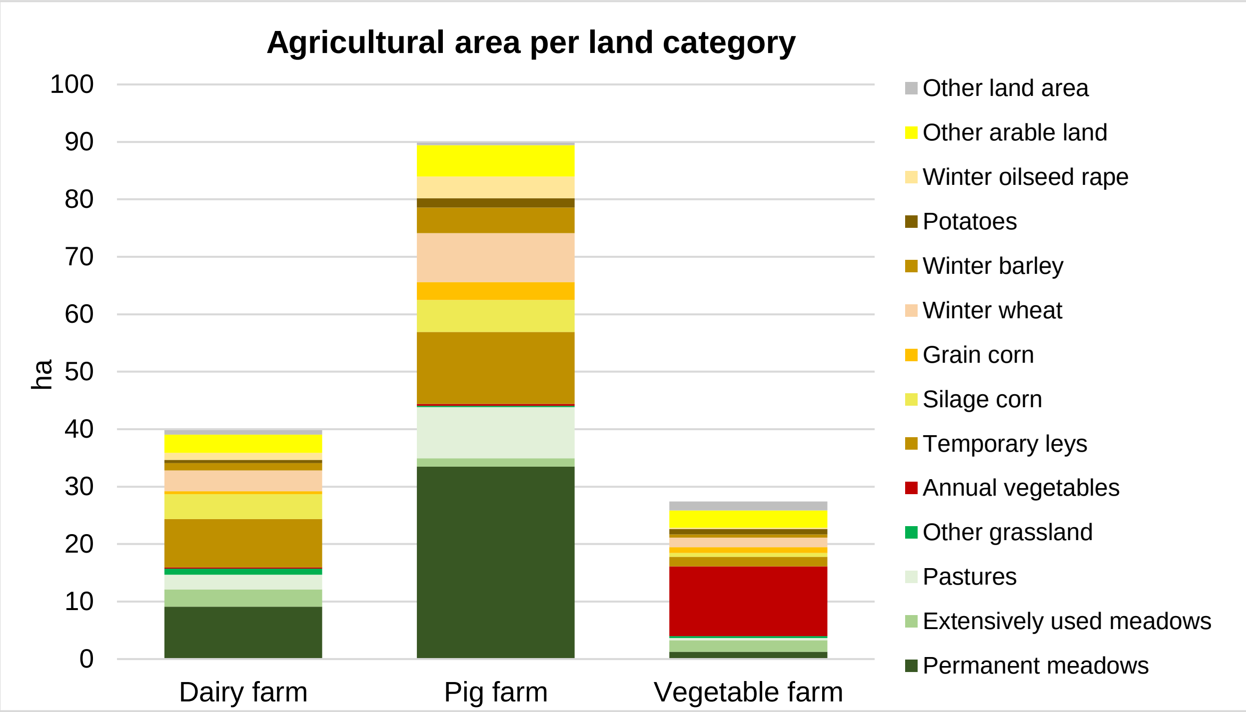


*Figure 9: Distribution between the different land categories of the utilized area per model farm.*

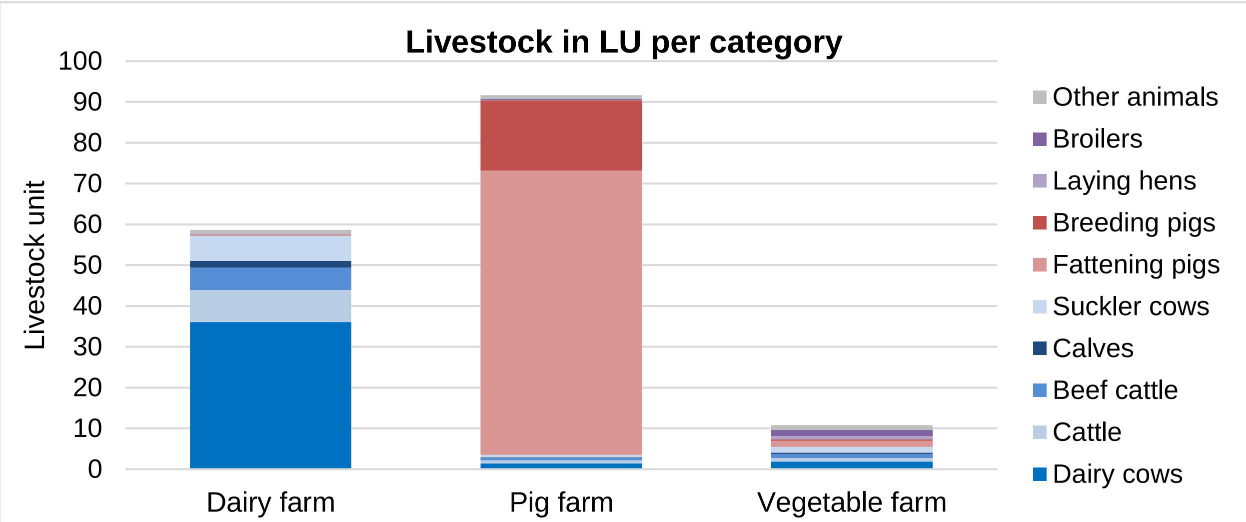


*Figure 10: Livestock (in LU) per category and per model farm.*

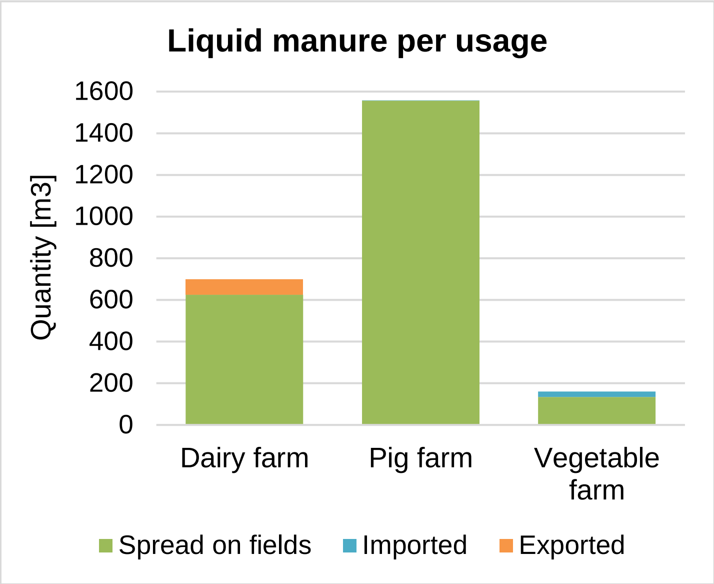


*Figure 11: Quantity of liquid manure per usage type and per model farm.*

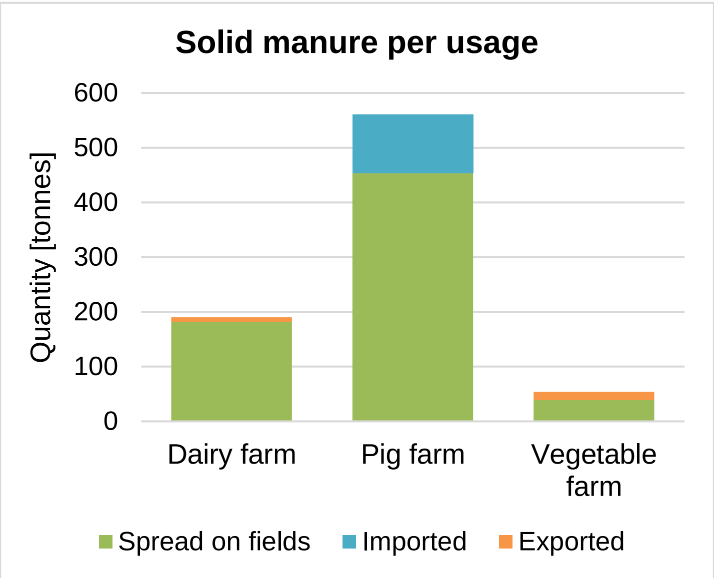


*Figure 12: Quantity of solid manure per usage type and per model farm.*

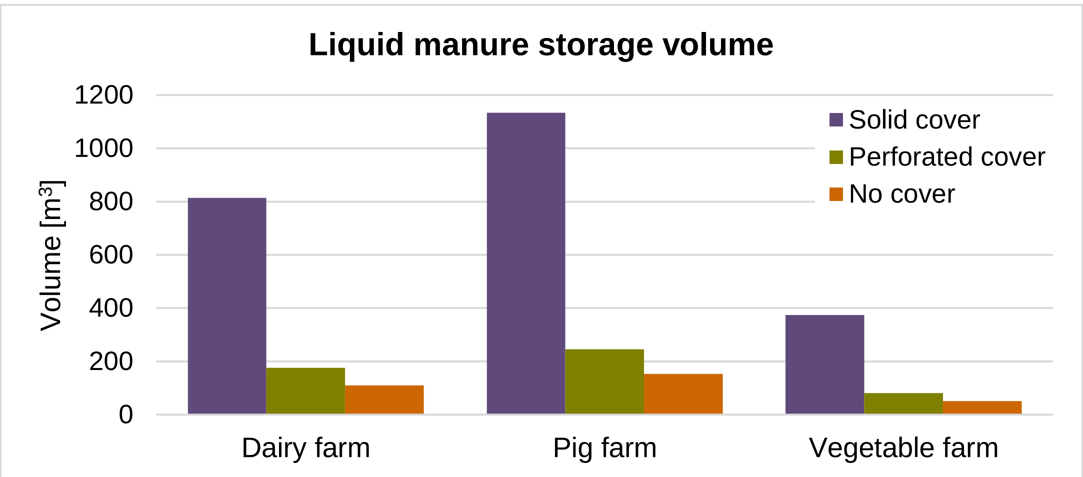


*Figure 13: Volume of liquid manure storage per cover type and per model farm.*

## 2.5 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) phase – the third LCA stage – translates the gathered LCI data on resource and material use into environmental impacts. LCIA distinguishes between midpoint and endpoint impact assessment levels. Midpoint indicators are closely linked to the inventory and capture the impact between emissions/resource use and final damage. By contrast, endpoint indicators focus on the final damage further along the cause-effect chain. This study focuses on GWP100, a midpoint indicator that quantifies the climate change impact related to GHG emissions. $CO_2$, $N_2O$, and $CH_4$ are relevant GHG in the context of agriculture. This method describes the radiative forcing accumulated over 100 years. This study used a recently updated LCIA framework, the SALCA-LCIA, version 2.01 (Douziech et al., 2024), which accounts for land use and land use change and carbon cycle response but ignores biogenic carbon emissions (IPCC, 2021). The results for midpoints other than the GWP can be found in the Appendix. Here, we provide relevant publication sources and units for selected midpoints and resources (Table 9).

Table 9: LCI and midpoint indicators (resources and environmental impacts), as suggested in SALCA v2.01. (*) Land occupation can also be computed separately for agricultural land/ non-agricultural land/ agricultural food and agricultural non-food.

| Impact category | LCI/ midpoint | Method used | Unit |
|---|---|---|---|
| Climate change impact GWP100 | Midpoint | GWP100 fossil & LULUC including carbon cycle response, without biogenic carbon dioxide emissions (IPCC, 2021) | kg $CO_2$ eq (kilograms of carbon dioxide equivalents) |
| Terrestrial acidification | Midpoint | ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017) | kg $SO_2$ eq (kilograms of sulphur dioxide equivalents) |
| Marine eutrophication | Midpoint | ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017) | kg N-eq (kilograms of nitrogen equivalents) |
| Freshwater eutrophication | Midpoint | ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017) | kg P-eq (kilograms of phosphorus equivalents) |
| Terrestrial eutrophication | Midpoint | Environmental Footprint 3.1 (Bassi et al., 2023) | mol N-eq (mols of nitrogen equivalents) |
| Water scarcity | Midpoint | Available Water Remaining AWARE (Boulay et al., 2018) | $m^3$ world-eq (impact of 1 $m^3$ water consumption, normalised to global average) |
| Freshwater ecotoxicity | Midpoint | USEtox 2 (recommended + interim) v2.12 (USEtox, 2019) | PAF $m^3$ day (potentially affected fraction (PAF) of species per cubic meter per day |
| Terrestrial ecotoxicity | Midpoint | LC-Impact - Terrestrial average, time horizon 100y (Verones et al., 2020) | PAF $m^3$ day (potentially affected fraction (PAF) of species per cubic meter per day |
| Abiotic resource use | LCI | CML-IA (baseline), abiotic depletion (elements, ultimate reserve) (CML, 2016) | kg Sb-eq (kilograms of antimony equivalents) |
| Renewable resource use | LCI | Cumulative energy demand for “renewable resources” (Frischknecht et al., 2007) | MJ |
| Non-renewable resource use | LCI | Cumulative energy demand for “renewable resources” (Frischknecht et al., 2007) | MJ |
| Water use | LCI | Based on LCI results | $m^3$ |
| Land occupation – Total (*) | LCI | ReCiPe Midpoint (H) v 2008, only Agricultural land occupation, urban land occupation (Goedkoop et al., 2009) | $m^2$ |

In addition, we list detailed results for the endpoint indicator UBP ("Umweltbelastungspunkte"). The calculation of the environmental impact points is based on the concept of ecological scarcity (Frischknecht et al., 2006). It allows a comparative weighting of different environmental effects through the use of so-called 'ecofactors'. It includes a weighting in terms of their impact on health, the climate, and various ecosystems.

## 2.6 Extrapolation to Switzerland

The extrapolation (projection) of the results (changes in emissions and environmental impacts) to the whole of Switzerland is one of the major goals of this project. To achieve this task, the results of the three model farms were multiplied by the number of farms they represent at the level of Switzerland. The dairy farm represents the average of 4,096 farms, the pig farms of 939 farms, and the vegetable farm of 654 farms. The pig farm used in the extrapolation is a modified pig farm with 89.9 ha UAA. Note that the extrapolation to the Swiss agricultural sector is *not* an upscaling to all Swiss farms but only to farms that already or would be ready to apply biochar on their farm. Thus, the sample includes 4096 + 939 + 654 = 5689 farms represented by the three model farms. This sample comprises 11.9% of all 47719 Swiss farms in 2023 (FSO, 2023).

As the percentage of the accounted UAA and livestock in the model farms was close to 100% (Table 7), we assumed that the modelled land and livestock categories represent 100% of the model farm. In other words, we ignored the land and livestock categories accounting for less than 0.1% of the total UAA or total livestock in our extrapolation. Another reason for this decision is that most land categories that accounted for less than 0.1% of total UAA of the farm were among others permanent cultures (e.g. trees) and other biodiversity surfaces, summer grazing areas, forest pastures, and were unlikely to be amended with biochar.

The three model farms represent an average of the three major types of farms with high potential for using biochar. Based on the results of the three model farms, we provide an extrapolation to Switzerland. As explained in Section 2.4, the farms expected to use biochar are more likely larger farms in the plain region. Therefore, the extrapolation to entire Switzerland should not account for the whole Swiss agricultural area but only for those larger farms with potential for biochar usage. Figure 14 confirms this assumption. With a total of 265,575 ha, the three model farms considered in this project represent 54% of the UAA of the plain region and 25% of the total Swiss UAA[5]. Per land category, this represents 47% of the arable land, 73% of the grassland, and 19% of the other land area[6] of the plain region (Figure 14).

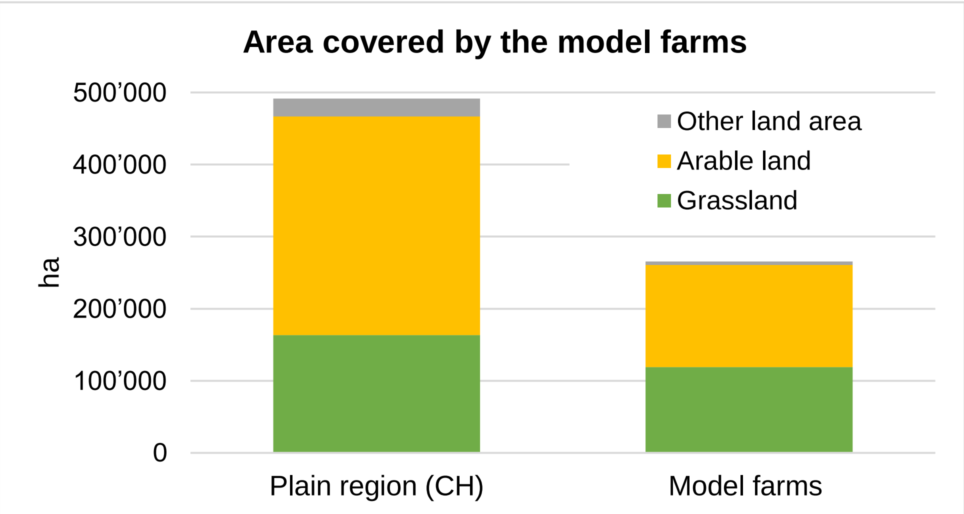


*Figure 14: Comparison of the total UAA in the Swiss plain region with the area represented by the model farms.*

[5] The total UAA in Switzerland is 1'043'558 ha, and the total UAA in the plain region is 491'525 ha.
[6] The category « other land area » includes, among others, permanent crops such as fruit trees and vines as well as land with other uses such as peatland.

# 3 Results

## 3.1 Emissions and environmental impacts of biochar production

In the following chapter, the GWP of biochar production is shown. Furthermore, we provide the contributions of $CO_2$, $CH_4$, and $N_2O$ to the GWP. Finally, the GWP of biochar produced from different feedstocks are compared. Most of the results refer to the LCI for "Biochar at farm", because it represents biochar applied on the farm. Environmental impacts other than GWP are displayed in Appendix A.

### 3.1.1 Contribution Analysis for Global Warming Potential

Most of the GWP impacts of biochar production from wood biomass are related to the use of wood biomass as feedstock, and more specifically to the biochar product used in the LCI "Biochar at farm" (153.5 $10^{-3}$ kg $CO_2$-eq). Transport and the use of tap water have only very small contributions (3.4 $10^{-3}$ kg $CO_2$-eq, and 0.01 $10^{-3}$ kg $CO_2$-eq).

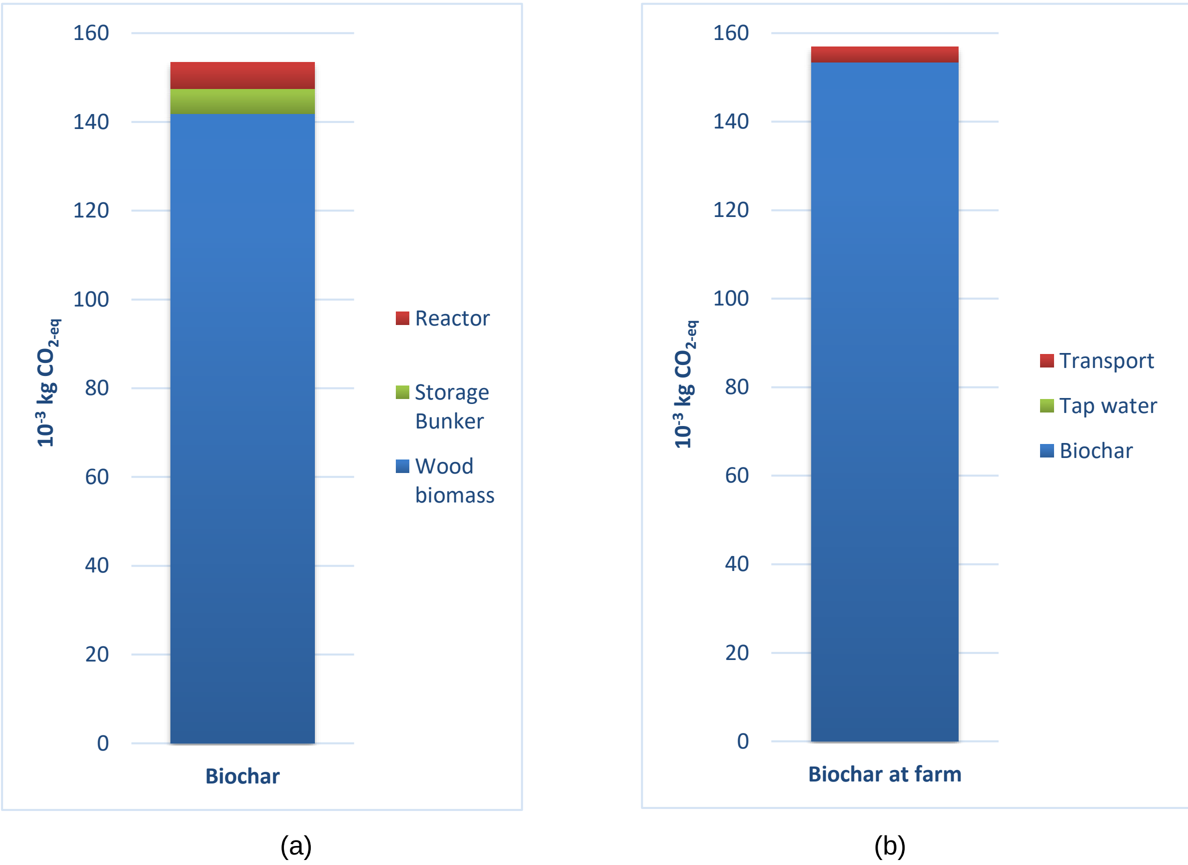


*Figure 15: (a) GWP of the LCI "Biochar" in the production of biochar (at farm gate) based on feedstock "Wood".*
*(b) GWP of the LCI "Biochar at farm" in the production of biochar (at farm gate) based on feedstock "Wood".*

### 3.1.2 Contributions of $CO_2$, $CH_4$, and $N_2O$

The last step in the environmental impact analysis is the contribution analysis of $CO_2$, $CH_4$, $N_2O$ in the LCI "Biochar at farm". As shown in the Table 10, $CO_2$ emissions contribute a percentage of 87% and $CH_4$ emissions a percentage of 12%, while $N_2O$ emissions have the smallest percentage, 1%. The $CH_4$ emissions at 12% are mainly related to producing the biochar feedstock, that is, from the input "wood biomass" in the LCI "Biochar" and the "wood chips" input used to produce the wood biomass. $CO_2$ and $N_2O$ emissions come from the production of wood biomass and biochar. The visualisation of the GHG contributions (in $CO_2$-eq) as a pie chart is presented in Table A20 (Appendix A9).

Table 10: Contribution of $CO_2$, $CH_4$, $N_2O$ to the GWP of biochar at farm (units: $CO_{2\text{-eq}}$).

| GHG | Amount | Unit | Share [%] |
|---|---|---|---|
| $CO_2$ | 134.4 | $10^{-3}$ kg $CO_{2\text{-eq}}$ | 87 |
| $N_2O$ | 1.31 | $10^{-3}$ kg $CO_{2\text{-eq}}$ | 1 |
| $CH_4$ | 18.3 | $10^{-3}$ kg $CO_{2\text{-eq}}$ | 12 |

### 3.1.3 Alternative Biomass Feedstock for Biochar Production

Figure 16 summarises the GWP for biochar production based on different feedstocks. If the biochar is made from wood chips, landscape conservation wood, or straw, its production emits 0.153, 0.063, and 0.373 kg $CO_2$-eq for 1 kg biochar, respectively. As for biochar produced from wood chips, the main contribution to the environmental impacts of biochar from landscape conservation wood and straw is feedstock (Appendix A10).

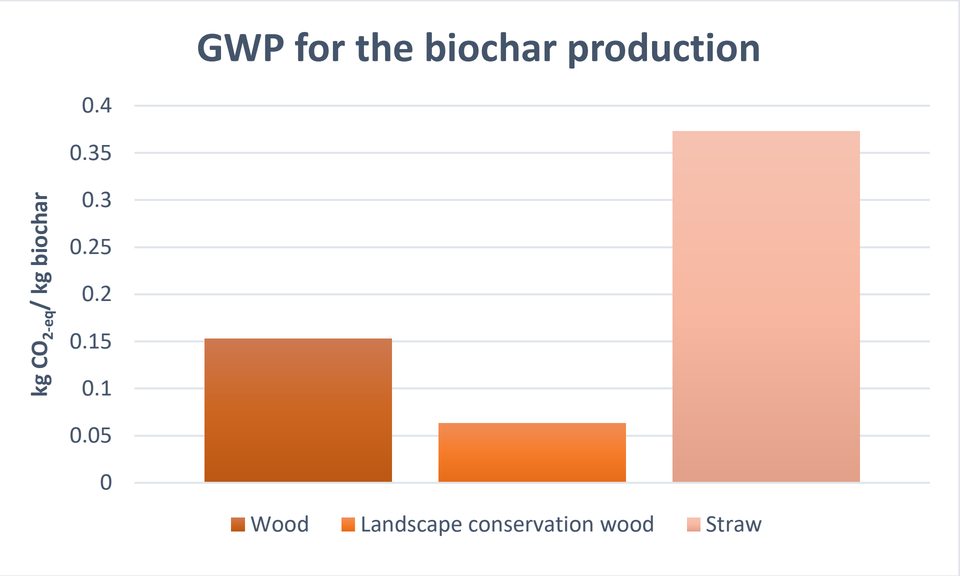


*Figure 16: GWP for the production of biochar from different feedstock.*

*Comparison of the three biochar feedstocks*

The comparison of the contribution analysis for the three analysed LCIs—(i) “Biochar (wood) at farm”, (ii) “Biochar (straw) at farm”, and (iii) “Biochar (landscape conservation wood) at farm”—reveals that in all three cases $CO_2$ contributes most to the GWP (Figure 17). The percentage contributions are 87%, 89%, and 52% for biochar produced with wood, landscape conservation wood, and straw, respectively. The smallest relative contribution of $N_2O$ to the GWP is found in the wood (1%) and landscape conservation wood (1%) biochar, while the smallest contribution of $CH_4$ is found in the straw biochar (7%). The small percentages of $CH_4$ for “Biochar (straw) at farm” are linked with the amounts of the “Straw biomass” and the “Straw stand alone” (“Straw, stand-alone production {CH}| straw production, stand-alone production | Cut-off, U” in the Ecoinvent database) that is used to produce the straw biomass (Table 11). The differences in the percentages of $CH_4$ and $N_2O$ for straw and landscape conservation wood biochar are due to the different feedstocks used for the production of biochar. $CH_4$ emissions occur during the intermediate storage of wood chips, which are less relevant in straw. Moreover, the amount (in kg) of each feedstock needed to produce biochar differs. Therefore, the feedstock material, as well as the amount required to produce a certain amount of biochar, plays an important role in the reduction of GHG emissions.

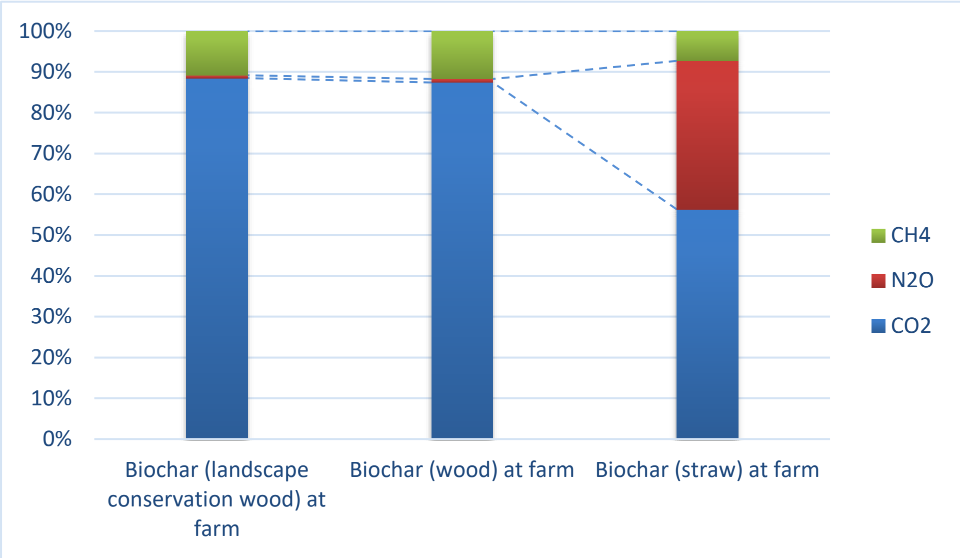


*Figure 17: Comparison of the contribution analysis for the LCI "Biochar at farm" for the three feedstocks.*

Table 11: Contributions of $CH_4$ and $N_2O$ for the production of biochar with straw as feedstock (at farm).

| | **Biochar straw** | **Straw biomass** | **Straw, standalone production** | **Unit** |
|---|---|---|---|---|
| **$N_2O$** | 0.131 | 0.157 | 0.046 | kg $CO_2$-eq |
| **$CH_4$** | 0.021 | 0.024 | 0.007 | kg $CO_2$-eq |

### 3.1.4 Ecological Scarcity Method (UBP Method)

Detailed results for the endpoint category "Ecological Scarcity" for the LCI "Biochar at farm" for all feedstocks (wood, straw, and landscape conservation wood) are presented in Appendix A10. For wood feedstock, the five impact categories—energy resources, land use, global warming, main air emissions pollutants and particulates, and water pollutants—contribute more than 91% to the total UBP. The same five impact categories contribute 95% and 88% to the biochar produced from straw and landscape conservation wood, respectively.

## 3.2 Global Warming Potential of Biochar Application Scenarios

This section starts by presenting the GWP results for the baseline model farms, which do not use biochar application. The effects of the eight biochar application scenarios are then discussed relative to the baseline scenario. This section focuses solely on the change in GWP between the baseline and biochar application scenarios. The GWP associated with biochar production or carbon sequestration is not considered in this section.

The GWP of the baseline simulations amounts to 529,703 kg $CO_2$-eq, 753,115 kg $CO_2$-eq, and 200,735 kg $CO_2$-eq per year for the dairy, pig, and vegetable farms, respectively (Figure 18). Figure 18 shows the total GWP for 16 contribution groups, providing a more detailed insight into the share of these groups in the total GWP. It is striking that the relative share of individual contribution groups differs markedly between the three model farms. For dairy farms, the GWP is driven mainly (about 55%) by direct animal emissions. The other contribution groups each have a share of less than 10% of the GWP. For pig and vegetable farms, direct animal emissions and the purchased mineral fertilisers each contribute about 15% to the GWP. In pig farms, the purchased concentrate feeds also contribute about 20% to the GWP, and in vegetable farms, the use of machinery and fieldwork processes contribute about 15%.

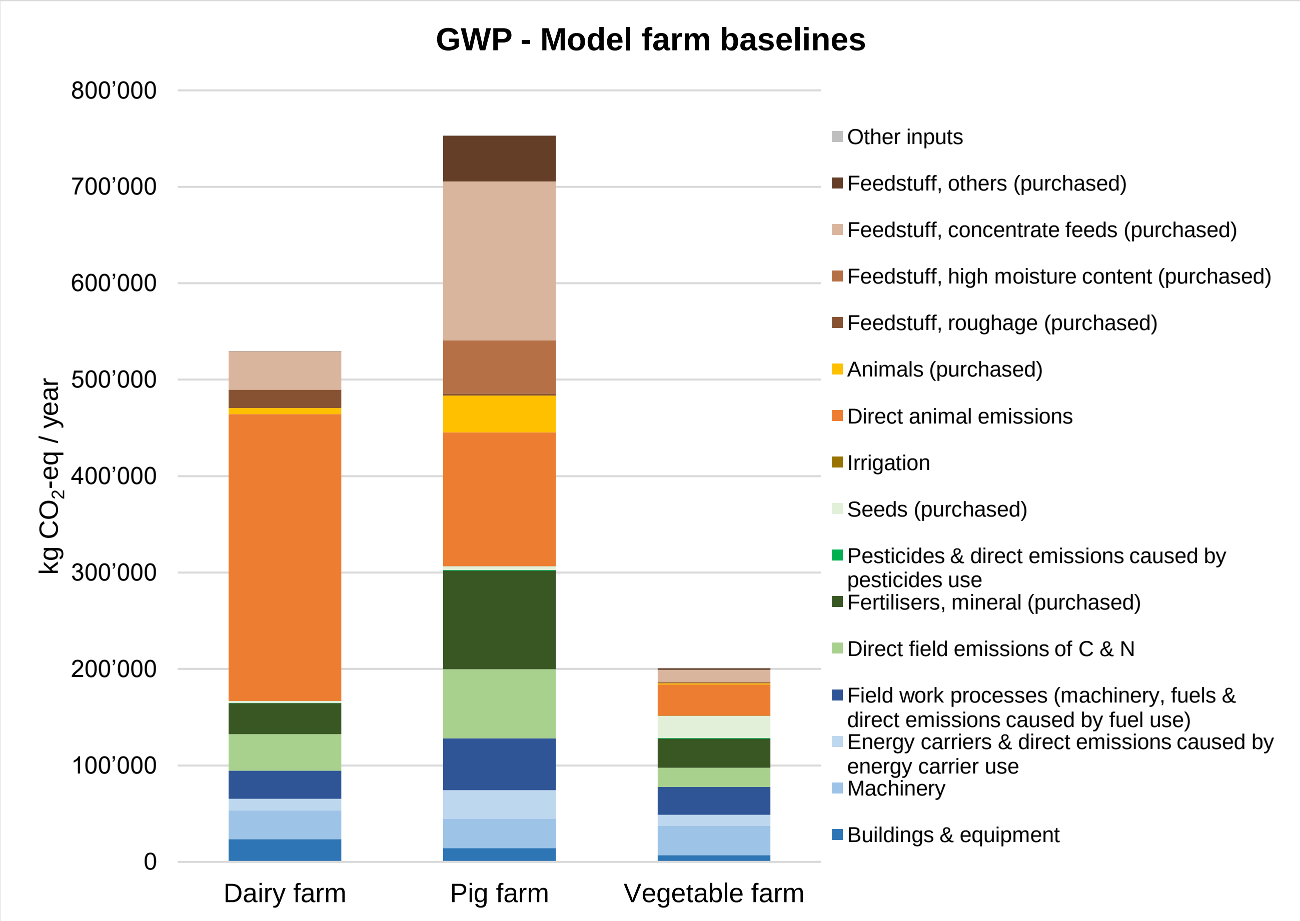


*Figure 18: GWP for the three analysed model farms (dairy/pig and vegetable farms).*

As described in Section 2.2.3.1, the impacts of the use of biochar were assessed for wood chip biochar and for the following three entry points: animal bedding, liquid manure storage, and direct soil application. The eight different scenarios considered are described in detail in Section 2.2.3.2 and are summarised in Table 12:

Table 12: Summary of the 8 scenarios to assess the cascade use of biochar with biochar quantity per scenario and per model farm.

| **Scenario** | **Entry point for biochar usage** | | | **Total biochar applied per model farm (kg)** | | |
|---|---|---|---|---|---|---|
| | **Animal bedding** | **Swimming layer in manure storage** | **Soil (kg/ha*)** | **Dairy farm** | **Pig farm** | **Vegetable farm** |
| **1** | 1% animal feed | - | - | 4,926.8 | 5,303.6 | 822.4 |
| **2** | 10% straw vol. | - | - | 27,851.8 | 8,765.5 | 5,123.7 |
| **3** | - | yes | - | 143.0 | 199.1 | 65.8 |
| 4 | - | - | 1000 | 238.3 | 297.0 | 12,157.7 |
| 5 | - | - | 5000 | 1190.4 | 1,483.9 | 60,739.7 |
| **6** | 1% animal feed | yes | 1000 | 5,308.1 | 5,799.8 | 13,045.8 |
| **7** | 10% straw vol. | yes | 5000 | 29,185.2 | 10,448.5 | 65,929.2 |
| **8** | 1% animal feed | - | 1000 | 5,165.1 | 5,600.7 | 12,980.0 |

*Only on land categories with annual field vegetables[7]

As discussed in detail in the next subsections, only two (out of the 16 shown in Figure 18) contribution groups are affected by the scenarios for biochar use:

- Direct field emissions of C and N: This group accounts for the emissions to air of $CO_2$, $NH_3$, $NO_x$, and $N_2O$, as well as for the emissions to water of $NO_3$ originating from mineral fertiliser and farm manure application, crop residues, leaching, runoff, and soil erosion.
- Direct animal emissions: This group accounts for the emissions to air of $NH_3$, biogenic $CH_4$, $NO_x$, $N_2O$ as well as for the emissions to water of $NO_3$ originating from the animal themselves, from the stable (e.g. from animal bedding), and manure storage.

### 3.2.1 Biochar in Animal Bedding

Scenarios 1 and 2 assess the impacts of biochar applied in animal bedding, irrespective of the housing system. Applying biochar to animal bedding leads to a reduction in the GWP compared to the baseline scenario (Figure 19). As the amount of biochar applied in animal bedding is higher in Scenario 2 than in Scenario 1 (see Table 12), the absolute difference between the GWP of Scenario 2 and the baseline is generally higher than for Scenario 1 (Figure 19). Dividing this result by the amount of biochar applied yields a GWP reduction that is similar for both scenarios (Figure 20). This is expected, as the quantification is the same (i.e. 1 g N sorbed per kg biochar). The decrease in GWP is related to decreasing direct field emissions of C and N and decreasing direct animal emissions. The latter can be explained by the sorption capacity of biochar, sorbing the nitrogen of animal excrements, which then reduces $NH_3$ volatilisation and $NO_x$ and $N_2O$ emissions from bedding. The decrease in direct field emissions relates to the reduction in $N_2O$ emissions and in $NO_3$ leaching from the soil from the field application of manure that contains biochar. The difference in total GWP therefore comes from the amount of biochar applied, which proportionally increases the emission reduction potential (see Figure 19).

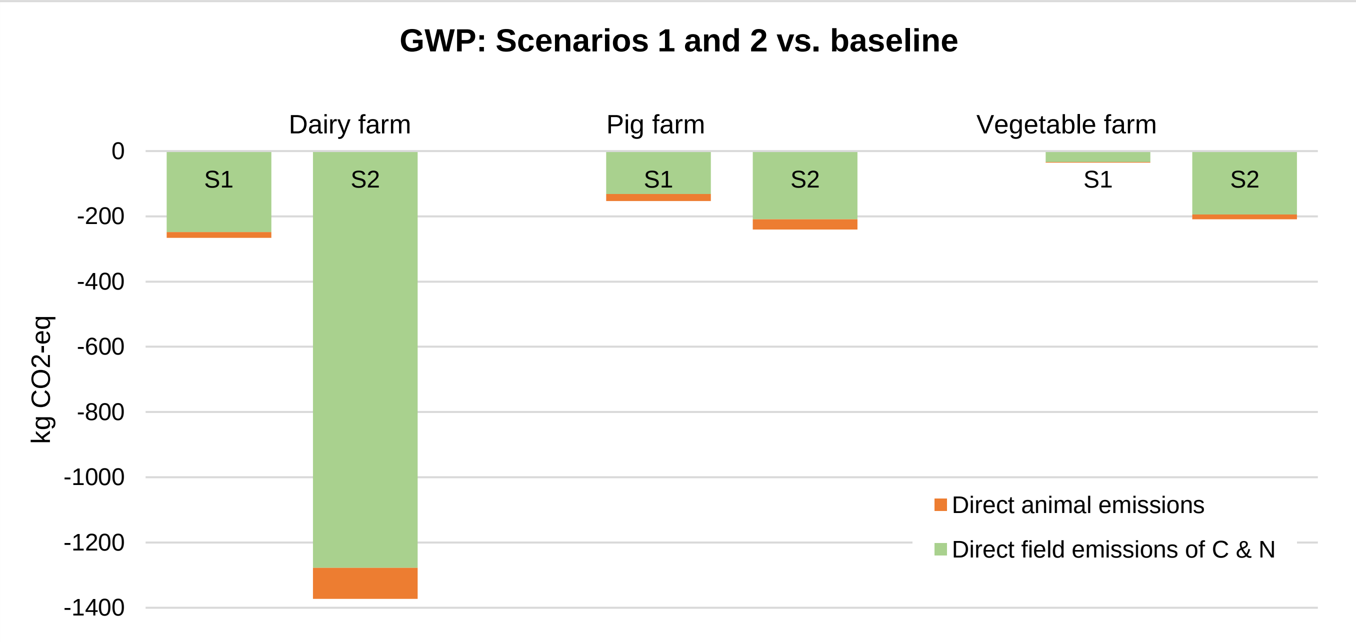


*Figure 19: Gross GHG emission reduction of biochar application to animal bedding: Difference in GWP between scenario and baseline for the Scenarios 1 and 2 and for each model farm. The results only show the GWP on the farm and do not include GWP from biochar production and carbon sequestration. Scenario 1 = biochar in animal bedding, 1% animal feed; Scenario 2 = biochar in animal bedding, 10% straw volume.*

[7] Accounting for one-year field vegetables excluding canned vegetables, multi-year vegetables and vegetables cultivated in greenhouses

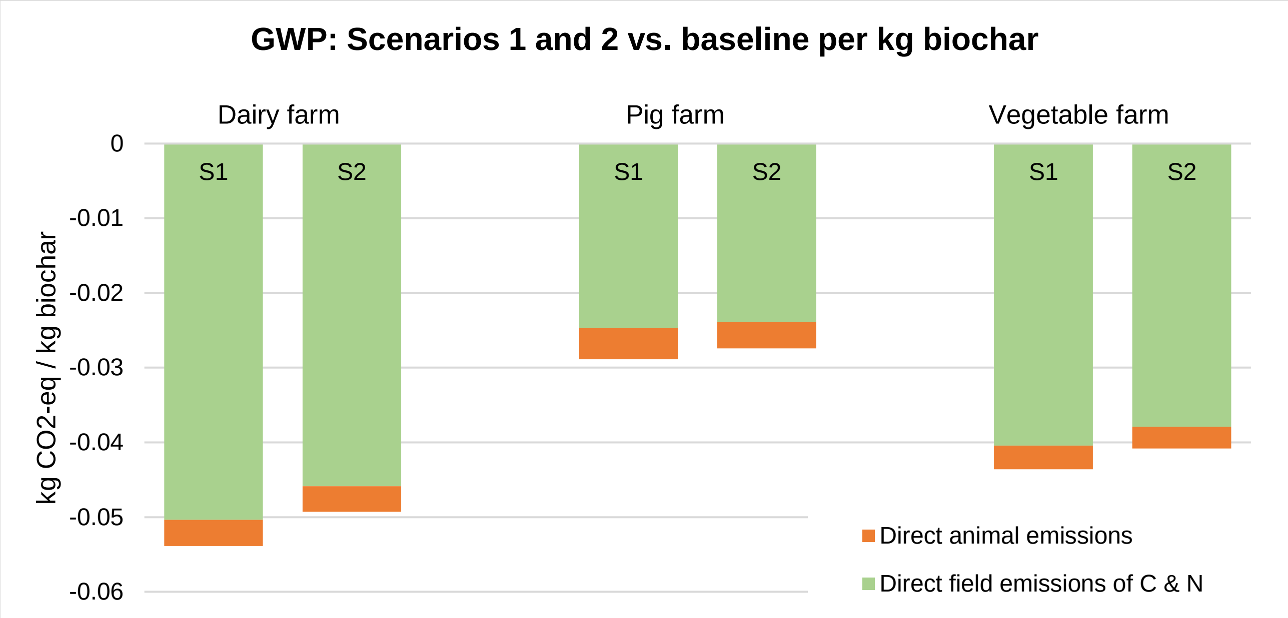


*Figure 20: Gross GHG emission reduction of biochar application: Difference in GWP between Scenarios 1 and 2 and baseline per kg biochar applied for each model farm. Scenario 1 = biochar in animal bedding, 1% animal feed; Scenario 2 = biochar in animal bedding, 10% straw volume.*

### 3.2.2 Biochar as a Swimming Layer in Liquid Manure Storage

Scenario 3 assesses the impacts of biochar when used as a swimming layer on liquid manure (slurry) storage—that is, as a replacement for manure storage without cover or with perforated cover. Interestingly, this is the only scenario that shows an increase in GWP compared to the baseline. As the number of animals and LU is higher for the pig farm (see Table 8), the manure storage volume is also higher, and the amount of biochar used for the swimming layer is larger; therefore, the GHG emissions are higher (see Figure 21). Here again, changes in the direct field emissions of C and N and direct animal emissions explain the results. Overall, direct animal emissions decrease because of the 60% reduction in $NH_3$ emissions at the manure storage and the slight decrease in $N_2O$ emissions (-0.7%). By contrast, direct field emissions increase because of the increase in the nitrogen content of the manure due to reduced $NH_3$ and $N_2O$ emissions during its storage, which leads to an increase in field $N_2O$ emissions and $NO_3$ leaching. It is worth mentioning that the original research paper from which we extracted the data on emission reduction during manure storage neither investigated downstream emissions nor the binding mechanisms of nitrogen species to biochar (Chen et al., 2021). Thus, we did not implement any further interaction between biochar and reactive nitrogen species. Note that the quantity of biochar applied in this scenario is not sufficient to induce $N_2O$ emission reduction.

Dividing the emissions by the amount of biochar applied results in the same GWP trends among the model farms as the total GWP (see Figure 22). This can be explained by the number of livestock and the UAA, which are quite different between the three model farms. The extent of direct field emissions and direct animal emissions seem to be more correlated with the UAA and total livestock of the model farms, respectively (i.e. both higher for the pig farm, and smallest for the vegetable farm, Table 8) than with the amount of applied biochar.

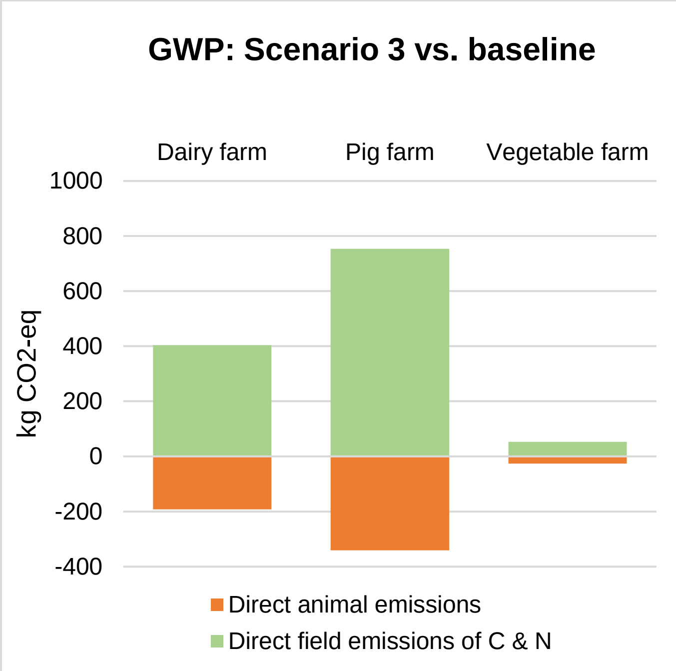


*Figure 21: Difference in GWP between Scenario 3 and baseline for each model farm. Scenario 3 = biochar as a swimming layer in liquid manure storage.*

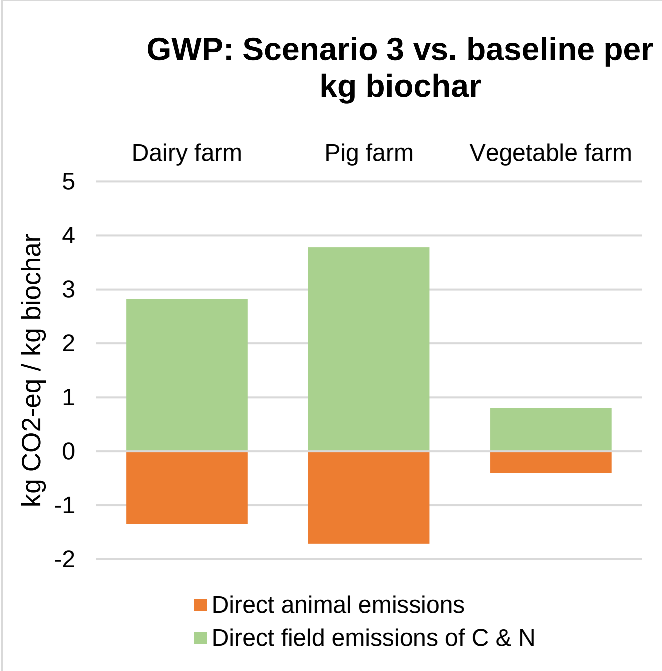


*Figure 22: Difference in GWP between Scenario 3 and baseline per kg of biochar applied for each model farm. Scenario 3 = biochar as a swimming layer in liquid manure storage.*

### 3.2.3 Biochar as a Soil Amendment on Surfaces with Annual Vegetables

Scenarios 4 and 5 assess the impacts of biochar when applied directly to the soil on agricultural land surfaces with annual vegetables. Both scenarios show a decrease in GWP when biochar is applied compared to the reference (Figure 23). As the amount of biochar applied to vegetables on the vegetable farm is much higher than on the dairy and pig farms (12.15 ha for the vegetable farm, 0.24 ha for the dairy farm, 0.30 ha for the pig farm, Table 8), the absolute difference between the GWP of Scenarios 4 and 5 and the baseline is higher for vegetable farms than for dairy and pig farms (see Figure 23). Unlike the other two biochar uses, only the direct field emissions of C and N are reduced by biochar application to soil. The decrease in direct field emissions can be explained by the reduction in $N_2O$ emissions and in $NO_3$ leaching when biochar is applied to the soil (see Section 2.3.1).

As with the other biochar applications, the GWP reduction per kg of biochar applied as a soil amendment is similar between the three model farms (Figure 23). The GWP reduction through biochar per kg biochar applied is ~2.5 times higher for Scenario 4 than for Scenario 5, at ~0.05 and ~0.02 kg $CO_2$-eq/kg biochar, respectively. This is also observed with the total GWP (Figure 24), with the GWP increasing by a factor ~2, while the amount of biochar applied increases by a factor of 5 (1000 kg/ha to 5000 kg/ha) from Scenario 4 to Scenario 5.

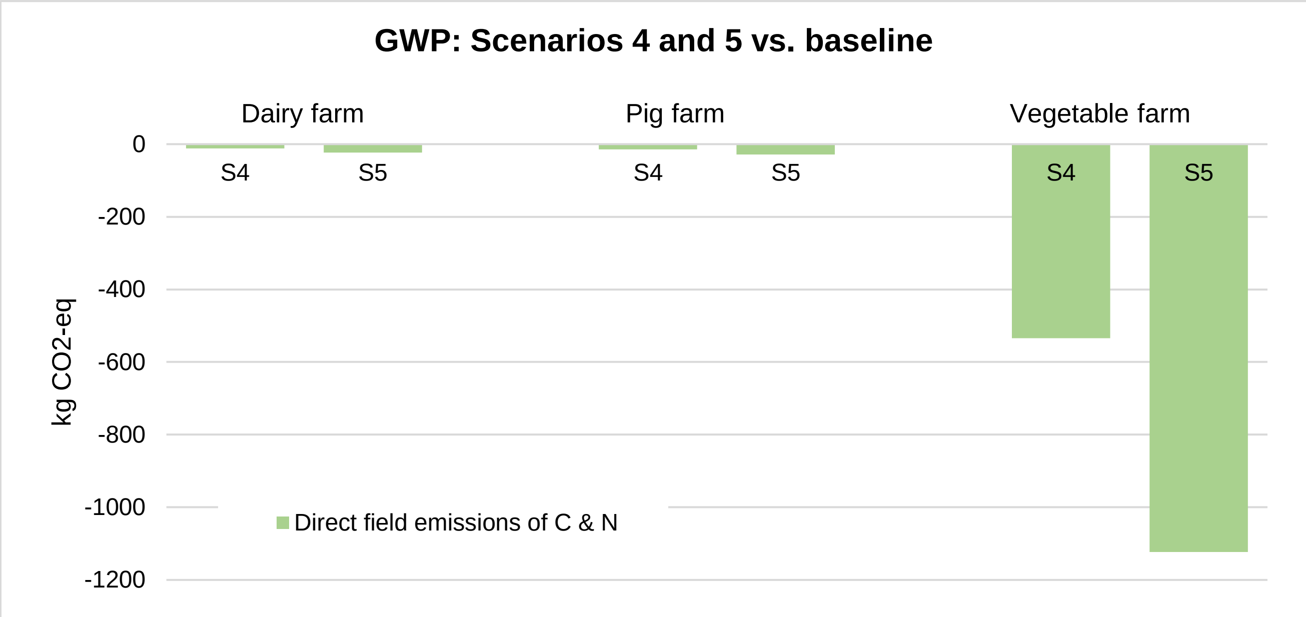


*Figure 23: Difference in GWP between Scenarios 4 and 5 and baseline for each model farm. Scenario 4 = 1000 kg biochar per ha directly to the soil on surfaces with annual vegetables; Scenario 5 = 5000 kg per ha.*

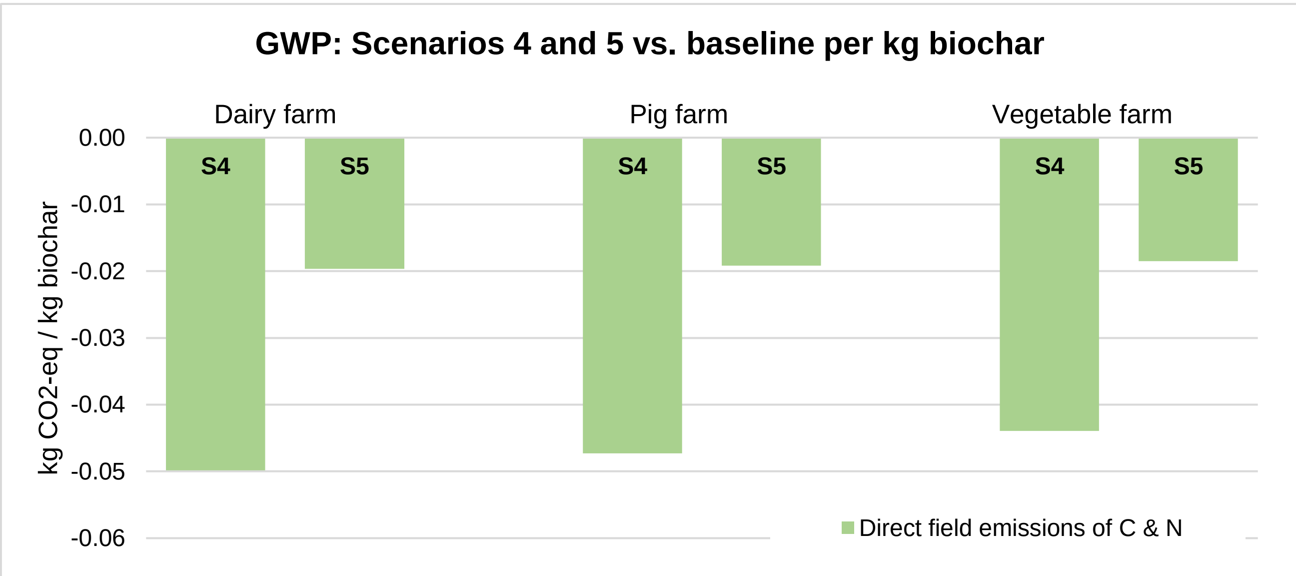


*Figure 24: Difference in GWP between Scenarios 4 and 5 and baseline per kg of biochar applied for each model farm. Scenario 4 = 1000 kg biochar per ha directly to the soil on surfaces with annual vegetables; Scenario 5 = 5000 kg per ha.*

### 3.2.4 Biochar Applied at Several Entry Points

Scenarios 6, 7, and 8 assess the environmental impacts of biochar when used at two or three entry points. The combined scenarios are not exactly the sum of the separated scenarios with one single entry point but are very close, with a difference between 0 and 12.7 kg $CO_2$-eq between the combined scenario and the sum of individual scenarios (see Table C10, C11, and C12, Appendix C4). The contribution group “Direct field emissions of C & N” explains 92–99% of this difference. The discrepancy observed in direct field emissions is due to the fact that the total amount of biochar spread to the field from animal bedding, manure storage, and direct soil application to vegetable surfaces does not have the same environmental effects when applied separately or combined. The main reason for this is the impact on $NO_3$ leaching, although $NH_3$, $NO_x$, and $N_2O$ field emissions are also slightly reduced. When the applied biochar reaches 1000 kg biochar per ha, the effect on $NO_3$ leaching reaches a steady effect of 13% reduction in $NO_3$ leaching (see Section 2.3.1), and therefore, the effect of biochar in the combined scenarios is less than the sum of the scenarios with a single entry point. The contribution group “Direct animal emissions” explains 1–8% of this difference. When part of the nitrogen content of the manure is sorbed to the biochar in animal bedding, then $NH_3$ and $N_2O$ emissions are reduced in the animal bedding as well as during manure storage due to this part of the manure nitrogen content still being sorbed to biochar in the manure.

As a short reminder, Scenario 6 is a combination of Scenarios 1, 3, and 4, where biochar is applied to animal bedding (1% animal feed), as a swimming layer to the manure storage, and directly to soil with annual vegetables at 1000kg/ha. Scenario 7 is a combination of Scenarios 2, 3, and 5, where biochar is applied to animal bedding (10% straw volume), as a swimming layer to the manure storage, and directly to soil with annual vegetables at 5000 kg/ha. Scenario 8 is a combination of Scenarios 1 and 4, where biochar is applied to animal bedding (1% animal feed), and directly to soil with annual vegetables at 1000 kg/ha.

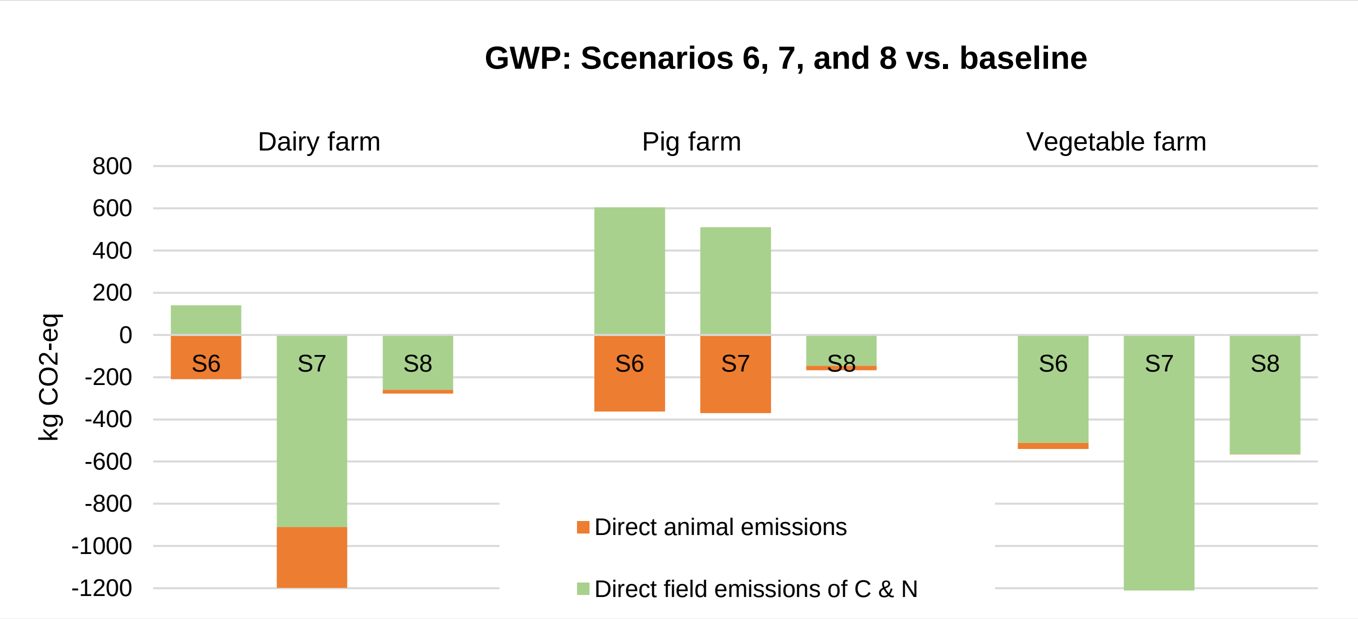


*Figure 25: Difference in GWP between Scenarios 6, 7, and 8 and baseline for each model farm.*

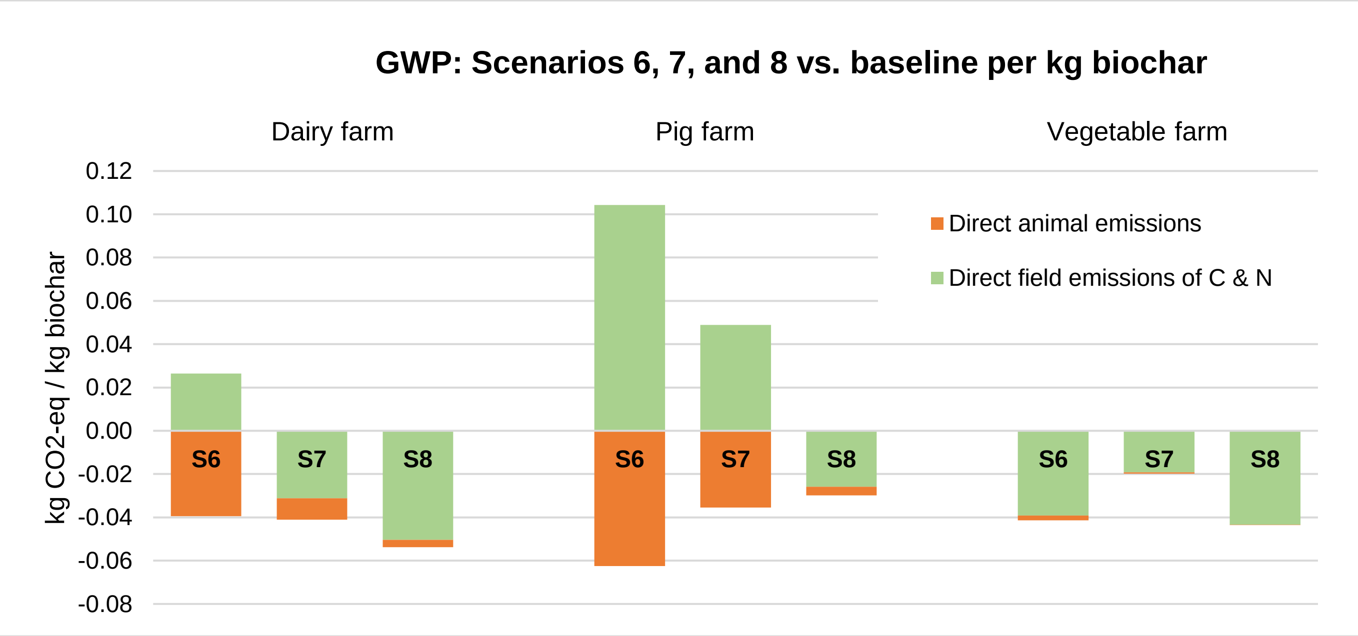


*Figure 26: Difference in GWP between Scenarios 6, 7, and 8 and baseline divided by the amount of biochar applied for each model farm.*

## 3.3 Other Environmental Impacts of the Biochar Application Scenarios

In this section, we focus on the environmental impacts for the production of biochar (till farm gate) from different feedstocks, including all upstream processes. The production of biochar has a different impact on the environment depending on its feedstock (Table 13). Straw biochar has the tendency to have the highest impact, followed by wood chips biochar and, lastly, landscape conservation wood biochar. Each environmental impact is described in Section 3.5.

Table 13: Environmental impacts for the production of 1 kg of biochar. Results shown for three different feedstocks.

| Impact category | Unit | Wood chips biochar | Landscape conservation wood biochar | Straw biochar |
|---|---|---|---|---|
| CML – Abiotic depletion potential | kg Sb-eq | 4.34E-07 | 2.88E-07 | 1.03E-06 |
| Water scarcity – AWARE | $m^3$ | 1.51E-02 | 6.22E-03 | 1.91E-02 |
| Water use – From LCI | $m^3$ | 9.64E-04 | 4.39E-04 | 5.88E-03 |
| Land transformation – Deforestation | $m^2$ | 4.45E-05 | 7.46E-06 | 1.41E-05 |
| Land occupation – Total | $m^2a$ | 3.82E+00 | 1.07E-02 | 1.15E+01 |
| IPCC 2021 – GWP100 (fossil & LULUC) | kg $CO_2$-eq | 1.53E-01 | 7.04E-02 | 2.53E-01 |
| Eutrophication – Marine | kg N-eq | 6.06E-06 | 4.64E-07 | 9.24E-07 |
| Eutrophication – Freshwater | kg P-eq | 6.73E-05 | 1.28E-06 | 1.91E-04 |
| Eutrophication – Terrestrial | mol N-eq | 2.30E-03 | 9.77E-04 | 4.34E-03 |
| Acidification – Terrestrial | kg $SO_2$-eq | 3.40E-04 | 1.60E-04 | 5.95E-04 |

The environmental impacts for the effects of the biochar cascade use on the three model farms are provided

In Appendix C7. We stress that the effect of the on-farm application of biochar should be interpreted with care. Indeed, in SALCAfuture, only the effects of biochar on GHG emissions have been modelled. The impacts of biochar on heavy metals, soil quality, soil density, or other environmental parameters have not been modelled and therefore are not translated in the results shown in Appendix C7. For a more complete assessment of biochar on environmental impacts other than on GWP, further research and the translation of the findings into the SALCAfuture model is needed. This does not concern the results shown in Table 13, as the production of biochar is not modelled in SALCAfuture. The results for the Ecological Scarcity Method (Method UBP) are available in Appendix C6.

## 3.4 Net Global Warming Potential

The net GWP accounts for the emissions linked to the production of biochar, the effects of the cascade use of biochar, and carbon sequestration. We provide first the results for the different contributions to net GWP (i.e. biochar production, cascade use of biochar, and carbon sequestration) before we show the net GWP for all three model farms

**Emissions linked to biochar production**
As discussed in Section 4.1, the GWP linked to biochar production depends on the biochar feedstock. For the production of 1 kg of biochar, the GWP is 0.153, 0.062, and 0.373 kg $CO_2$-eq if the biochar is made from wood chips, landscape conservation wood, or straw, respectively (Figure 16).

**Emissions linked to the cascade use of biochar**
In Section 3.2, we discuss the effects of wood chips biochar in different application scenarios. Figure 27 summarises the change in GWP from biochar application for each scenario and the model farm evaluated per kg of biochar applied. When biochar is applied in animal bedding, its potential in emission reduction per kg of biochar is relatively similar between Scenario 1 (mass of biochar equivalent to 1% of animal feed) and Scenario 2 (volume of biochar equivalent to 10% straw volume) for all three model farms. The change in GWP is therefore proportional to the quantity of biochar applied. Applying biochar as a swimming layer on manure storage (Scenario 3) leads to an increase in emissions up to 2.07 kg $CO_2$-eq per kg biochar (see Section 4.2.2 and Figure 27). When biochar is applied

directly to the soil on vegetable surfaces, the change in GWP is approximately 2.5 times smaller per kg of biochar when applied at a rate of 5000 kg/ha (Scenario 5, 0.02 kg $CO_2$-eq / kg biochar) than at a rate of 1000 kg/ha (Scenario 4, 0.05 kg $CO_2$-eq / kg biochar). For Scenarios 6, 7, and 8, the effect of biochar on the GWP is slightly lower than the sum of the scenarios with a single entry point. The various reasons for this discrepancy are discussed in Section 3.2.4.

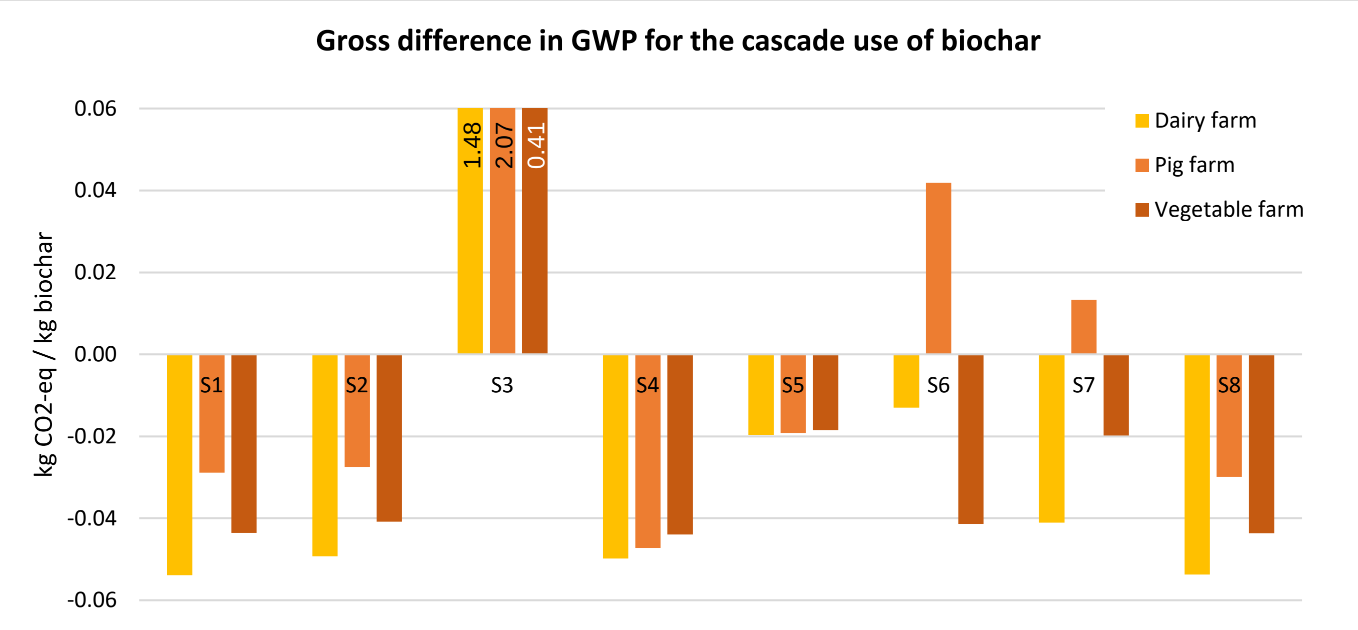


*Figure 27: Gross difference in GWP between scenario and baseline for the cascade use of biochar per kg of biochar applied. The value does not include biochar production or carbon sequestration. For Scenario 3, the values are larger than 0.06 kg $CO_2$-eq/kg biochar and numbers are denoted on the colour bars.*

**Emissions linked to carbon sequestration**

Biochar offers the potential to store long-term carbon in the soil. As detailed in Section 2.2.3.1 the potential of wood biochar for carbon sequestration is 2.51 kg $CO_2$-eq/kg biochar.

**Net emissions reduction linked to biochar application**

Figure 28 shows the GWP for the three model farms for the biochar production, the change related to the cascade use of biochar, and the carbon sequestration for wood chips biochar. The net impact of biochar is dominated by carbon sequestration and is highly dependent on the amount of biochar applied (see Table 12 for the amount of biochar per scenario). Scenario 3 shows very low values, as low amounts of biochar are applied in this scenario. The remarkably high values found for carbon sequestration in Scenarios 5 and 7 for the vegetable farm are due to the high amounts of applied biochar, at 60,740 kg and 65,929 kg, respectively (see Table 12). The three contributions to the net GWP per model farm and per kg biochar are shown in Figure 29. The only GWP that varies among the scenarios and the model farm is from the cascade use of biochar. The GWP from biochar production and carbon sequestration are identical for all scenarios.

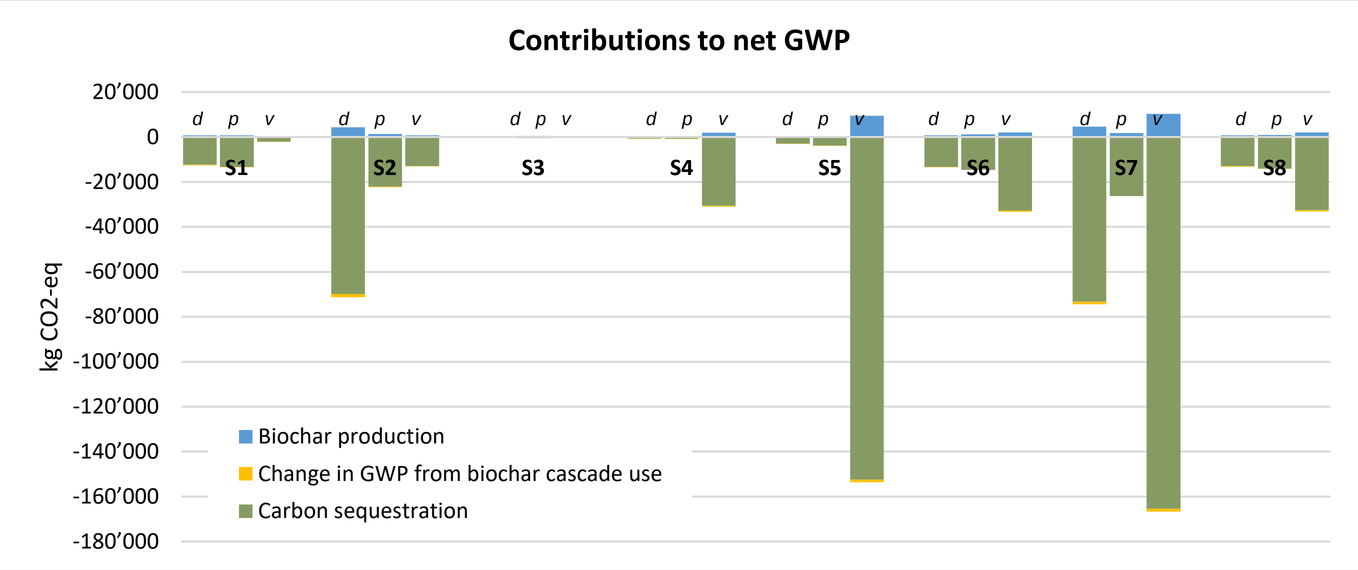


*Figure 28: Contributions to net GWP: (i) biochar production (from wood chips), (ii) the change in GWP on the model farm from cascade use of biochar, and (iii) carbon sequestration in the soil. For each scenario, "d", "p", and "v" stand for dairy farm, pig farm, and vegetable farm, respectively.*

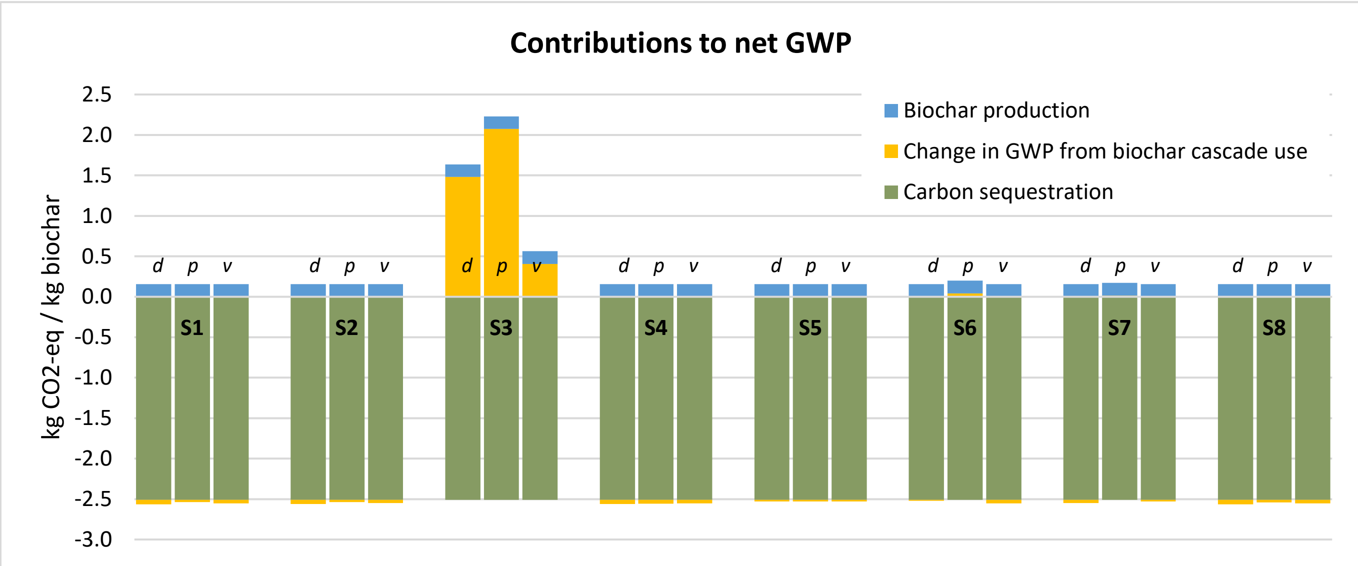


*Figure 29: Contributions to net GWP in per kg of used biochar: (i) biochar production (from wood chips), (ii) the change in GWP on the model farm from cascade use of biochar, and (iii) carbon sequestration in the soil. For each scenario, "d", "p", and "v" stand for dairy farm, pig farm, and vegetable farm, respectively.*
*GWPs are given per kg of used biochar.*

## 3.5 Extrapolation to Switzerland

For each scenario, the total emissions reduced by the cascade use of biochar are given in Table 14. The total emission reduction (ER) accounts for the biochar production, the biochar application scenario, and the carbon sequestration and extrapolates from the three model farms to Switzerland, as explained in Section 3.6.

$ER_{total} = ER_{dairy} + ER_{pig} + ER_{vegetable}$ (for the results see Table 14)

$ER_{dairy} = (GWP_{biochar\ prod._{dairy}} + GWP_{biochar\ cascade\ use_{dairy}} + ER_{C\ seq.}) * 4096$ (Table C13, Appendix C5)

$ER_{pig} = (GWP_{biochar\ prod._{pig}} + GWP_{biochar\ cascade\ use_{pig}} + ER_{C\ seq.}) * 939$ (Table C14, Appendix C5)

$ER_{vegetable} = (GWP_{biochar\ prod._{veg.}} + GWP_{biochar\ cascade\ use_{veg.}} + ER_{C\ seq.}) * 654$ (Table C15, Appendix C5)

For simplification purposes, the results are only discussed for biochar made out of wood chips. Table C16 in Appendix C5 shows, however, the total emission reduction for the three types of biochar feedstocks. It is clear that using landscape conservation wood instead of wood chips increases the total emission reduction by ~3.5%, and using straw instead of wood chips decreases the total emission reduction by ~10%.

The line "% of total emissions" in Table 14 indicates the percentage of total emissions over the extrapolation of the three model farms that are avoided by the use of biochar. This value varies from 0.01% to 4.88% and indicates the high variability of biochar potential in GHG emission reduction, depending on how much biochar is applied and at which entry point(s). The smallest potential of biochar is 0.01% of emission reduction and is for Scenario 3, when the biochar is used as a swimming layer in the liquid manure storage. The highest potential is 4.88% and is for Scenario 7, when biochar is applied in animal bedding as 10% of straw volume (Scenario 2), as a swimming layer in the liquid manure storage (Scenario 3), and on vegetable surfaces at a rate of 5000 kg biochar/ha (Scenario 5). Note that this high potential in Scenario 7 is linked to the high amount of biochar used, which leads to a large potential for carbon sequestration. Indeed, the emission reduction per kg of biochar is relatively similar among all scenarios, except for Scenario 3, averaging around -2.4 kg $CO_2$-eq/kg biochar (Table 14). For comparison, the emissions of 411'464 t $CO_2$-eq avoided in scenario 7 are equivalent to the total annual GHG emissions of 777 baseline dairy farms (or 546 pig farms or 2050 vegetable farms).

Table 14: Net emission reduction from the use of wood chips biochar per scenario in Switzerland. The net emission reduction includes GWP from biochar production, the change in GWP in the model farm from biochar usage, and biochar carbon sequestration in the soil.

| Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Amount of biochar used (t) | 25,698 | 125,663 | 816 | 9,206 | 45,993 | 35,720 | 172,471 | 34,904 |
| Net emission reduction (t $CO_2$-eq) | -61,724 | -301,680 | -647 | -22,073 | -109,082 | -84,460 | -411,464 | -83,795 |
| Net emission reduction per kg biochar (kg $CO_2$-eq/kg biochar) | -2.40 | -2.40 | -0.79 | -2.40 | -2.37 | -2.36 | -2.39 | -2.40 |
| % of total GWP | -0.73% | -3.57% | -0.01% | -0.26% | -1.29% | -1.00% | -4.88% | -0.99% |

To summarise the main results, we provide relative emission savings either per kg of biochar or compared to the model farm baseline. The use of biochar as a bedding material and as a soil amendment in vegetable production only results in comparatively small emission reductions of between 0.02 kg $CO_2$-eq/kg biochar and 0.05 kg $CO_2$-eq/kg biochar (depending on the model farm). The use of biochar as a floating layer in slurry storage is the only scenario that shows an increase in the GWP compared to the baseline. The production of wood chips biochar emits 0.16 kg $CO_2$-eq per kg biochar, which is already more than the GHG emissions saved by the use of biochar as a bedding material or as a soil amendment. The wood chips biochar stores 2.51 kg $CO_2$-eq per kg of biochar in the long term.

Based on the analysis of the different contributions to net GWP from all scenarios, we can conclude that the net effect of biochar application on GWP is dominated by carbon sequestration and depends heavily on the amount of biochar applied in that scenario. The other effects of the cascade use of biochar investigated here are comparatively minor.

# 4 Discussion

## 4.1 Quantity of Biochar Used

### 4.1.1 Biomass Needed and C-Sinks Created

In the project, the quantities of biochar used were defined according to the type of application (entry point) used in the scenarios. The total amount of biochar used was then calculated for each combination of scenario and model farm. This resulted in a range of 65.8 to 65,929.2 kg of biochar per year and farm. Extrapolated to Switzerland, this corresponds to the annual use of 816–172,471 tonnes of biochar. In 2023, 7310 t of biochar were produced in Switzerland (Hagemann et al., 2024; no precise data are available on imports and exports), but these are not used exclusively in agriculture, but also in substrates for urban trees, in concrete or asphalt. Nevertheless, Scenario 3 (816 t biochar) could represent current biochar application in agriculture.

Across Europe, annual growth in the production capacity of biochar in the order of 50% is observed, and the European Biochar Industry Association expects this trend to continue. Assuming a conservative growth rate of 25% would imply that in 2032, 54,464 tonnes of biochar could be produced annually in Switzerland, easily covering the biochar demand of one of the moderate scenarios (Scenarios 1, 4, 5, 6, or 8, Table 12). The scenario with the highest biochar demand of 172,471 t (Scenario 7) could be applied by 2038, based on this conservative assessment. This exemplary calculation shows that, from a techno-economic point of view, sufficient Swiss biochar can be made available for the scenarios calculated here.

Table 15: Annual biochar demand for different application scenarios. Biochar production capacity in Switzerland is calculated using the 2023 baseline of 7310 t $yr^{-1}$ and a growth rate of 25%.

| Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Amount of biochar used (t) | 25,698 | 125,663 | 816 | 9,206 | 45,993 | 35,720 | 172,471 | 34,904 |
| **Biomass demand** (t)<br>- wood[1] | 85,660 | 418,877 | 2,720 | 30,687 | 153,310 | 119,067 | 574,903 | 116,347 |
| - landscape conservation wood[2] | 77,873 | 380,797 | 2,473 | 27,897 | 139,373 | 108,242 | 522,639 | 105,770 |
| - straw[3] | 128,490 | 628,315 | 4,080 | 46,030 | 229,965 | 178,600 | 862,355 | 174,520 |
| **Biochar C-sink**[5] (t $CO_2$-eq)<br>- woody biomass | 64,502 | 315,414 | 2,048 | 23,107 | 115,442 | 89,657 | 432,902 | 87,609 |
| - straw | 54,480 | 266,406 | 1,730 | 19,517 | 97,505 | 75,726 | 365,639 | 73,996 |
| Net useable heat provided by biochar production (GWh)[4] | 120 | 586 | 4 | 43 | 215 | 167 | 805 | 163 |
| Biochar production capacity in Switzerland sufficient from year…onwards (calculated production capacity in the given year in t $yr^{-1}$) | 2029 (27,885) | 2036 (132,968) | 2023 (7,310) | 2025 (11,422) | 2032 (54,464) | 2031 (43,571) | 2038 (207,763) | 2031 (43,571) |

[1]30% mass yield (0.30 kg biochar $kg^{-1}$ wood)

[2]33% mass yield (0.33 kg biochar $kg^{-1}$ landscaping wood)

[3]20% mass yield (0.20 kg biochar $kg^{-1}$ straw)

[4]1.4 MWh $t^{-1}$ wood biomass; the energy produced will be similar for the other biomass. Empirical data were obtained from the database of the European Biochar Certificate from industrial pyrolysis units in Europe processing predominantly woody biomass. Data provided by the Ithaka Institute.

[5]Long-term C-sink (100 years) calculated according to the IPCC method and thus with the same carbon content assumed for both wood and landscape conservation wood.

From a biomass point of view, up to 574,903, 522,639, or 862,355 t of wood, landscape conservation wood, or straw are needed to produce the largest amount of biochar needed (Scenario 7). Producing this amount of biochar results in the co-production of 805 GWh of net useable heat for district heating or industrial processes.

For moderate scenarios requiring moderate amounts of biochar (Scenarios 1, 4, 5, 6, or 8), 30–116, 28–105, 46–<174 thousand t of wood, landscape conservation wood, or straw are required, respectively. The sustainable potential of field wood (“Flurholz”/landscape conservation wood) in Switzerland is approximately 0.3 million tonnes, of which only 0.1 million tonnes are being used so far and could therefore already cover this biomass demand (Thees et al., 2017). Irrespective of this, other sources of biomass could also be used for the production of biochar. This could include straw that is not used in animal husbandry and secondary biomass from agriculture or elsewhere, as discussed below. These findings are rough approximations, as no thorough feasibility study was conducted in this report. From the perspective of a farm, the moderate Scenario 1 in animal husbandry leads to a demand of approximately 5 t of biochar. At a purchase price of CHF 1000-2000, this results in costs of CHF 5000-10000.

### 4.1.2 Current Biochar Production in Switzerland

The operation of pyrolysis plants is based on mixed calculations with several revenues. The first plants in the 2010s were still pioneering projects driven solely by the motivation for biochar production. By the beginning of the 2020s at the latest, pyrolysis plants are being planned, where the heat can be utilised all year round. These plants generate revenue from:

- Sale of biochar
- Sale or self-use of heat
- If applicable, sale of certified negative emissions after material application of biochar has been carried out
- If applicable, the production of electricity
- If applicable, fees for accepting the biomass/biomass disposal

To the best of the project team’s knowledge, fees for biomass disposal have not yet been implemented by projects in Switzerland, but examples are known from Germany, where the disposal of a specific biomass was already subject to a charge, and the implementation of pyrolysis now offers a more economical pathway. In Switzerland, pyrolysis plants that buy biomass externally receive biogenic residues free of charge, but they pay for processing and transport or use biomass from their own operations. Examples include:

- Verora AG in Neuheim ZG recycles pruning and tree trimmings from landscape maintenance into wood chips as energy sources. During processing, fine particles are separated and pyrolysed. The heat is used to dry the wood chips and increase their calorific value.[8]
- Philip Morris AG pyrolyses its own waste (cardboard, paper, and tobacco) in Neuchâtel NE to use the heat within the company.[9] This biochar is presumably not used for agricultural applications.
- Bioenergie Frauenfeld sources forest wood within a radius of 50 km and, in addition to biochar, generates electricity for 8000 households and heat for the sugar factory.[10]
- Industrielle Werke Basel sources landscape conservation wood with a high ash content from a recycling plant. This material had not previously been recycled in any economically meaningful way. The pyrolysis plant feeds energy into the district heating network.

### 4.1.3 Perspectives on Biochar Production in Switzerland

While biochar production for agriculture was previously limited to wood, the Fertilizer Ordinance now allows the production of biochar from a broad range of biomass, which is expected to diversify biochar production. Novel feedstocks for the biochar production may include spent coffee grounds (Mantonanaki et al., 2014; Mantonanaki et al., 2016), manure in areas of intense animal husbandry (Rathnayake et al., 2023) and plastic contaminated biomass (Hilber et al., 2024) as investigated by the project team in other projects, as well as other types of secondary biomass. For use in feed, biochar production will remain limited to pristine biomass from well-defined and well-controlled sources.

Biochar can also be produced on the farm using pyrolysis heating systems, which is of interest to farms that have their own forests and may already be using wood chips for heating. Heating systems that produce biochar that meet the requirements of the Fertilizer Ordinance are currently being offered by an Austrian[11] and a Swiss[12] company, for

[8] https://www.verora.ch/page/de/holz
[9] https://www.pmi.com/markets/switzerland/de/ueber-uns/60-jahre-praesenz
[10] https://www.bioenergie-frauenfeld.ch/bioenergie/restlos-wertvoll/
[11] https://www.biomasseverband.at/wp-content/uploads/Powerchip-Biochar.pdf
[12] https://www.pyronet.ch/unternehmen/

example. At present, one farm in Switzerland is known to use such a system to produce 5 t of biochar as a by-product of providing heating and hot water for four residential units on the farm[13]. This means that farms can produce enough biochar to implement, for example, Scenario 1. The biomass required could be obtained from 1.5–4 ha of forest, short-rotation coppice (assuming 25–33% biochar mass yield and 5–10 t ha-1 annual biomass yield). This demand for land would be reduced by using straw, pruning, and other by-products.

Thus, the costs of biochar production can be reduced by the selection of feedstock, which, however, is limited for feed biochar. A further reduction in the costs of biochar is expected due to improvements in biochar production technology. However, the greatest leverage is presumably the price of the C-sink certificates, which are currently mainly sold on the voluntary market at CHF 100–250. An increase in revenue from those certificates could dramatically reduce biochar prices.

## 4.2 Sensitivity Study

Regarding biochar production, this report shows that there are significant variations in GWP depending on the biochar feedstock (Figure 16). Other biochar feedstocks could be further evaluated, but the three types of feedstocks analysed provide sufficient information, indicating that the net GWP is only influenced by ± 4%, depending on the biochar feedstock. Indeed, a major reduction in net GWP is achieved through long-term carbon sequestration. For this reason, no sensitivity analysis was performed on the different parameters linked to GWP reduction from the cascading use of biochar. For animal bedding, the impacts were quantified by considering the highest N sorption potential reported in the literature. With this value, the impact on the reduction of farm emissions is clear, accounting for -0.029 to -0.054 kg $CO_2$-eq/kg biochar, at 50–100 times lower compared to the potential in carbon sequestration of -2.51 kg $CO_2$-eq/kg biochar. We observe that changes in on-farm emissions do not even compensate for the emissions of biochar production (i.e. 0.074 kg $CO_2$-eq/kg biochar for the biochar feedstock with the lowest GWP). Therefore, no sensitivity analysis was performed for this entry point.

For the effect of soil application of biochar, either directly on vegetable surfaces or through field manure application, we also see that the impacts on emission reduction are relatively low (-0.019 to -0.050 kg $CO_2$-eq/kg biochar). Similar to biochar in animal bedding, we decided not to perform further sensitivity analyses on the impact of biochar on $N_2O$ emission or on $NO_3$ leaching. For the biochar usage as a swimming layer in manure storage, no sensitivity analysis was performed either. As the farm GWP increased when biochar is applied at this entry point, we decided not to investigate it further.

Farm composition could have a significant impact on total emission reduction potential. If the model farms were selected using other threshold values, the total emission reduction over Switzerland would change. For example, if farms with $LU_{cattle} > 20$ instead of $LU_{cattle} > 30$ were selected for the dairy model farm, the extrapolation to Switzerland would account for more farms, more UAA, and more livestock. However, we have observed that the impact of biochar on GWP (in kg $CO_2$-eq/kg biochar) is very similar among the three model farms (see Section 3.2), although their farm composition is highly different (see Section 2.4.1). Therefore, the impact of biochar on the emission reduction of Switzerland is more dependent on the quantity of biochar used on the farm (and the induced carbon sequestration), as well as on the total UAA and livestock accounted for in the area covered by the model farms. Consequently, the results in total GWP could be linearly adapted if more UAA or livestock were to be accounted for in the extrapolation to Switzerland. The extrapolation of the three model farms (accounting for the modified pig farm) corresponded to 54% of the UAA and 54% of the livestock (in LU) of the plain region. To account for the entire plain region in Switzerland instead of the region represented by the model farms, we simply have to multiply the total reduction in GWP obtained in Section 3.5 by 1/0.54. For this reason, no sensitivity analysis was performed on farm composition.

A change in climate or soil properties would likely impact the GWP of the model farms. However, our parameters linked to the impacts of biochar on the GWP were taken according to the average climate and soil types in Switzerland and have been implemented in SALCAfuture in a way that they are independent of soil or climate changes. This results in a difference of GWP with the baseline of the cascade use of biochar that would stay identical; therefore, no sensitivity analysis was performed for climate or soil properties.

[13] https://www.pyronet.ch/pyrofarm/

## 4.3 LCA of Biochar Production

In this section, we present a comparison of the LCA for biochar production with the results from other publications. A direct comparison of LCA results from different studies is difficult due to the different functional units, system boundaries, pyrolysis systems, and LCA software tools/ background databases used in each study (Matuštík et al., 2022; Patel et al., 2023; Yu et al., 2022; Zhu et al., 2022). Moreover, critical factors for biochar production, such as pyrolysis conditions and techniques (e.g. temperature, time, and pyrolyser type), can enhance the differences when comparing different studies (Zhu et al., 2022). In addition, the choice of biomass feedstock and the climate in different regions can change the LCA results (Yu et al., 2022). Although biochar carbon sequestration is well understood, the computation of GHG emissions related to biochar production is challenging due to the diverse carbonisation methods. To address this complexity, researchers use LCIA (Kavindi et al., 2025), with the majority of studies focusing on GWP, as it is one of the most relevant and frequently used indicators for investigating the pressure on the environment (Xia et al., 2024; Yu et al., 2022).

Sahoo et al. (2021) studied three different types of on-site biochar production from forest residues (Oregon Kiln [OK], air curtain burners [ACB], and Biochar Solutions Incorporated [BSI]) and reported GWP of 0.25–1.0, 0.55, and 0.61 t $CO_2$eq/t biochar applied to the field for the BSI, OK, and ACB, respectively. This is above the value we found in the present study (0.153 t $CO_2$eq/t biochar produced from wood chips), although in the same order of magnitude. Differences in GWP are likely due to the different biochar production methods. In their review study, Yu et al. (2022) pointed out that using forest residues as feedstock leads to lower GHG emissions than agricultural residues. This is in line with our result: the GWP for biochar produced from wood chips is below that produced from straw (Figure 18). Nevertheless, forest wood is an important resource that is in demand from many sides. Therefore, the GWP for biochar production cannot be the sole decision criterion.

Harvest residues, such as straw, are admissible for the production of biochar, since this biomass meets all the European Biochar Certificate (EBC) classes, as the EBC indicates in the positive list of permissible biomasses for the production of biochar (D'Urso, 2023). Ji et al. (2018) found that for biochar produced from straw—including carbon sequestration—the GWP was 0.94 t $CO_{2eq}$ per t of straw (Xia et al., 2024). Assuming that 5 kg of straw is necessary to produce 1 kg of biochar (see Section 2.3.1.2), this result is almost twice as high as in our study (2.40/5= 0.48 t $CO_{2eq}$ per t of straw).

In the present study, the contribution of $CO_2$, $CH_4$, $N_2O$ emissions to GWP for the production of biochar from different biomass feedstocks (wood, straw, and landscape conservation wood) were analysed and compared. The comparison reveals that the percentage contributions of $CH_4$, $CO_2$, and $N_2O$ clearly depend on the feedstock from which biochar is produced. For all three analysed feedstocks, $CO_2$ contributes most to the GWP. These differences are due to the different amounts (mass in kg) of each feedstock needed to produce biochar. This is consistent with the findings of other scientists, who also emphasised that different feedstocks influence the LCI of biochar production, since different feedstocks have different physicochemical properties, resulting in different yields and qualities (Matuštík et al., 2022; Sahoo et al., 2021; Zhu et al., 2022). According to Patel et al. (2023), both the biochar yield and the emissions during production largely influence the biochar LCI and, thus, the environmental impacts.

Bauer et al. (2024) used an LCA approach to compare the environmental impacts of different carbon dioxide removal (CDR) technologies, including biochar production and application to soil. Regarding biochar-to-soil application, the authors referred to Hoeskuldsdottir (2022), who found that, depending on the scenario and per kg of biochar, a net reduction of about 2-5 kg of $CO_2$-eq can be achieved with biochar-to-soil application. This corresponds well with the results found in our study (0.79–2.4 kg $CO_2$-eq per kg of biochar). However, the results are not directly comparable because of methodological differences between the two studies. Regarding the impacts on soils, both studies made no assumptions of any increase in yield. However, we conservatively included the reduction of $N_2O$ emissions, while Bauer et al. (2024) decided not to include this.

Regarding biochar persistence, Bauer et al. (2024) referred to Hoeskuldsdottir (2022) and Woolf et al. (2021), while our study uses the IPCC approach, which, although similar, uses slightly different values. We chose the IPCC approach because it is generally accepted, although not without controversy, since biochar is classified according to production parameters and not on the basis of analysis. However, we compared the IPCC values with the properties of the biochar typical for Switzerland and the persistence calculations used in the voluntary market. For Swiss conditions, both approaches are largely consistent for the purposes of this study. Both studies include biomass production, processing, and transport in LCA. Whereas we included the environmental impacts from straw harvest and transport, Hoeskuldsdottir (2022) and Bauer et al. (2024) assumed no environmental burdens for residues like straw. However, they assumed up to 300 km transport of biomass (as a reference: Zurich – Geneva = 280 km), which is considerably longer than the distances used in our study that were selected to represent the specific situation in Switzerland. Moreover, this study only examined woody biomass. In compiling the inventory, Bauer et al. (2024) used data from the literature and provided a flexible model in terms of pyrolysis parameters. They used a pyrolysis temperature of 400–600°C, pyrolysis plants consuming 10‘000 t biomass p.a., and an initial moisture content of the biomass of 40% as the default values.

In our study, we used real-world data on both pyrolysis units relevant to Swiss conditions (approx. 3000 t biomass p.a.) and biochar properties for the EBC database from Switzerland. Another major difference is in our consideration of the energy generated by burning pyrolysis gas and bio-oil. In line with the current situation in Switzerland for the production of biochar for soil application, we assume that only usable heat will be provided, without electricity generation, as included by Bauer et al. (2024), who used a system expansion approach that included environmental credits for produced heat and electricity. By contrast, we used an allocation approach based on physical properties.

Hamedani et al. (2019) performed an LCIA for two different biochar production systems in Belgium using willow and pig manure. They provide all midpoints derived from the IMPACT2002+ method. They computed a GWP of -2063 kg $CO_{2eq}$ and -472 kg $CO_{2eq}$ for willow and pig manure per tonne of biochar. The difference mainly refers to the higher potential of willow biochar with regard to carbon stored in the soil (carbon sequestration) compared with pig manure biochar. These results are comparable to our findings when considering both emissions from production and carbon sequestration.

## 5.4 Limitations of the study

This study used environmental LCA to quantify the environmental impacts of biochar application on Swiss farms. This section provides an assessment of the limitations of this approach. LCA is a widely used and accepted method for analysing the environmental impacts of production systems, which allows to draw a comprehensive picture of the environmental impacts across the most important environmental impact categories, along with any trade-offs between them. However, due to the complexity of the analysed systems and the combination of different data sources and models (for calculating emissions and estimating impacts), the results are also subject to a certain degree of uncertainty. We have taken this aspect into account by considering various scenarios and conducting a sensitivity study. Still, it should be kept in mind that the assumptions related to emissions changes by biochar application heavily rely on available literature and might need to be revised as more knowledge becomes available. It is also important to emphasise that, by definition, an LCA only allows a relative statement in relation to the functional unit and the results are only valid within the specific temporal and spatial system boundaries of the respective study. This study is based on an attributional LCA approach, which is used statically and ex-post. As a result, neither macro- economic interactions nor dynamic effects or future developments are depicted. Methodological extensions of LCA for dynamic and prospective modelling are under development but cannot yet be used without reservation in agricultural LCA. Furthermore, the focus of this study is on the environmental LCA and no economic or social effects are modelled, nor are the effects of biochar use on animal welfare. It is also important to mention that the approach chosen in this study focuses on modelling GWP. Other environmental impacts are listed in the appendix of the study but are not discussed.
Further effects of the use of biochar were excluded from the analysis because they are either not scientifically proven or because there is a lack of (Swiss-specific) data (Schmidt et al., 2021):

- **Yield effects**: Contrary to findings in tropical or degraded soils, no consistent yield increases have been demonstrated in Swiss agricultural soils following biochar application. This limits assumptions about productivity benefits in local conditions.

- **Soil interactions and long-term dynamics**: The impact of biochar on soil organic matter turnover is complex and insufficiently understood. Priming effects—both positive and negative—have been observed but only over short timescales. Long-term field studies are lacking.
- **Soil biology and ecosystem functions**: Biochar can affect microbial communities, nutrient cycling, and soil fauna, such as earthworms. These effects can be beneficial or harmful, depending on dosage and context. Notably, negative effects on earthworms have been reported at high application rates, raising concerns about ecosystem function.
- **Pollutant dynamics**: In its course of immobilising nutrients and some contaminants, biochar can also bind pesticides, potentially reducing their efficacy and altering degradation pathways. This can lead to unintended accumulation of agrochemicals in soils.
- **Lack of long-term data**: Many of the environmental, biological, and climate-related effects of biochar remain insufficiently studied, particularly in long-term, field-scale trials under Swiss conditions.

In summary, although LCA offers valuable insights into the environmental profile of biochar systems, its outputs must be interpreted within the context of significant scientific uncertainty, especially concerning soil dynamics, pollutant interactions, and long-term climate impacts. Further field research and refinement of dynamic LCA methodologies are necessary to fully understand the role of biochar in sustainable Swiss agriculture.

# 5 Conclusions

This study investigates the climate change impact of biochar production and on-farm applications using the GWP and following the LCA approach. The main motivation was to determine the combined effects of the cascading use of biochar on a Swiss farm on the generation of emissions. Cascading use refers, for example, to the use in animal feed that further results in biochar effects in the manure and eventually in the soil. The goal was to quantify the contribution of biochar use to emission reduction in the Swiss agricultural sector as a whole. We used three different model farms to upscale the expected net GWP change to the entire Swiss agricultural sector. Modell farms were designed based on data on the current main usage of biochar, that is, in animal husbandry and vegetable farming, and on Swiss census data on respective farms in Switzerland. Quantitative assessment of GWP changes related to biochar production and on-farm applications were addressed through eight scenarios considering different entry points of biochar, such as animal bedding, liquid manure storage, and direct soil application.

There is compelling evidence for the beneficial effects biochar can have on agriculture, especially in mitigating undesired side effects, such as nutrient leaching and soil-borne GHG emissions. However, it has been shown that, for example, increases in agricultural yields have not been systematically demonstrated in temperate climates with a mean annual temperature of <10°C. Accordingly, our literature research focused on the impacts of biochar that have been proven to occur under Swiss conditions (soil, climate, << 10 t $ha^{-1}$ biochar application). We implemented the use of biochar as a floating layer on open slurry storage to reduce $NH_3$ (as one example of many different options to use biochar in manure management), $N_2O$ emissions, and nitrogen sorption from manure in the LCA and made them dependent on the actual biochar dose applied.

The analysis reveals that net GWP (including biochar production, on-farm emissions through the cascade use of biochar, and carbon sequestration) is dominated by carbon sequestration of up to 2.40 kg $CO_2$-eq per kg of biochar applied. Carbon sequestration by biochar remains the most important contributor to GHG mitigation. Co-benefits, such as the reduction of soil-borne $N_2O$ emissions, are present, but they play a secondary role. Thus, the climate benefits of the scenarios depend heavily on the amount of biochar applied in that scenario. Extrapolating our findings to the entire agricultural sector in Switzerland shows that the GWP can be reduced by up to approximately 411,000 t $CO_2$-eq, corresponding to close to 4.9% of the total current GWP, although this scenario also exceeds current application limits. Scenario 2 leads to the largest reduction in GWP (3.6% corresponding to around 301,680 t $CO_2$-eq) which fulfils the current legal requirements.

How to quantify the negative emissions generated by biochar production with non-oxidative use is already well understood. Furthermore, the effects of biochar, for example, on soil-borne gas emissions, have been studied intensively. Nevertheless, while offering robust insights, the study has several limitations: There are still uncertainties in field emissions due to variations in soil, climate, and application practices, as studies with relevance to the specific conditions in Switzerland are limited, despite the huge amount of biochar literature available. Thus, these effects were modelled conservatively. Further, our study considered only the first year of implementation of the biochar scenarios; thus, we used scenarios with higher biochar dosages to provide additional insights. Yet, biochar impact on climate remained dominated by the carbon sink rather than by co-benefits such as reducing $N_2O$ emissions. Our study focused on climate impacts and excluded environmental categories such as biodiversity, water use, human toxicity, or animal health, which may influence the net sustainability of biochar strategies.

The economic feasibility of large-scale biochar deployment in Swiss agriculture was not assessed. Current costs (approx. CHF 1000/t) remain a major barrier, which may be overcome, for example, by on-farm biochar production using automated small-scale pyrolysis units to heat farm buildings or supply small district heating systems.

To enhance the reliability and policy relevance of LCA-based insights, further research is needed, particularly regarding (long-term) field data obtained under Swiss field conditions. Such data should also be obtained from farmers directly, for example, on the impacts of biochar on animal husbandry under real-world conditions. More research is also needed on alternative feedstocks, especially secondary materials from agriculture or materials such as source-separated biowaste. Innovative biochar products and cascade applications could maximise both climate and agronomic benefits. To this end, the systemic interaction of biochar with other mitigation strategies, such as cover cropping, reduced tillage, or agroforestry, needs further attention.

The Swiss approach towards CDR is agnostic to the approaches used to achieve its targets, and biochar is among several options. Biochar production and use can be combined and co-deployed with other CDR methods. Pyrolysis units can be equipped with $CO_2$ capture units, as used in BECCS (bioenergy carbon capture and storage), to increase the amount of carbon sequestration per unit of biomass. Biochar use should be combined with other agricultural methods for carbon sequestration, as suggested above, which could also include the use of rock powder for enhanced rock weathering.

Overall, this study demonstrates that while biochar is not a panacea, it is a potent component of a broader climate-smart agriculture strategy. Strategic deployment of biochar application aligned with regulatory frameworks could meaningfully contribute to Swiss climate targets.

# 6 Abbreviations

| | |
|---|---|
| AWARE | Available Water REmaining |
| BC | Biochar |
| CDR | Carbon dioxide removal |
| CML | Center of Environmental Science of Leiden University |
| FOAG | Federal Office of Agriculture |
| FOEN | Federal Office for the Environment |
| FSO | Federal Statistical Office |
| GWP | Global warming potential |
| HCV | High calorific value |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Standard Organisation |
| Kt | kiloton |
| kWh | kilowatt hour |
| LANCA | LANd use indicator value CAlculation |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| LU | Livestock units |
| LULUC | Land use and land-use changes |
| NET | Negative emission technologies |
| P | piece |
| PEF | Product environmental footprint |
| SALCA | Swiss Agricultural Life Cycle Assessment |
| SOC | Soil organic carbon |
| STPV | Standardproduktion-Variante |
| Tkm | tonkilometer |
| UAA | Used agriculture area |
| UBP | Umweltbelastungspunkte |
| WC | Woodchips |
| W40 | Water content 40% |
| W15 | Water content 15% |

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# 8 Appendix

## A. Biochar Production

### A1: LCI of Biochar (Wood) Production

This section presents tables with the LCI data for biochar (wood) production.

Table A1: LCI data for wood biomass production.

| | Amount | Unit | Allocation |
|---|---|---|---|
| **Outputs: Products** | | | |
| Wood biomass | 1 | kg | 100% |
| **Inputs from technosphere: Materials/fuels** | | | |
| Wood chips, wet, measured as dry mass {CH}\| market for wood chips, wet, measured as dry mass \| Cut-off, U | 1 | kg | |
| Transport, freight, lorry 3.5–7.5 metric ton, EURO4 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 \| Cut-off, U | 0.025 | tkm | |

Table A2: LCI data for pyrolysis system operation.

| | Amount | Unit | Allocation |
|---|---|---|---|
| **Outputs: Products** | | | |
| Biochar | 746,400 | kg | 69% |
| Pyrogas | 32,567,920 | MJ | 31% |
| **Inputs from nature** | | | |
| Air | 599,608 | kg | |
| **Inputs from technosphere: Materials/fuels** | | | |
| Wood biomass | 2,488,000 | kg | |
| Storage bunker | 0.05 | p | |
| Reactor | 0.05 | p | |

Table A3: LCI data for the storage bunker.

| | Amount | Unit |
|---|---|---|
| **Products** | | |
| Storage bunker | 1 | p |
| **Inputs from nature** | | |
| Occupation, grassland | 27,000 | $m^2a$ |
| Transformation, from grassland | 900 | $m^2$ |
| **Inputs from technosphere: Materials/fuels** | | |
| Excavation, hydraulic digger {RER}\| excavation, hydraulic digger \| Cut-off, U | 558 | $m^3$ |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}\| transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 39,900 | tkm |
| Concrete, normal strength {CH}\| market for concrete, normal strength \| Cut-off, U | 108 | $m^3$ |
| Reinforcing steel {GLO}\| market for reinforcing steel \| Cut-off, U | 16,800 | kg |
| Sawnwood, softwood, dried (u=20%), planed {CH}\| sawnwood production, softwood, dried (u=20%), planed \| Cut-off, U | 76 | $m^3$ |
| Steel, low-alloyed, hot rolled {GLO}\| market for steel, low-alloyed, hot rolled \| Cut-off, U | 14.7 | kg |

| | | |
|---|---|---|
| Steel, chromium steel 18/8, hot rolled {GLO}\| market for steel, chromium steel 18/8, hot rolled \| Cut-off, U | 300 | kg |
| Machine operation, diesel, < 18.64 kW, generators {GLO}\| machine operation, diesel, < 18.64 kW, generators \| Cut-off, U | 250 | hr |
| Electricity, high voltage {CH}\| market for electricity, high voltage \| Cut-off, U | 500 | kWh |
| Concrete, 25- 30MPa {CH}\| market for concrete, 25- 30MPa \| Cut-off, U | 56 | $m^3$ |
| **Outputs to technosphere: Waste treatment** | | |
| Waste concrete {CH}\| market for waste concrete \| Cut-off, U | 404 | ton |
| Waste building wood, chrome preserved {CH}\| market for waste building wood, chrome preserved \| Cut-off, U | 26.6 | ton |
| Scrap steel {CH}\| market for scrap steel \| Cut-off, U | 16.8 | ton |

Table A4: LCI data for the reactor.

| | Amount | Unit |
|---|---|---|
| **Products** | | |
| Reactor | 1 | p |
| **Inputs from technosphere: Materials/fuels** | | |
| Steel, low-alloyed, hot rolled {GLO}\| market for steel, low-alloyed, hot rolled | 36,800 | kg |
| Refractory, fireclay, packed {GLO}\| market for refractory, fireclay, packed \| Cut-off, U | 20,800 | kg |
| Heat, central or small-scale, natural gas {CH}\| market for heat, central or small-scale, natural gas \| Cut-off, U | 6,720 | MJ |
| Electricity, low voltage {CH}\| market for electricity, low voltage \| Cut-off, U | 4,130 | kWh |
| Sheet rolling, steel {GLO}\| market for sheet rolling, steel \| Cut-off, U | 1,100 | kg |
| Cast iron {RER}\| cast iron production \| Cut-off, U | 802 | kg |
| Stone wool {GLO}\| market for stone wool \| Cut-off, U | 812 | kg |
| Iron-nickel-chromium alloy {RER}\| iron-nickel-chromium alloy production \| Cut-off, U | 371 | kg |
| Polystyrene foam slab {RER}\| polystyrene foam slab production \| Cut-off, U | 205 | kg |
| Aluminium, wrought alloy {GLO}\| market for aluminium, wrought alloy \| Cut-off, U | 73.1 | kg |
| Steel, chromium steel 18/8 {RER}\| steel production, electric, chromium steel 18/8 \| Cut-off, U | 57.2 | kg |
| Drawing of pipe, steel {RER}\| drawing of pipe, steel \| Cut-off, U | 57.2 | kg |
| Concrete, normal strength {CH}\| market for concrete, normal strength \| Cut-off, U | 42.4 | $m^3$ |
| Copper, cathode {GLO}\| market for copper, cathode \| Cut-off, U | 32.4 | kg |
| Polyethylene, high density, granulate {CH}\| polyethylene, high density, granulate, recycled to generic market for high density PE granulate \| Cut-off, U | 18 | kg |
| Electronics, for control units {RER}\| electronics production, for control units \| Cut-off, U | 12 | kg |
| Alkyd paint, white, without solvent, in 60% solution state {RER}\| market for alkyd paint, white, without solvent, in 60% solution state \| Cut-off, U | 8.23 | kg |
| Lubricating oil {RER}\| market for lubricating oil \| Cut-off, U | 13.1 | kg |
| Iron scrap, unsorted {GLO}\| iron scrap, unsorted, Recycled Content cut-off \| Cut-off, U | 802 | kg |
| Transport, freight, lorry >32 metric ton, EURO4 {RER}\| market for transport, freight, lorry >32 metric ton, EURO4 \| Cut-off, U | 18,000 | tkm |
| **Outputs to technosphere: Waste treatment** | | |
| Waste mineral oil {CH}\| market for waste mineral oil \| Cut-off, S - Copied from Ecoinvent | 13.1 | kg |
| Electronics scrap from control units {GLO}\| market for electronics scrap from control units \| Cut-off, U | 12 | kg |
| Waste polyethylene {CH}\| treatment of waste polyethylene, municipal incineration FAE \| Cut-off, U | 18 | kg |
| Copper scrap, sorted, pressed {RER}\| treatment of copper scrap by electrolytic refining \| Conseq, U | 32.4 | kg |

| | | |
|---|---|---|
| Scrap aluminium {CH}\| market for scrap aluminium \| Cut-off, U | 73.1 | kg |
| Waste polystyrene isolation, flame-retardant {CH}\| market for waste polystyrene isolation, flame-retardant \| Cut-off, U | 205 | kg |
| Waste mineral wool {CH}\| treatment of waste mineral wool, collection for final disposal \| Cut-off, U | 812 | kg |
| Inert waste, for final disposal {CH}\| market for inert waste, for final disposal \| Cut-off, U | 20,800 | kg |
| Scrap steel {CH}\| market for scrap steel \| Cut-off, U | 36,800 | kg |
| Waste concrete {CH}\| market for waste concrete \| Cut-off, U | 99,700 | kg |

Table A5: LCI data for "Concrete 25-30MPA {CH}| market for concrete, 25-30MPa | Cut-off, U".

| | Amount | Unit |
|---|---|---|
| **Products** | | |
| Concrete, 25-30MPa {CH}\| market for concrete, 25-30MPa \| Cut-off, U | 2 | $m^3$ |
| **Inputs from technosphere: Materials/fuels** | | |
| Concrete, 25MPa {CH}\| concrete production, 25MPa, for building construction, with cement, CEM II/A \| Cut-off, U | 0.5 | $m^3$ |
| Concrete, 25MPa {CH}\| concrete production, 25MPa, for building construction, with cement, CEM II/B \| Cut-off, U | 0.5 | $m^3$ |
| Transport, freight train {CH}\| market for transport, freight train \| Cut-off, U | 9.03 | tkm |
| Transport, freight, lorry, unspecified {RER}\| market for transport, freight, lorry, unspecified \| Cut-off, U | 63.2 | tkm |
| Concrete, 30MPa {CH}\| concrete production, 30MPa, for drilled piles, with cement, CEM II/A \| Cut-off, U | 0.3 | $m^3$ |
| Concrete, 30MPa {CH}\| concrete production, 30MPa, for drilled piles, with cement, CEM II/B \| Cut-off, U | 0.1 | $m^3$ |
| Concrete, 30MPa {CH}\| concrete production, 30MPa, for drilled piles, with cement, Portland \| Cut-off, U | 0.6 | $m^3$ |
| Transport, freight train {CH}\| market for transport, freight train \| Cut-off, U | 8.83 | tkm |
| Transport, freight, lorry, unspecified {RER}\| market for transport, freight, lorry, unspecified \| Cut-off, U | 61.77 | tkm |

Table A6: LCI data for "Exhaust gas heat for district heating".

| | Amount | Unit | Allocation |
|---|---|---|---|
| **Outputs: Products** | | | |
| Exhaust gas heat for district heating | 18,460,960 | MJ | 100% |
| **Inputs from nature** | | | |
| Air | 11,071,600 | kg | |
| **Inputs from technosphere: Materials/fuels** | | | |
| Pyrogas | 32,592,800 | kg | |
| Nitrogen, liquid {RER}\| market for nitrogen, liquid \| Cut-off, U | 62,200 | kg | |
| Liquefied petroleum gas {CH}\| market for liquefied petroleum gas \| Cut-off, U | 4,700 | kg | |
| Electricity, low voltage {CH}\| market for electricity, low voltage \| Cut-off, U | 288,000 | kWh | |
| **Emissions to air** | | | |
| Carbon | 818.6 | kg | |
| Wood (dust) | 129.4 | kg | |
| Sulphur dioxide, CH | 2,786.56 | kg | |
| Carbon dioxide, biogenic | 2,687,040 | kg | |
| Carbon monoxide, biogenic | 1,042.5 | kg | |
| Nitrogen dioxide, CH | 3,284.16 | kg | |

| | | | |
|---|---|---|---|
| Methane, biogenic | 103.50 | kg | |
| Ammonia, CH | 12.94 | kg | |
| Hydrogen chloride | 181.13 | kg | |
| Heat, waste | 7,339,600 | MJ | |

## A2: Alternative Modelling of the "Wood Biomass" Life-Cycle Inventory

In the LCI biochar production, the "Wood chips" are selected as a main input for the modelling of the life-cycle inventory "Wood biomass". In this section, an alternative for the modelling of the "Wood biomass" life-cycle inventory is proposed. This alternative is to model the "Wood biomass" with different harvesting methods and not use the "Wood chip" inventory from the Ecoinvent database. The LCI for these different harvesting methods and logs harvested (logs motor-manual, logs woodliner, log liftliner) are created according to Kumar (2024) and Sistek (2021). Inventories for Switzerland are chosen whenever possible. The time period is 2024, and the technology level is the most recent.

For each harvesting method, the following amounts are used:

- 1 kg logs of the harvesting method as output from the technosphere – Products.
- 1 kg wood, unspecified, standing-kg as input from nature to represent the biomass feedstock.

- **Wood biomass production**

This inventory describes the production of the wood biomass that will be used and imported to the reactor to produce biochar. The biomass feedstock is forest wood, which is obtained through three different harvesting techniques: motor-manual, woodliner, and liftliner methods. The three different harvesting methods contribute differently to the total amount of biomass harvested, and for each harvesting method, 1 kg wood is used as input from nature to represent the biomass feedstock. In addition, the forest wood is harvested within a 25-km radius of the pyrolysis plant and then transported to the pyrolysis plant by lorry, minimising logistical complexities. The next step is the chipping of wood logs only a few days before pyrolysis to avoid methane emissions. The activity starts with harvesting wood logs and ends when the chipping process is finished and the wood biomass is ready for the reactor. This inventory is modelled for 1 kg of wood biomass.

Table A7: LCI data for wood biomass (alternative modelling).

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Wood biomass | 1 | kg | Mass | 100% |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Logs motor-manual | 0.02 | kg | | - |
| Logs woodliner | 0.36 | kg | | - |
| Log liftliner | 0.62 | kg | | - |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 \| Cut-off, U | 0.025 | tkm | | - |
| Wood chipping, chipper, mobile, diesel, at forest road {RER}\| wood chipping, mobile chipper, at forest road \| Cut-off, U | 6.00E-05 | hr | | - |

Figure A1 shows the steps for the wood biomass production.

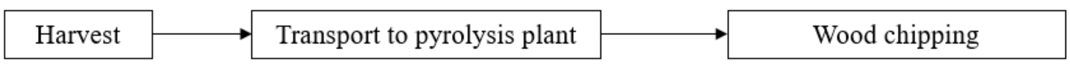



*Figure A1: Description of wood biomass production (alternative modelling).*

The harvest method includes cutting the wood logs with a motor (manual), a woodliner, and a liftliner machine, as shown in Figure A2.

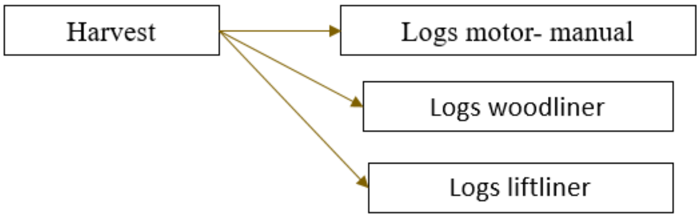



*Figure A2: Description of the harvesting methods of wood logs (alternative modelling).*

The inventories for each input from the technosphere for the wood biomass production inventory are described below.

- **Logs motor-manual**

This inventory describes how wood logs are cut with a manual machine. For the motor-manual harvesting process, the “Power sawing, with catalytic converter {GLO}| market for | Cut-off, U” is used as an input from the technosphere. The hours of operation for two power saws are 0.003 h per reference flow based on the literature (Sistek, 2021). In addition, the “Transport, tractor and trailer, agricultural {CH}| transport, tractor and trailer, agricultural | Cut-off, U” is used as another input from the technosphere. The calculation of transportation processes in the unit of tonkilometer (tkm) follows Sistek (2021). The activity starts with the cutting of wood logs and ends with the preparation of transportation of wood logs to the pyrolysis plant. The LCI data for this inventory are shown in Table A8.

Table A8: LCI data for logs motor-manual (alternative modelling).

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Logs motor-manual | 1 | kg | Mass | 100% |
| **Inputs from nature** | | | | |
| Wood, unspecified, standing/kg | 1 | kg | | |
| Inputs from the technosphere: Materials/fuels | | | | |
| Power sawing, with catalytic converter {GLO}\| market for \| Cut-off, U | 0.003 | hr | | - |
| Transport, tractor and trailer, agricultural {CH}\| transport, tractor and trailer, agricultural \| Cut-off, U | 0.00007 | tkm | | |

- **Logs woodliner**

This process describes another way of cutting wood logs with an automatic small machine. The inputs from the technosphere are the “Diesel, burned in building machine {GLO}| diesel, burned in building machine | Cut-off, U” and the “Power sawing, with catalytic converter {GLO}| market for power sawing, with catalytic converter | Cut-off, U”. The latest is used, since the specific machinery (woodliner) is not available in SimaPro. According to Sistek (2021), the “Diesel, burned in building machine” represents the impact of diesel burned in any type of machine and is, therefore, assumed to be a well replacement. Moreover, the woodliner process requires three power saws with a total operating time of 0.0002 h, each per reference flow.

The LCI data for this inventory are shown in Table A9.

Table A9: LCI data for logs woodliner (alternative modelling).

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Logs woodliner | 1 | kg | Mass | 100% |

| | | | | |
|---|---|---|---|---|
| Inputs from nature | | | | |
| Wood, unspecified, standing/kg | 1 | kg | | |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Diesel, burned in building machine {GLO}\| diesel, burned in building machine \| Cut-off, U | 0.0949 | MJ | | - |
| Power sawing, with catalytic converter {GLO}\| market for power sawing, with catalytic converter \| Cut-off, U | 0.0002 | hr | | - |

- **Log liftliner**

This inventory describes another way to cut wood logs with a liftliner machine. For this process, the “Diesel, burned in building machine” is selected as input from the technosphere, since it represents the impact of diesel burned in any type of machine, and is therefore assumed to be a well replacement. In addition, the liftliner machinery is not available in SimaPro, so the “Power sawing, with catalytic converter {GLO}| market for power sawing, with catalytic converter | Cut-off, U” is selected to represent this as input from the technosphere. According to Sistek (2021), this process requires three power saws, with a total operating time of 0.0002 hours per reference flow and 0.0539 MJ per reference flow for the remaining.

The LCI data for the log liftliner are shown in Table A10.

Table A10: LCI data for log liftliner (alternative modelling).

| | **Amount** | **Unit** | **Quantity** | **Allocation** |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Log liftliner | 1 | kg | Mass | 100% |
| Inputs from nature | | | | |
| Wood, unspecified, standing/kg | 1 | kg | | |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Diesel, burned in building machine {GLO}\| diesel, burned in building machine \| Cut-off, U | 0.0539 | MJ | | - |
| Power sawing, with catalytic converter {GLO}\| market for power sawing, with catalytic converter \| Cut-off, U | 0.0002 | hr | | - |

### A3: Allocation for Biochar (Wood) Production

The allocation factor in this project was calculated based on the following equation:

$$f_{biochar} = \frac{H_{i,biochar}}{H_{i,biochar} + E_{Strom} + EW}$$

where:

$E_{Strom}$: the amount of electricity sold from a pyrolysis unit (set to 0)

$H_{i\_biochar}$: the gross calorific value of biochar produced (set to 9.2)

$EW$: the amount of heat that is used/sold from the pyrolysis unit (set to 1.40 MWh × 3 = 4.2 MWh)

$f_{biochar}$: allocation factor

Assuming a yield of 30%, this leads to:

$$f_{biochar} = \frac{H_{i,biochar}}{H_{i,biochar} + E_{Strom} + EW} = \frac{9.2}{9.2 + 4.2} = 0.686$$

Therefore, the allocation factors for each product are 69% and 31% for biochar and pyrogas, respectively.

### A4: LCI of Biochar (Straw) Production

The first LCI for the production of straw biochar is straw biomass. This inventory describes the production of the straw biomass that will be used and imported to the reactor to produce biochar. For this reason, the "Straw, stand-alone production {CH}| straw production, stand-alone production | Cut-off, U" and the "Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Cut-off, U" were selected as inputs from the technosphere. This inventory was modelled for 1 kg of straw biomass, while the biomass was transported to the pyrolysis plant by lorry, minimising logistical complexities within a 25-km radius. For the production of straw biochar, 5 kg of straw were needed to make 1 kg of biochar (IWB, personal communication, 2024). The detailed data for this inventory are shown in Table A11.

Table A11: LCI data for straw biomass.

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Straw biomass | 5 | kg | Mass | 100% |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Straw, stand-alone production {CH}\| straw production, stand-alone production \| Cut-off, U | 5 | kg | | - |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 \| Cut-off, U | 0.025 | tkm | | |

After the straw biomass production, biochar and pyrogas from straw are produced. The life-cycle inventory "pyrolysis system operation" was modelled using the straw biomass, the storage bunker, and the reactor as inputs from the technosphere, while the air that enters the reactor for its operation was used as an input from nature. The detailed data for this LCI are shown in Table A12.

Table A12: LCI data for pyrolysis system operation (straw biochar).

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Biochar (straw) | 746,400 | kg | Mass | 69% |
| Pyrogas (straw) | 32,567,920 | MJ | Energy | 31% |
| **Inputs from nature** | | | | |
| Air | 599,608 | kg | | - |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Straw biomass | 3,732,000 | kg | | - |
| Storage bunker | 0.05 | p | | |
| Reactor | 0.05 | p | | |

The modelling of the LCI "Exhaust gas heat for district heating (straw)" is presented in Table A13. This inventory describes the combustion of pyrogas (straw). The pyrogas produced from the pyrolysis plant goes into a combustion chamber. Before entering the combustion chamber, the pyrogas passes through a liquid-nitrogen filter to remove any contaminants that may be present after the pyrolysis process and achieve a high-quality gas. The pyrogas then enters the combustion chamber where it is ignited with air due to the existing combustion using liquefied petroleum gas during the startup of the combustion chamber.

Table A13: LCI data for exhaust gas heat for district heating (straw biochar).

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Exhaust gas heat for district heating (straw) | 18,460,960 | MJ | Energy | 100% |
| **Inputs from nature** | | | | |
| Air | 11,071,600 | kg | | |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Pyrogas (straw) | 32,592,800 | kg | | |
| Nitrogen, liquid {RER}\| market for nitrogen, liquid \| Cut-off, U | 62,200 | kg | | |
| Liquefied petroleum gas {CH}\| market for liquefied petroleum gas \| Cut-off, U | 4,700 | kg | | |
| Electricity, low voltage {CH}\| market for electricity, low voltage \| Cut-off, U | 288,000 | kWh | | |
| **Emissions to air** | | | | |
| Carbon | 818.552 | kg | | |
| Wood (dust) | 129.376 | kg | | |
| Sulphur dioxide, CH | 2,786.56 | kg | | |
| Carbon dioxide, biogenic | 2,687,040 | kg | | |
| Carbon monoxide, biogenic | 1,042.472 | kg | | |
| Nitrogen dioxide, CH | 3,284.16 | kg | | |
| Methane, biogenic | 103.5008 | kg | | |
| Ammonia, CH | 12.9376 | kg | | |
| Hydrogen chloride | 181.1264 | kg | | |
| Heat, waste | 7,339,600 | MJ | | |

The last LCI for the straw biochar is the “Biochar (straw) at farm”. The modelling of this inventory with all the data is listed in Table A14.

Table A14: LCI data for biochar (straw) at farm.

| | Amount | Unit | Allocation |
|---|---|---|---|
| **Outputs: Products** | | | |
| Biochar (straw) at farm | 895,680 | kg | 100% |
| **Inputs from technosphere: Materials/fuels** | | | |
| Biochar (straw) | 746,400 | kg | |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 \| Cut-off, U | 4,515.72 | tkm | |
| Tap water {CH}\| market for tap water \| Cut-off, U | 149,280 | kg | |

### A5: LCI of Biochar (Landscape Conservation Wood) Production

The first LCI for the production of landscape conservation wood biochar is landscape conservation wood biomass. This inventory describes the production of the biomass that will be used and imported to the reactor to produce biochar. For this reason, suitable inputs from the Ecoinvent database were selected. This inventory was modelled for 1 kg of landscape conservation wood biomass, while the biomass was transported to the pyrolysis plant by lorry within a 15 km radius. For the production of this biomass, 3 kg is needed to produce 1 kg of biochar (IWB, personal communication, 2024).

The detailed data for this LCI are shown in Table A15.

Table A15: LCI data for landscape conservation wood biomass production.

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Landscape conservation wood biomass | 1 | kg | Mass | 100% |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO4 \| Cut-off, U | 0.045 | tkm | | |

The next LCI is the "pyrolysis system operation", from which Biochar and Pyrogas are produced. As inputs from the technosphere, the landscape conservation wood biomass, the storage bunker, and the reactor were selected, while as an input from nature the air that inserts in the reactor for its operation was used. The detailed data for this inventory are shown in Table A16.

Table A16: LCI data for the pyrolysis system operation for landscape conservation wood biochar.

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Biochar (Landscape conservation wood) | 746,400 | kg | Mass | 69% |
| Pyrogas (Landscape conservation wood) | 32,567,920 | MJ | Energy | 31% |
| **Inputs from nature** | | | | |
| Air | 599,608 | kg | | - |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Landscape conservation wood biomass | 2,161,815 | kg | | - |
| Storage bunker | 0.05 | p | | |
| Reactor | 0.05 | p | | |

Table A17: LCI for the Exhaust gas heat for district heating for the landscape conservation wood biochar.

| | Amount | Unit | Quantity | Allocation |
|---|---|---|---|---|
| **Outputs: Products** | | | | |
| Exhaust gas heat for district heating (Landscape conservation wood) | 18,460,960 | MJ | Energy | 100% |
| **Inputs from nature** | | | | |
| Air | 11,071,600 | kg | | |
| **Inputs from technosphere: Materials/fuels** | | | | |
| Pyrogas (Landscape conservation wood) | 32,592,800 | kg | | |
| Nitrogen, liquid {RER}\| market for nitrogen, liquid \| Cut-off, U | 62,200 | kg | | |
| Liquefied petroleum gas {CH}\| market for liquefied petroleum gas \| Cut-off, U | 4,700 | kg | | |
| Electricity, low voltage {CH}\| market for electricity, low voltage \| Cut-off, U | 288,000 | kWh | | |
| **Emissions to air** | | | | |
| Carbon | 818.552 | kg | | |
| Wood (dust) | 129.376 | kg | | |
| Sulphur dioxide, CH | 2786.56 | kg | | |
| Carbon dioxide, biogenic | 2,687,040 | kg | | |
| Carbon monoxide, biogenic | 1,042.472 | kg | | |
| Nitrogen dioxide, CH | 3,284.16 | kg | | |
| Methane, biogenic | 103.5008 | kg | | |
| Ammonia, CH | 12.9376 | kg | | |

| | | | | |
|---|---|---|---|---|
| Hydrogen chloride | 181.1264 | kg | | |
| Heat, waste | 7,339,600 | MJ | | |

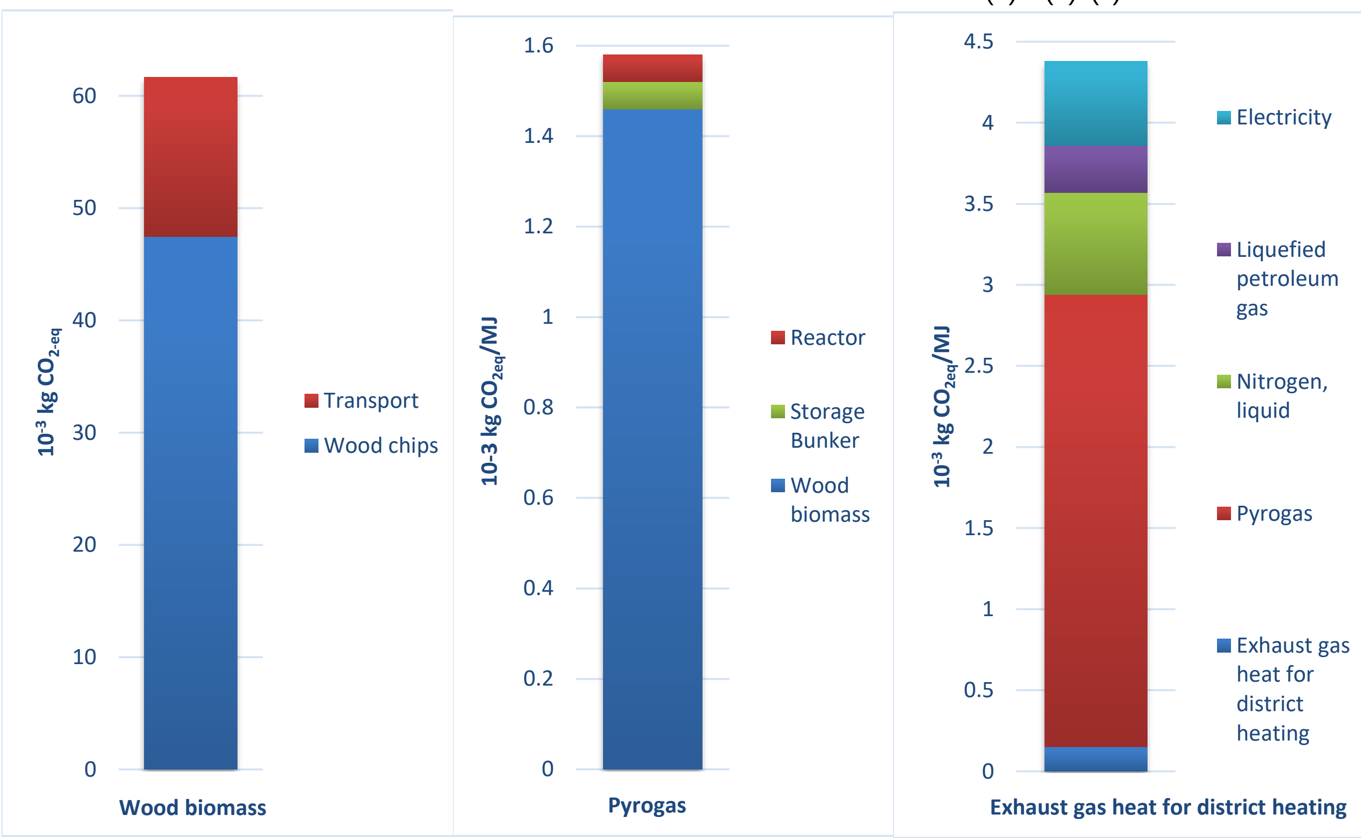
The modelling of “Biochar (landscape conservation wood) at farm” includes the biochar produced in the pyrolysis system operation, the tap water spread over the biochar to prevent any fire from the ashes, and last the transportation of this biochar to the farm. Table A18 lists all the data for the LCI “Biochar at farm”.

Table A18: LCI for Biochar (landscape conservation wood) at farm.

| | Amount | Unit | Allocation |
|---|---|---|---|
| **Outputs: Products** | | | |
| Biochar (Landscape conservation wood) at farm | 895,680 | kg | 100% |
| **Inputs from technosphere: Materials/fuels** | | | |
| Biochar (Landscape conservation wood) | 746,400 | kg | |
| Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 \| Cut-off, U | 4,515.72 | tkm | |
| Tap water {CH}\| market for tap water \| Cut-off, U | 149,280 | kg | |

## A6: GWP for Production of Biochar (at the Farm Gate) From “Wood” Feedstock

(a) (b) (c)




(a) (b) (c)

*Figure A3 (a): GWP for the LCI “Wood biomass” in the production of biochar (wood); (b): GWP for the LCI “Pyrogas” in the production of biochar (wood); (c): GWP for the LCI “Exhaust gas heat for district heating” in the production of biochar (wood).*

Figures A3 (a), (b), and (c) present the LCI data for GWP of “Wood biomass”, “Pyrogas”, and “Exhaust gas heat for district heating” in the biochar production. Regarding the LCI of “Wood biomass”, the largest contribution comes from “Wood chips” with 47.5 $10^{-3}$ kg $CO_2$-eq. In the “Exhaust gas heat for district heating” LCI, the largest emissions with

2.8 $10^{-3}$ kg $CO_2$-eq/MJ come from “Pyrogas”, while for the “Pyrogas” LCI, the “Wood biomass” contributes the most with 1.5 $10^{-3}$ kg $CO_2$-eq/MJ.

### A7: Contribution Analysis for the GWP of Biochar Production

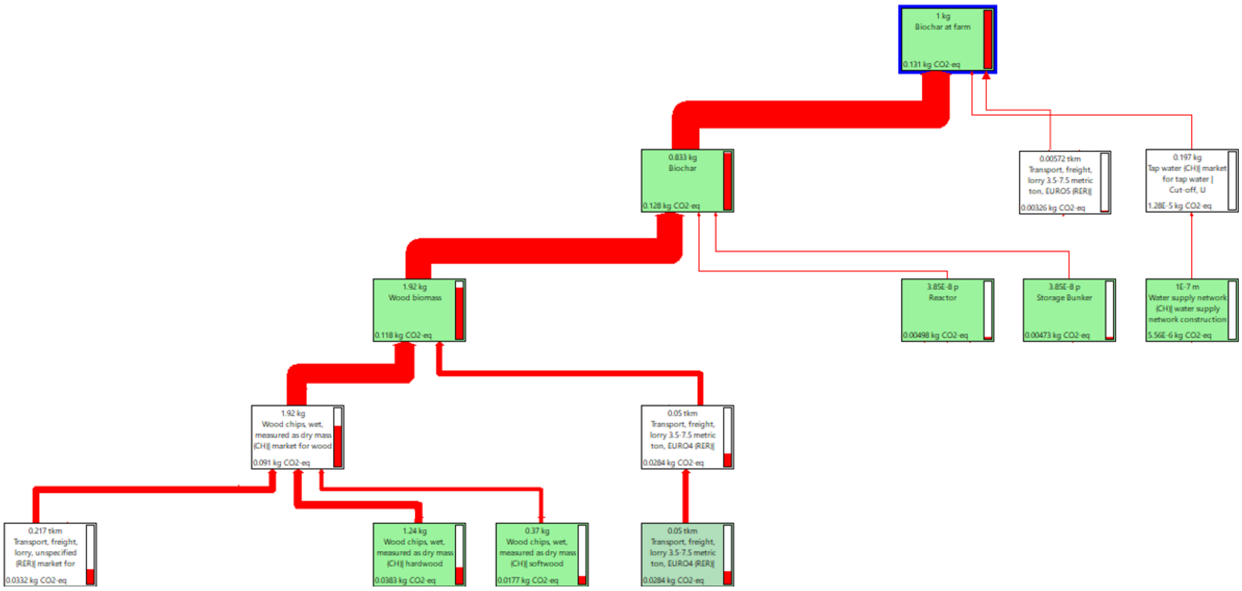



*Figure A4: Main contributing processes for biochar production (feedstock: wood).*

### A8: Additional Data for Nutrient-Related Midpoints for Biochar Production

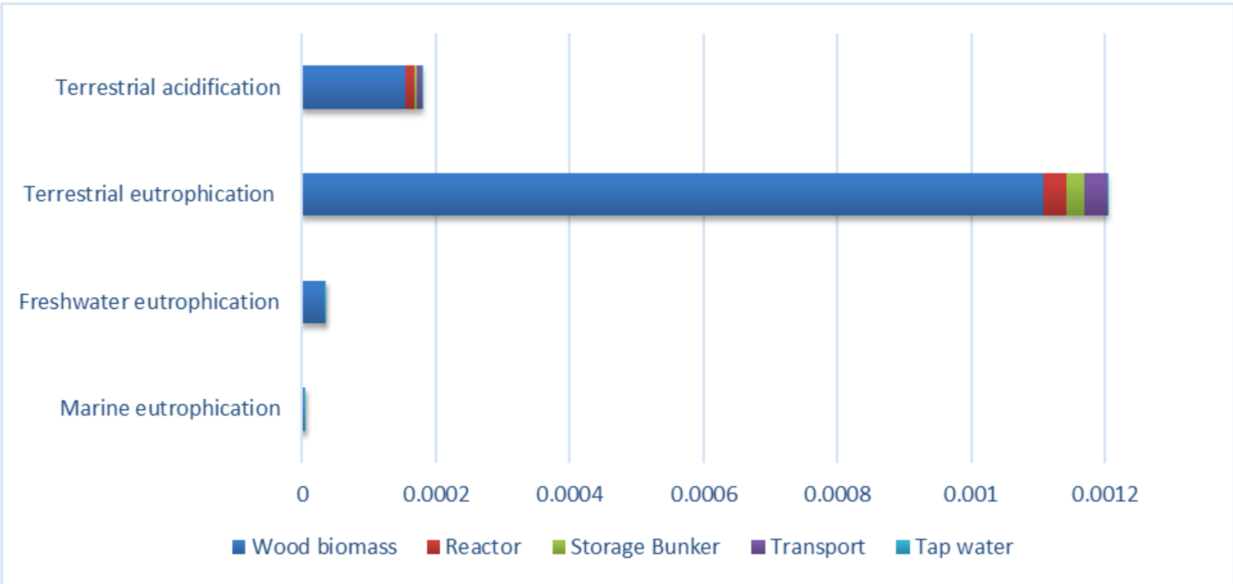



*Figure A5: Results on nutrient- related midpoints impact categories (Terrestrial acidification [kg $SO_{2\text{-}eq}$], Terrestrial eutrophication [mol $N_{\text{-}eq}$], Freshwater eutrophication [kg $P_{\text{-}eq}$], Marine eutrophication [kg $N_{\text{-}eq}$]) for the LCI “Biochar at farm”.*

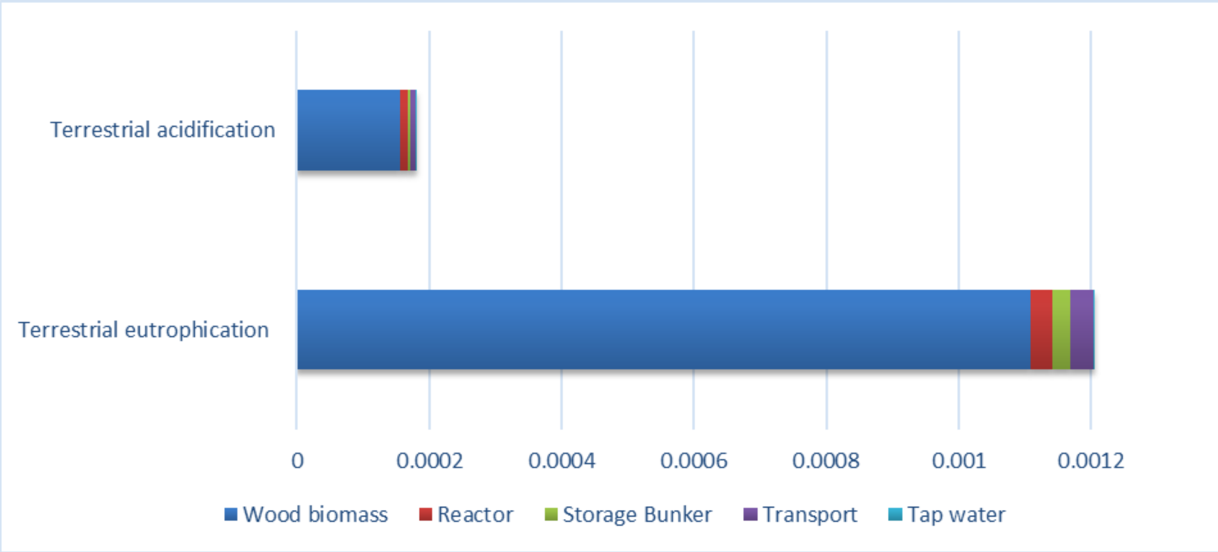



*Figure A6: Results on the "Terrestrial acidification" [kg $SO_{2\text{-}eq}$] and "Terrestrial eutrophication" [mol $N_{\text{-}eq}$] midpoints impact categories for the LCI "Biochar at farm".*

Table A19: Nutrient-related midpoints impact categories in the LCI "Biochar at farm".

| Impact category | Unit | Wood biomass | Storage Bunker | Reactor | Transport | Tap water |
|---|---|---|---|---|---|---|
| **Marine eutrophication** | kg N-eq | $4.9\ 10^{-6}$ | $3.5\ 10^{-8}$ | $6.6\ 10^{-8}$ | $1.7\ 10^{-8}$ | $1.6\ 10^{-10}$ |
| **Freshwater eutrophication** | kg P-eq | $5.6\ 10^{-5}$ | $2.5\ 10^{-7}$ | $2.9\ 10^{-7}$ | $3.1\ 10^{-8}$ | $5.4\ 10^{-10}$ |
| **Terrestrial eutrophication** | mol N-eq | $1.8\ 10^{-3}$ | $4.2\ 10^{-5}$ | $5.4\ 10^{-5}$ | $2.9\ 10^{-5}$ | $1.7\ 10^{-7}$ |
| **Terrestrial acidification** | kg $SO_2$-eq | $2.6\ 10^{-4}$ | $8.2\ 10^{-6}$ | $2.0\ 10^{-5}$ | $5.1\ 10^{-6}$ | $5.6\ 10^{-8}$ |

Figure A6 and Table A19 reveal that "Wood biomass" contributes the most to the nutrition-related midpoints, while "Tap water" contributes the least.

### A9: Additional Data on GHG Contribution to the GWP

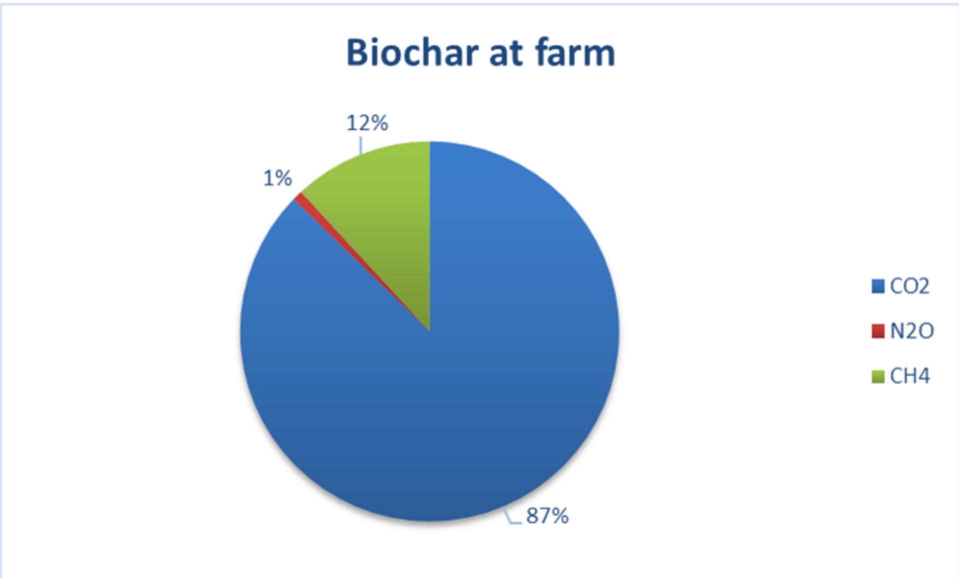


*Figure A7: Contributions (%) of $CO_2$, $CH_4$ and $N_2O$ to the Global Warming Potential of the LCI "Biochar at farm", biochar produced with wood feedstock (processes included: biochar (wood), tap water, transport- freight lorry).*

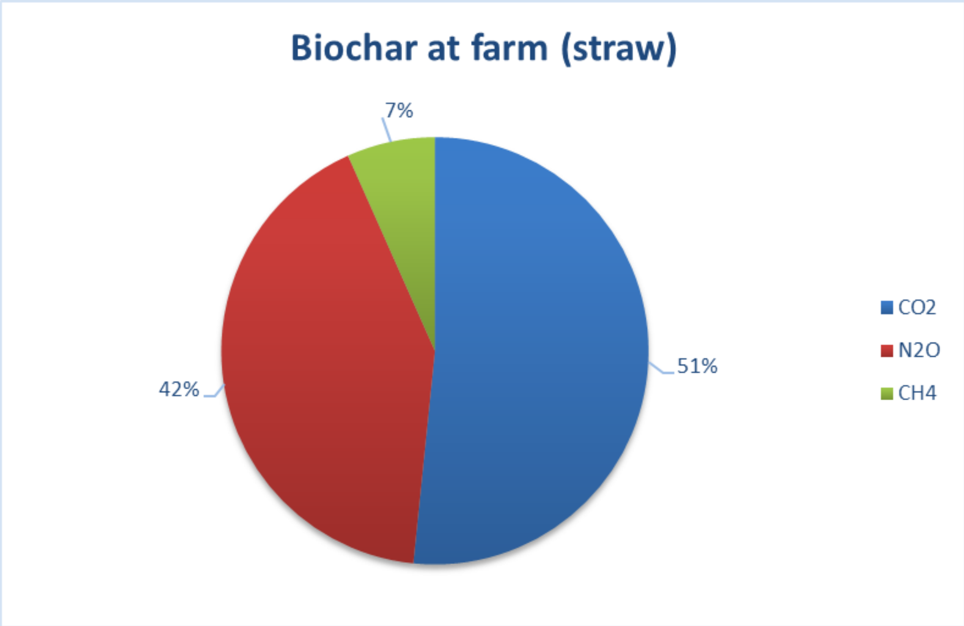



*Figure A8: Contributions (%) of $CO_2$, $CH_4$ and $N_2O$ to the Global Warming Potential of the LCI "Biochar at farm", biochar produced with straw (processes included: biochar(straw), tap water, transport-freight lorry).*

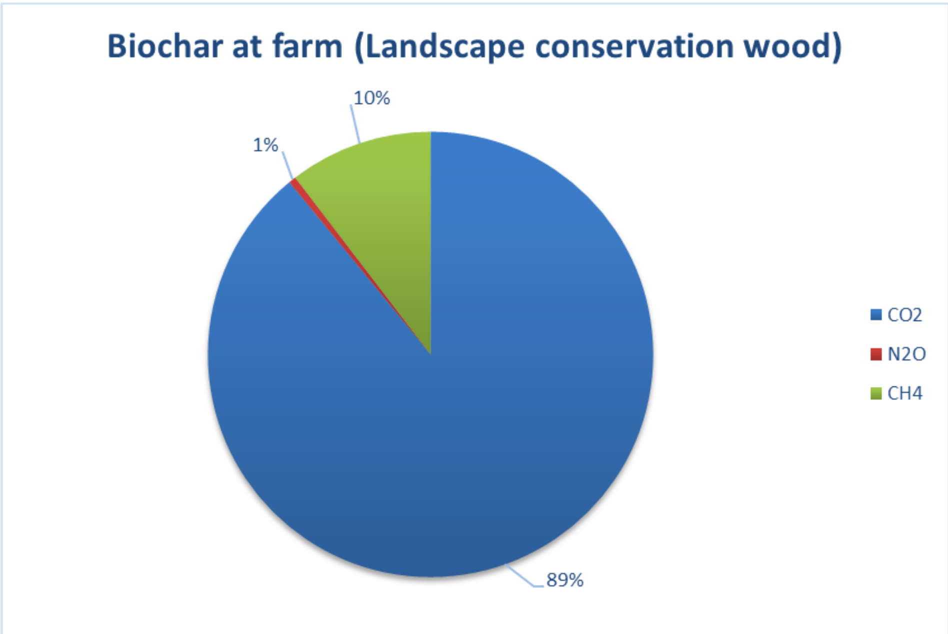



*Figure A9: Contributions (%) of $CO_2$, $CH_4$ and $N_2O$ to the Global Warming Potential of the LCI "Biochar at farm", biochar produced with landscape conservation wood (processes included: biochar(landscape conservation wood),tap water, transport-freight lorry).*

Table A20: Contribution of $CH_4$ to the LCI "Biochar" (wood) and its subprocesses [unit: $CO_{2\text{-eq}}$]. Biochar is produced from wood biomass derived from wood chips.

| Process | Total | Unit |
|---|---|---|
| **Biochar** | 1.3 | $10^{-3}$ kg $CO_2$-eq |
| **Wood biomass** | 16.9 | $10^{-3}$ kg $CO_2$-eq |
| **Wood chips** | 5.8 | $10^{-3}$ kg $CO_2$-eq |

## A10: Results on Alternative Biomass Feedstock for Biochar Production

*Straw as feedstock for biochar production*

Figure A10 shows the LCI data when straw is used as feedstock in the biochar production. The LCI "Pyrolysis system operation" has two products: the "Biochar" and the "Pyrogas", both with the inputs as "Straw biomass", "Reactor", and "Storage bunker". Regarding the "Biochar" product, these inputs amount to 241.2 $10^{-3}$ kg $CO_2$-eq, 5.9 $10^{-3}$ kg $CO_2$-eq, and 5.7 $10^{-3}$ kg $CO_2$-eq, for 1 kg biochar, respectively. The contributions of the pyrogas to GWP for the storage bunker, reactor, and straw amount to 2.48 $10^{-3}$ $CO_2$-eq/MJ, 0.061 $10^{-3}$ $CO_2$-eq/MJ, and 0.058 $10^{-3}$ $CO_2$-eq/MJ, respectively. Based on these results, the "Biochar (straw)" product has a notably higher impact on the GWP than the "Pyrogas (straw)" product due to the different allocation percentages applied to them. The input "Straw biomass" has the largest contribution for both biochar and pyrogas produced from straw feedstock.

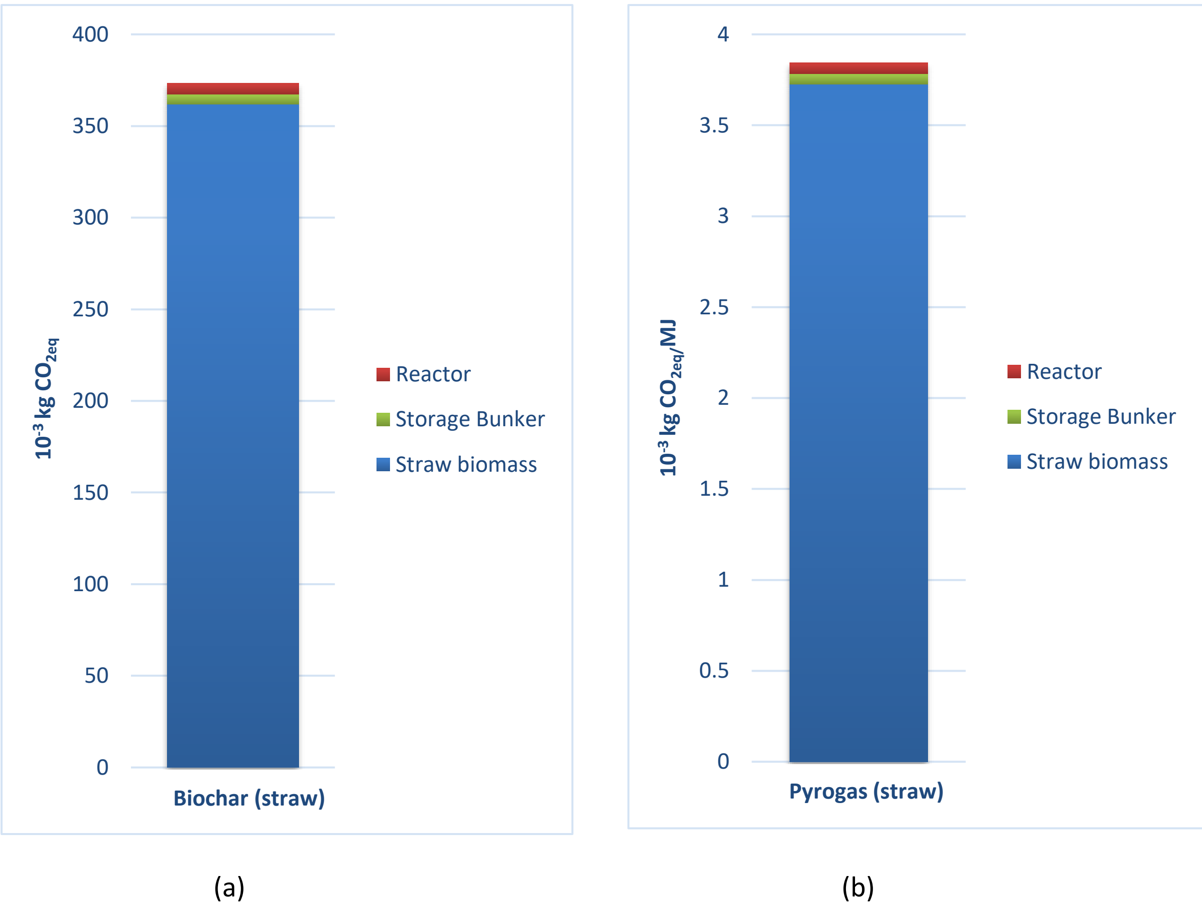
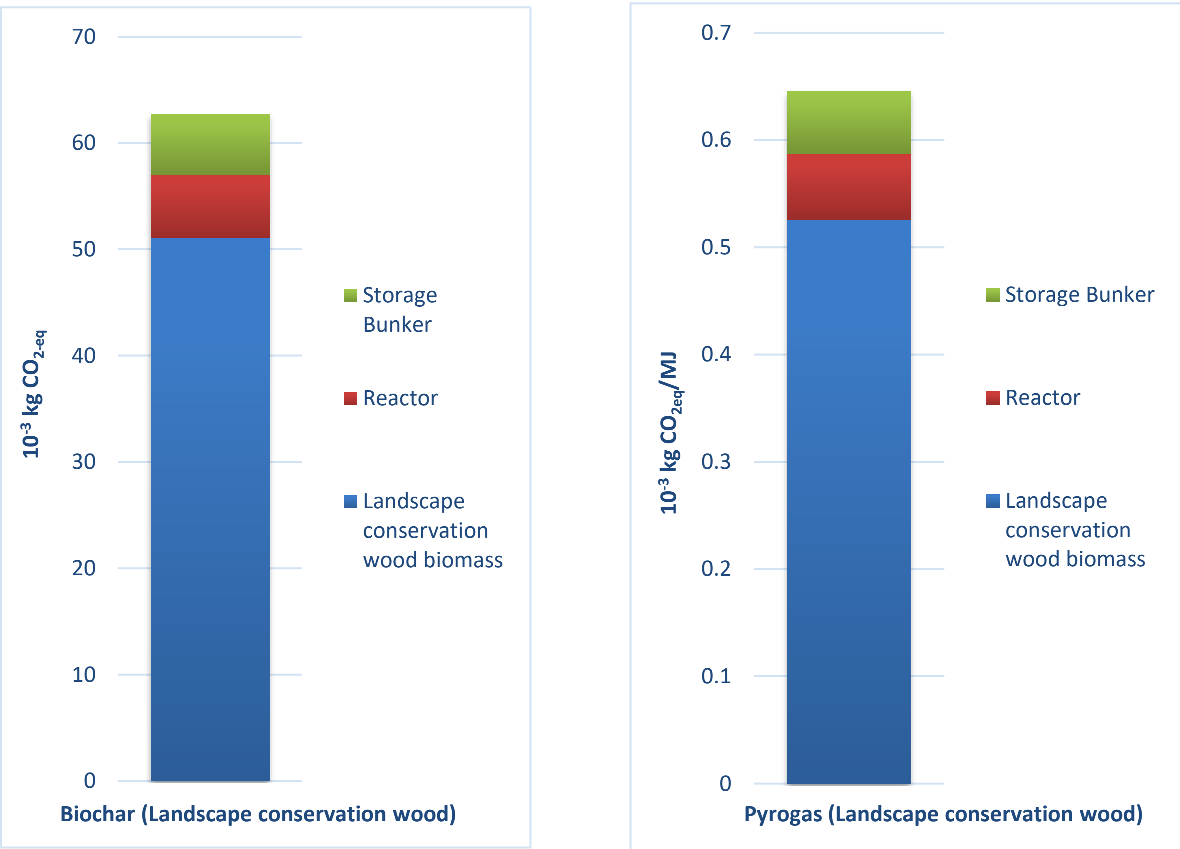



*Figure A10 (a): GWP of "Biochar (straw)" in the production of biochar (at the farm gate) from "straw" feedstock; (b): GWP of "Pyrogas (straw)" in the production of biochar (at the farm gate) from "straw" feedstock.*

*Landscape conservation wood as feedstock for biochar production*

Figure A11 displays the LCI data when landscape conservation wood is used as feedstock in the biochar production. The "Pyrolysis system operation" inventory has two products: the "Biochar" and the "Pyrogas", both with the inputs as "landscape conservation wood biomass", "Reactor", and "Storage bunker". Here, for the "Biochar (landscape conservation wood)" product, the inputs contribute almost equally, at 59 $10^{-3}$ kg $CO_2$-eq, 6 $10^{-3}$ kg $CO_2$-eq, and 6 $10^{-3}$ kg $CO_2$-eq, for 1 kg biochar, respectively. For the "Pyrogas" product, the inputs contribute to the GWP with 0.6 $10^{-3}$ kg $CO_2$-eq/MJ for "landscape conservation wood biomass", 61.5 $10^{-3}$ kg $CO_2$-eq/MJ for "Reactor", and 58.4 $10^{-3}$ $CO_2$-eq/MJ for "Storage Bunker". Based on these results, "Biochar (landscape conservation wood)" has a larger impact on the GWP than "Pyrogas (landscape conservation wood)", and "Straw biomass" has the largest impact on the GWP for both products.




(a) (b)

*Figure A11(a): GWP of "Biochar (landscape conservation wood)" in the production of biochar (at the farm gate) from "landscape conservation wood" feedstock; (b): GWP of "Pyrogas (landscape conservation wood)" in the production of biochar (at the farm gate) from "landscape conservation wood" feedstock.*

*Comparison of the three biochar feedstocks*

Table A21 shows the GHG contribution to the production of biochar with straw as feedstock (at the farm). Here, $CO_2$ contributes the most (52%), while $N_2O$ and $CH_4$ contribute 41% and 7%, respectively. The LCI "Biochar (straw)" has higher GHG emissions ($CO_2$, $N_2O$, $CH_4$) than biochar produced from wood biomass (wood chips or landscape conservation wood).

Table A21: Contributions of $CO_2$, $CH_4$, and $N_2O$ to the GWP of biochar (straw) at farm (units: $10^{-3}$ $CO_{2\_eq}$).

| GHG | Amount | Unit | Share [%] |
|---|---|---|---|
| **$CH_4$** | 17.2 | $10^{-3}$ kg $CO_{2-eq}$ | 7 |
| **$N_2O$** | 104.7 | $10^{-3}$ kg $CO_{2-eq}$ | 41 |
| **$CO_2$** | 134.0 | $10^{-3}$ kg $CO_{2-eq}$ | 52 |

Table A22 shows the contributions of $CO_2$, $CH_4$, and $N_2O$ that contribute to the GWP of biochar landscape conservation wood at farm produced with landscape conservation wood. This table shows that $CO_2$ has the largest contribution (89%), while $N_2O$ and $CH_4$ are contributing with 1% and 10%, respectively. The inventory “Biochar (landscape conservation wood)” is the main contributor to the GHG emissions emitted from the “Biochar at farm (straw),” since it has the highest $CO_2$, $N_2O$, and $CH_4$ emissions.

Table A22: Contribution of $CH_4$ to biochar at farm (units: $10^{-3}$ $CO_{2-eq}$).

| GHG | Amount | Unit | Share [%] |
|---|---|---|---|
| **$CH_4$** | 7.7 | $10^{-3}$ kg $CO_{2-eq}$ | 10 |
| **$N_2O$** | 0.4 | $10^{-3}$ kg $CO_{2-eq}$ | 1 |
| **$CO_2$** | 65.6 | $10^{-3}$ kg $CO_{2-eq}$ | 89 |

## A11: Ecological Scarcity Method for Biochar at farm

Table A23: LCI data of the endpoint category “Ecological Scarcity” for the LCI “Biochar at farm” with “wood chips” feedstock.

| Impact category | Biochar at farm | Biochar | Tap water | Transport | Total | Unit |
|---|---|---|---|---|---|---|
| Water resources, net balance | 0 | 1.1 | $4.3\ 10^{-3}$ | $3.4\ 10^{-2}$ | 1.1 | UBP |
| Energy resources | 0 | 109 | $3.6\ 10^{-3}$ | $3.5\ 10^{-1}$ | 109.4 | UBP |
| Mineral resources | 0 | 6.9 | $4.1\ 10^{-4}$ | $6.0\ 10^{-2}$ | 7 | UBP |
| Land use | 0 | 38.3 | $2.5\ 10^{-4}$ | $5.8\ 10^{-2}$ | 38.3 | UBP |
| Global warming | 0 | 130.6 | $1.3\ 10^{-2}$ | 2.9 | 133.5 | UBP |
| Ozone layer depletion | 0 | 0.1 | $6.6\ 10^{-6}$ | $1.0\ 10^{-3}$ | 0.1 | UBP |
| Main air pollutants and particulates | 0 | 38.2 | $4.4\ 10^{-3}$ | $5.6\ 10^{-1}$ | 38.7 | UBP |
| Carcinogenic substances into air | 0 | 3.5 | $1.3\ 10^{-3}$ | $4.9\ 10^{-2}$ | 3.5 | UBP |
| Heavy metals into air | 0 | 6.2 | $4.6\ 10^{-3}$ | $1.7\ 10^{-1}$ | 6.4 | UBP |
| Water pollutants | 0 | 51.2 | $5.6\ 10^{-4}$ | $8.7\ 10^{-2}$ | 51.3 | UBP |
| Persistent organic pollutants into water | 0 | 0.4 | $1.9\ 10^{-4}$ | $9.7\ 10^{-3}$ | 0.4 | UBP |
| Heavy metals into water | 0 | 1.2 | $3.7\ 10^{-4}$ | $7.8\ 10^{-3}$ | 1.2 | UBP |
| Pesticides into soil | 0 | 9.6 | $1.1\ 10^{-4}$ | $1.2\ 10^{-2}$ | 9.6 | UBP |
| Heavy metals into soil | 0 | 1 | $2.6\ 10^{-5}$ | $2.9\ 10^{-2}$ | 1 | UBP |
| Radioactive substances into air | 0 | $1.7\ 10^{-5}$ | $5.7\ 10^{-8}$ | $2.9\ 10^{-7}$ | $1.7\ 10^{-5}$ | UBP |
| Radioactive substances into water | 0 | $4.1\ 10^{-2}$ | $1.1\ 10^{-4}$ | $7.9\ 10^{-4}$ | $4.2\ 10^{-2}$ | UBP |
| Noise | 0 | 0 | 0 | 0 | 0 | UBP |
| Waste, non-radioactive | 0 | 2.8 | 0 | 0.1 | 2.8 | UBP |

| | | | | | | |
|---|---|---|---|---|---|---|
| Radioactive waste to deposit | 0 | 2 | 5.5 $10^{-3}$ | 3.9 $10^{-2}$ | 2 | UBP |
| Biotic resources | 0 | 4.4 $10^{-16}$ | 5.6 $10^{-18}$ | 8.6 $10^{-18}$ | 4.5 $10^{-16}$ | UBP |

Table A24: LCI data of the endpoint category “Ecological Scarcity” for LCI “Biochar at farm” with “straw” feedstock.

| Impact category | Biochar at farm (straw) | Biochar (straw) | Tap water | Transport | Total | Unit |
|---|---|---|---|---|---|---|
| Water resources, net balance | 0 | 1.4 | 4.25 $10^{-3}$ | 3.4 $10^{-2}$ | 1.4 | UBP |
| Energy resources | 0 | 161.6 | 3.6 $10^{-3}$ | 3.5 $10^{-1}$ | 161.9 | UBP |
| Mineral resources | 0 | 3.03 | 4.1 $10^{-4}$ | 6.0 $10^{-2}$ | 3.1 | UBP |
| Land use | 0 | 7621.3 | 2.4 $10^{-4}$ | 5.8 $10^{-2}$ | 7621.4 | UBP |
| Global warming | 0 | 311.8 | 1.3 $10^{-2}$ | 2.9 | 314.7 | UBP |
| Ozone layer depletion | 0 | 6.3 $10^{-2}$ | 6.6 $10^{-6}$ | 1.0 $10^{-3}$ | 6.4 $10^{-2}$ | UBP |
| Main air pollutants and particulates | 0 | 87.1 | 4.4 $10^{-3}$ | 5.6 $10^{-1}$ | 87.7 | UBP |
| Carcinogenic substances into air | 0 | 9.7 | 1.3 $10^{-3}$ | 4.9 $10^{-2}$ | 9.7 | UBP |
| Heavy metals into air | 0 | 9 | 4.6 $10^{-3}$ | 1.7 $10^{-1}$ | 9.2 | UBP |
| Water pollutants | 0 | 169.8 | 5.6 $10^{-4}$ | 8.7 $10^{-2}$ | 169.8 | UBP |
| Persistent organic pollutants into water | 0 | 0.5 | 1.9 $10^{-4}$ | 9.7 $10^{-3}$ | 0.5 | UBP |
| Heavy metals into water | 0 | 1.1 | 3.7 $10^{-4}$ | 7.8 $10^{-3}$ | 1.2 | UBP |
| Pesticides into soil | 0 | 0.9 | 1.1 $10^{-4}$ | 1.2 $10^{-2}$ | 0.9 | UBP |
| Heavy metals into soil | 0 | -388.4 | 2.6 $10^{-5}$ | 2.93 $10^{-2}$ | -388.4 | UBP |
| Radioactive substances into air | 0 | 2.1 $10^{-5}$ | 5.7 $10^{-8}$ | 2.9 $10^{-7}$ | 2.1 $10^{-5}$ | UBP |
| Radioactive substances into water | 0 | 5.7 $10^{-2}$ | 1.1 $10^{-4}$ | 7.9 $10^{-4}$ | 5.8 $10^{-2}$ | UBP |
| Noise | 0 | 0 | 0 | 0 | 0 | UBP |
| Waste, non-radioactive | 0 | 4.2 | 5.5 $10^{-4}$ | 5.7 $10^{-2}$ | 4.3 | UBP |
| Radioactive waste to deposit | 0 | 2.8 | 5.5 $10^{-3}$ | 3.9 $10^{-2}$ | 2.8 | UBP |

| | | | | | | |
|---|---|---|---|---|---|---|
| Biotic resources | 0 | 1.1 | $5.6\ 10^{-18}$ | $8.6\ 10^{-18}$ | $1.2\ 10^{-16}$ | UBP |

Table A25: LCI data of the endpoint category “Ecological Scarcity” for the LCI “Biochar at farm” with “Landscape conservation wood” feedstock.

| Impact category | Biochar at farm (landscape conservation wood) | Biochar (landscape conservation wood) | Tap water | Transport | Total | Unit |
|---|---|---|---|---|---|---|
| Water resources, net balance | 0 | 0.6 | $4.3\ 10^{-3}$ | $3.4\ 10^{-2}$ | $6.6\ 10^{-1}$ | UBP |
| Energy resources | 0 | 6.3 | $3.6\ 10^{-3}$ | $3.5\ 10^{-1}$ | $6.6\ 10^{-1}$ | UBP |
| Mineral resources | 0 | 1.7 | $4.1\ 10^{-4}$ | $6.0\ 10^{-2}$ | 1.8 | UBP |
| Land use | 0 | 1.0 | $2.4\ 10^{-4}$ | $5.9\ 10^{-2}$ | 1.1 | UBP |
| Global warming | 0 | 52.5 | $1.2\ 10^{-2}$ | 2.9 | 55. 4 | UBP |
| Ozone layer depletion | 0 | $1.7\ 10^{-2}$ | $6.6\ 10^{-6}$ | $1.0\ 10^{-3}$ | $1.9\ 10^{-2}$ | UBP |
| Main air pollutants and particulates | 0 | 13.0 | $4.4\ 10^{-3}$ | $5.6\ 10^{-1}$ | 13.6 | UBP |
| Carcinogenic substances into air | 0 | 1.9 | $1.3\ 10^{-3}$ | $4.9\ 10^{-2}$ | 1.9 | UBP |
| Heavy metals into air | 0 | 3.4 | $4.6\ 10^{-3}$ | $1.7\ 10^{-1}$ | 3.5 | UBP |
| Water pollutants | 0 | 1.7 | $5.6\ 10^{-4}$ | $8.7\ 10^{-2}$ | 1.8 | UBP |
| Persistent organic pollutants into water | 0 | 0.2 | $1.9\ 10^{-4}$ | $9.7\ 10^{-3}$ | $1.7\ 10^{-1}$ | UBP |
| Heavy metals into water | 0 | 0.4 | $3.7\ 10^{-4}$ | $7.8\ 10^{-3}$ | $4.5\ 10^{-1}$ | UBP |
| Pesticides into soil | 0 | 0.3 | $1.1\ 10^{-4}$ | $1.2\ 10^{-2}$ | $2.7\ 10^{-1}$ | UBP |
| Heavy metals into soil | 0 | 0.5 | $2.5\ 10^{-5}$ | $2.9\ 10^{-2}$ | $4.9\ 10^{-1}$ | UBP |
| Radioactive substances into air | 0 | $5.8\ 10^{-6}$ | $5.7\ 10^{-8}$ | $2.8\ 10^{-7}$ | $6.2\ 10^{-6}$ | UBP |
| Radioactive substances into water | 0 | $1.6\ 10^{-2}$ | $1.1\ 10^{-4}$ | $7.9\ 10^{-4}$ | $1.7\ 10^{-2}$ | UBP |
| Noise | 0 | 0 | 0 | 0 | 0 | UBP |
| Waste, non-radioactive | 0 | 1.1 | $5.5\ 10^{-4}$ | $5.7\ 10^{-2}$ | 1.2 | UBP |
| Radioactive waste to deposit | 0 | 0.8 | $5.5\ 10^{-3}$ | $3.9\ 10^{-2}$ | $8.5\ 10^{-1}$ | UBP |
| Biotic resources | 0 | $1.5\ 10^{-16}$ | $5.6\ 10^{-18}$ | $8.6\ 10^{-18}$ | $1.6\ 10^{-16}$ | UBP |

# B. Development of the model farms

## B1: Land Categories Attributed to the Same Inventory

The land categories are summed up and presented as a list in Table B1 as well as in the SALCA inventory to which they are attributed.

Table B1: List of land categories merged based on a common SALCA inventory attribution.

| Merged land categories | SALCA inventory |
|---|---|
| • Potatoes<br>• Seed potatoes | potatoes, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| • Grain corn<br>• Seed corn<br>• Millet for grain<br>• Sorghum for grain | grain maize, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| • Silage and green corn<br>• Millet for whole plant use<br>• Sorghum for whole plant use | silage maize, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| • Sugar beets<br>• Fodder beets | sugar beets, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| • Fodder wheat according to Swiss granum variety list<br>• Cereals ensiled | fodder wheat, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| • Temporary leys (excluding pastures)<br>• Other temporary leys, eligible for subsidies | temp. ley, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| • Other grassland (permanent grassland), eligible for subsidies<br>• Other grassland (permanent grassland), not eligible for subsidies | perm. meadow intensive, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |

## B2: Attribution of Livestock Categories to SALCA Inventories

The 51 livestock categories from the farm census FSO data had to be assigned to the 15 available SALCA inventories. The attribution can be found in Table B2. Note that three livestock categories could not be attributed to a SALCA inventory. These categories were > 0.1% total GVE only for vegetable farms (2.39% for Junghennen, Junghähne und Küken (ohne Mastpoulets), 0.37% for Andere Raufutter verzehrende Nutztiere, and 0.24% for Trutenausmast).

Table B2: List of livestock categories and their attribution to the 15 livestock SALCA inventories.

| Livestock group | Revised livestock category | SALCA inventory name | FSO farm census livestock categories |
|---|---|---|---|
| Horses | Horses | Horse husbandry | • Females and castrated males over 900 days old, withers height up to 148 cm<br>• Females and castrated males over 900 days old, withers height from 148 cm<br>• Stallions over 900 days old, withers height up to 148 cm<br>• Stallions over 900 days old, withers height from 148 cm<br>• Colts over 180 days and up to 900 days old, withers height up to 148 cm<br>• Colts over 180 days and up to 900 days old, withers height from 148 cm<br>• Foals up to 180 days old, withers height up to 148 cm<br>• Foals up to 180 days old, withers height from 148 cm |
| Cattle and buffaloes | Dairy cows | Dairy cow husbandry | • Dairy cows |
| Cattle and buffaloes | Suckler cows | Suckler cow husbandry | • Other cows |
| Cattle and buffaloes | Cattle | Cattle raising husbandry | • Animals over 730 days old, female<br>• Animals 365–730 days old, female<br>• 0.5* Animals 160–365 days old, female<br>• 0.5* Animals up to 160 days old, female |
| Cattle and buffaloes | Calves | Calf husbandry | • 0.5* Animals up to 160 days old, female<br>• Animals up to 160 days old, male |
| Cattle and buffaloes | Beef cattle | Beef cattle husbandry | • Animals over 730 days old, male<br>• Animals 365–730 days old, male<br>• Animals 160–365 days old, female<br>• Animals 160–365 days old, male |
| Sheep | Sheep (for meat production) | Sheep (for meat) | • Other female sheep over 1 year old<br>• Ram (male sheep) over 1 year old<br>• Pasture lambs (fattening lambs under 0.5 years old) that are not counted with the mother animals |
| Sheep | Milked sheep | Sheep (milked) | • Sheep milked |
| Goats | Goats (for meat production) | Goats (for meat) | • Other female goats over 1 year old<br>• Billy goats (male goats) over 1 year old<br>• Dwarf goats over 1 year old, kept as livestock (larger numbers for commercial purposes)<br>• Dwarf goats under 1 year old, kept as livestock (larger numbers for commercial purposes) |
| Goats | Milked goats | Goats (milked) | • Goats milked |
| Poultry | Broilers | Broiler husbandry | • Broiler chickens of all ages<br>• Breeding hens and cocks (hatching egg production for broiler lines) |
| Poultry | Laying hens | Laying hen husbandry | • Laying hens<br>• Breeding hens and cocks (hatching egg production for laying lines) |
| Poultry | Young hens, | --- | • Young hens, young cocks and chicks (excluding broiler chickens) |

| | | | |
|---|---|---|---|
| | cocks, and chicks | | |
| Poultry | Turkeys | --- | • Turkeys of all ages (approx. 3 cycles per place)<br>• Turkey pre-fattening (approx. 6 cycles per year)<br>• Turkey fattening |
| Pigs | Breeding pigs | Breeding pig husbandry | • Lactating breeding sows<br>• Non-lactating breeding sows over 6 months old (approx. 3 cycles per place)<br>• Breeding boar |
| Pigs | Fattening pigs | Fattening pig husbandry | • Weaned piglets<br>• Remonts and fattening pigs (approx. 3 cycles per place) |
| Other roughage-consuming livestock | Other roughage-consuming livestock | --- | • Bison over 900 days old<br>• Bison under 900 days old<br>• Fallow deer of all ages<br>• Red deer of all ages<br>• Lamas over 2 years old<br>• Lamas under 2 years old<br>• Alpacas over 2 years old<br>• Alpacas under 2 years old |

### B3: Dairy Farm – Model Farm Description

Table B3: List of all land categories of the dairy model farm and their respective land areas in hectares.

| Land category | Area (ha) |
|---|---:|
| Other permanent meadows (excluding pastures) | 9.13 |
| Temporary leys | 8.39 |
| Silage maize (millet, sorghum) | 4.33 |
| Winter wheat (excluding feed wheat according to the Swiss granum variety list) | 3.60 |
| Extensively used meadows (excluding pastures) | 2.98 |
| Pastures (permanent pastures, other pastures excluding summer pastures) | 2.58 |
| Winter barley | 1.31 |
| Winter oilseed rape | 1.17 |
| Sugar beet | 0.92 |
| Extensively used pastures | 0.80 |
| Potatoes | 0.57 |
| Fodder wheat according to Swiss granum variety list | 0.52 |
| Grain maize (millet, sorghum) | 0.51 |
| Spelt | 0.34 |
| Triticale | 0.34 |
| Straw meadows within the utilised agricultural area (meadows mown for animal bedding) | 0.25 |
| Annual field vegetables (excluding canned vegetables) | 0.24 |
| Hedgerows, field and riparian trees and shrubs | 0.23 |
| Oilseed sunflowers | 0.19 |
| Low-intensity meadows (excluding pastures) | 0.16 |
| Soya | 0.10 |
| Fruit orchards (apples) | 0.09 |
| Canned field vegetables | 0.09 |
| Wildflower strips | 0.09 |

| | |
|---|---|
| Oats | 0.08 |
| Rye | 0.08 |
| Mixtures of beans, vetches, peas, chickpeas and lupins with cereals or camelina, with a legume content of at least 30% at harvest (for grain production) | 0.07 |
| Peas for grain production (e.g. protein peas) | 0.07 |
| Vineyards | 0.07 |

Table B4: List of all livestock categories of the dairy model farm and their respective livestock quantity in number of animals and livestock unit (LU).

| Revised livestock category | Livestock group | Nb Animal | LU |
|---|---|---|---|
| Dairy cows | Cattle and buffaloes | 36.03 | 36.03 |
| Cattle | Cattle and buffaloes | 21.39 | 7.84 |
| Suckler cows | Cattle and buffaloes | 6.12 | 6.12 |
| Beef cattle | Cattle and buffaloes | 15.68 | 5.52 |
| Calves | Cattle and buffaloes | 12.55 | 1.63 |
| Horses | Horses | 1.15 | 0.62 |
| Fattening pigs | Pigs | 1.65 | 0.23 |
| Sheep (for meat production) | Sheep | 1.42 | 0.22 |
| Laying hens | Poultry | 19.67 | 0.20 |
| Broilers | Poultry | 19.60 | 0.08 |
| Goats (for meat production) | Goats | 0.42 | 0.06 |
| Breeding pigs | Pigs | 0.16 | 0.06 |

## B4: Pig Farm – Model Farm Description

Table B5: List of all land categories of the pig model farm and their respective land areas in hectares.

| Land category | Area (ha) |
|---|---|
| Winter wheat (excluding feed wheat from the Swiss granum variety list) | 2.34 |
| Winter barley | 2.08 |
| Grain maize (millet, sorghum) | 1.61 |
| Other permanent meadows (excluding pastures) | 1.52 |
| Temporary leys | 1.48 |
| Winter oilseed rape | 1.47 |
| Extensively used meadows (excluding pastures) | 1.45 |
| Silage maize (millet, sorghum) | 1.25 |
| Sugar beet | 1.15 |
| Fodder wheat according to Swiss granum variety list | 1.15 |
| Potatoes | 0.67 |
| Pastures (permanent pastures, other pastures without summer pastures) | 0.40 |
| Annual field vegetables (without canned vegetables) | 0.30 |
| Oilseed sunflowers | 0.26 |
| Triticale | 0.26 |
| Spelt | 0.25 |
| Extensively used pastures | 0.16 |
| Hedgerows, field and riparian trees and shrubs | 0.12 |

| | |
|---|---|
| Peas for grain (e.g. protein peas) | 0.11 |
| Canned field vegetables | 0.08 |
| Oats | 0.08 |
| Soya | 0.07 |
| Wildflower strip | 0.07 |
| Fruit orchards (apples) | 0.07 |
| Straw meadows within the utilised agricultural area (meadows mown for animal bedding) | 0.06 |
| Rye | 0.05 |
| Spring wheat (excluding feed wheat from the Swiss granum list of varieties) | 0.05 |
| Low-intensity meadows (excluding pastures) | 0.05 |
| Beans and vetches for grain (e.g. field beans) | 0.04 |
| Christmas trees | 0.04 |
| Annual berries (e.g. strawberries) | 0.03 |
| Fruit orchards (stone fruit) | 0.03 |
| Vineyards | 0.03 |
| Spring barley | 0.02 |
| Vineyards with natural biodiversity | 0.02 |
| Chicory roots | 0.02 |
| Feed wheat according to Swiss granum variety list - added | 0.84 |
| Grain maize (millet, sorghum) - added | 1.47 |
| Other permanent meadows (without pastures) - added | 32.00 |
| Pastures (permanent pastures, other pastures without summer pastures) - added | 8.47 |
| Potatoes - added | 0.98 |
| Silage maize (millet, sorghum) - added | 4.34 |
| Spelt - added | 0.78 |
| Temporary leys - added | 11.06 |
| Winter barley - added | 2.33 |
| Winter oilseed rape - added | 2.30 |
| Winter wheat (excluding feed wheat from the Swiss granum list of varieties) - added | 6.21 |

Table B6: List of all livestock categories of the pig model farm and their respective livestock quantity in number of animals and in livestock unit (LU).

| Revised livestock category | Livestock group | Nb Animal | LU |
|---|---|---|---|
| Fattening pigs | Pigs | 503.59 | 69.62 |
| Breeding pigs | Pigs | 53.12 | 17.24 |
| Dairy cows | Cattle and buffaloes | 1.39 | 1.39 |
| Cattle | Cattle and buffaloes | 2.15 | 0.77 |
| Suckler cows | Cattle and buffaloes | 0.63 | 0.63 |
| Beef cattle | Cattle and buffaloes | 1.55 | 0.54 |
| Horses | Horses | 0.83 | 0.46 |
| Sheep (for meat production) | Sheep | 2.27 | 0.36 |
| Broilers | Poultry | 52.19 | 0.21 |
| Calves | Cattle and buffaloes | 1.54 | 0.20 |
| Laying hens | Poultry | 11.01 | 0.11 |

## B5: Vegetable Farm – Model Farm Description

Table B7: List of all land categories of the vegetable model farm and their respective land areas in hectares.

| Land category | Area (ha) |
|---|---|
| Annual field vegetables (excluding canned vegetables) | 12.15 |
| Potatoes | 2.13 |
| Extensively used meadows (excluding pastures) | 2.02 |
| Winter wheat (excluding feed wheat from the Swiss granum variety list) | 1.67 |
| Temporary leys | 1.67 |
| Other permanent meadows (excluding pastures) | 1.24 |
| Grain maize (millet, sorghum) | 0.97 |
| Canned field vegetables | 0.73 |
| Silage maize (millet, sorghum) | 0.67 |
| Sugar beet | 0.58 |
| Winter barley | 0.55 |
| Pastures (permanent pastures, other pastures excluding summer pastures) | 0.42 |
| Winter oilseed rape | 0.23 |
| Spelt | 0.22 |
| Extensively used pastures | 0.18 |
| Wildflower strips | 0.14 |
| Hedgerows, field and riparian trees and shrubs | 0.13 |
| Spring wheat (excluding feed wheat from the Swiss granum variety list) | 0.12 |
| Feed wheat according to Swiss granum variety list | 0.11 |
| Soya | 0.09 |
| Straw meadows within the utilised agricultural area (meadows mown for animal bedding) | 0.09 |
| Annual berries (e.g. strawberries) | 0.08 |
| Oilseed sunflowers | 0.08 |
| Fruit orchards (apples) | 0.07 |
| Perennial berries | 0.07 |
| Oats | 0.07 |
| Low-intensity meadows (without grazing) | 0.06 |
| Peas for grain (e.g. protein peas) | 0.06 |
| Fruit orchards (stone fruit) | 0.06 |
| Other areas within the utilized agricultural area | 0.05 |
| Vineyards | 0.05 |
| Rotational fallow | 0.05 |
| Other grassland (permanent grassland) | 0.04 |
| Triticale | 0.04 |
| Christmas trees | 0.04 |
| Vineyards with natural biodiversity | 0.04 |
| Rye | 0.03 |
| Strips of beneficial plants in open arable land | 0.03 |
| Other open arable land, not eligible for subsidies | 0.03 |

Table B8: List of all livestock categories of the dairy model farm and their respective livestock quantity in number of animals and livestock unit (LU).

| Revised livestock category | Livestock group | Nb Animal | LU |
|---|---|---|---|
| Dairy cows | Cattle and buffaloes | 1.83 | 1.83 |
| Broilers | Poultry | 381.73 | 1.53 |
| Fattening pigs | Pigs | 9.02 | 1.47 |
| Suckler cows | Cattle and buffaloes | 1.38 | 1.38 |
| Beef cattle | Cattle and buffaloes | 2.98 | 1.04 |
| Cattle | Cattle and buffaloes | 2.47 | 0.85 |
| Laying hens | Poultry | 80.29 | 0.80 |
| Horses | Horses | 0.83 | 0.46 |
| Calves | Cattle and buffaloes | 2.84 | 0.37 |
| Breeding pigs | Pigs | 1.30 | 0.35 |
| Sheep (for meat production) | Sheep | 2.20 | 0.34 |
| Young hens, cocks and chicks | Poultry | 64.24 | 0.26 |
| Other roughage-consuming livestock | Other roughage-consuming livestock | 0.36 | 0.04 |
| Turkeys | Poultry | 1.00 | 0.03 |
| Goats (for meat production) | Goats | 0.12 | 0.02 |

## B6: Attribution Lists for Land Categories and Livestock Categories

Table B9: Attribution list for land categories. List of all land categories present in the three model farms and the name of the corresponding SALCA inventory.

| Land category | SALCA inventory |
|---|---|
| Other permanent meadows (excluding pastures) | perm. meadow intensive, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Temporary leys | temp. ley, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Silage maize (Millet, Sorghum) | silage maize, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Winter wheat (excluding feed wheat according to the Swiss granum variety list) | winter wheat, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Extensively used meadows (excluding pastures) | perm. meadow extensive, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Pastures (home pastures, other pastures excluding summer pastures) | permanent pastures, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Winter barley | winter barley, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Winter oilseed rape | winter rapeseed, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Sugar beet | sugar beets, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Extensively used pastures | extensive pastures, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Potatoes | potatoes, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Grain maize (millet, sorghum) | grain maize, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Fodder wheat according to Swiss granum variety list | fodder wheat, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Spelt | spelt, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |

| | |
|---|---|
| Triticale | winter triticale, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Straw meadows within the utilized agricultural area (meadows mown for animal bedding) | reeds and bog area, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Annual field vegetables (excluding canned vegetables) | mix of annual vegetables, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Hedgerows, field and riparian trees and shrubs | hedgerows, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Oilseed sunflowers | sunflowers, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Low-intensity meadows (excluding pastures) | perm. meadow less-intensive, conventional, plain region, Q1, STPV, at farm/ha/CH SALCAv4 |
| Soya | soybeans, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Fruit orchards (apples) | apples (orchard), conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Canned field vegetables | spinach, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Wildflower strips | perennial wildflower strip, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Oats | spring oat, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Rye | winter rye, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Mixtures of beans, vetches, peas, chickpeas and lupins with cereals or camelina, with a legume content of at least 30% at harvest (for grain production) | mixtures of legumes with cereals for feeding, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Peas for grain (e.g. protein peas) | protein peas as feed, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Vineyards | vineyard, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Spring wheat (excluding feed wheat from the Swiss granum variety list) | spring wheat, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Beans and vetches for grain (e.g. field beans) | field beans as feed, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Christmas trees | --- |
| Annual berries (e.g. strawberries) | annual berries, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Fruit orchards (stone fruit) | stone fruits (orchard), conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Spring barley | spring wheat, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Vineyards with natural biodiversity | vineyard, conventional, plain region, BPA, STPV, at farm/ha/CH SALCAv4 |
| Chicory roots | mix of annual vegetables, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Perennial berries | perennial berries, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Other areas within utilised agricultural area | --- |
| Rotational fallow | perennial wildflower strip, conventional, plain region, rot. fallow, STPV, at farm/ha/CH SALCAv4 |
| Other grassland (permanent grassland) | perm. meadow intensive, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Strips of beneficial plants in open arable land | annual wildflower strip, conventional, plain region, default, STPV, at farm/ha/CH SALCAv4 |
| Other open arable land, not eligible for subsidies | --- |

Table B10: Attribution list for livestock categories. List of all livestock categories present in the three model farms and the name of the corresponding SALCA inventory.

| Livestock group | Revised livestock category | SALCA inventory |
|---|---|---|
| Cattle and buffaloes | Dairy cows | dairy cow husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Cattle and buffaloes | Cattle | cattle raising husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Cattle and buffaloes | Suckler cows | suckler cow husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Cattle and buffaloes | Calves | calf husbandry (for meat), conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Cattle and buffaloes | Beef cattle | beef cattle husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Horses | Horses | horse husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Pigs | Fattening pigs | fattening pig husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Sheep | Sheep (for meat production) | sheep (for meat), conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Poultry | Laying hens | laying hen husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Poultry | Broilers | broiler husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Poultry | Turkeys | --- |
| Poultry | Young hens, cocks and chicks | --- |
| Goats | Goats (for meat production) | goats (for meat), conventional, mountain region, STPV, at farm/p/CH SALCAv4 |
| Pigs | Breeding pigs | breeding pig husbandry, conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Goats | Milking goats | goats (milked), conventional, mountain region, STPV, at farm/p/CH SALCAv4 |
| Sheep | Milking sheep | sheep (milked), conventional, plain region, STPV, at farm/p/CH SALCAv4 |
| Other roughage-consuming livestock | Other roughage-consuming livestock | --- |

# C. Emissions and Environmental Impacts of Biochar Cascade Use

## C1: Dairy Farms – GWP Results

Table C1: Impact data for the midpoint category "IPCC 2021 - GWP100 (fossil & LULUC)" for dairy farms. Units: kg $CO_2$-eq.

| Impact category | Baseline | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Buildings & equipment | 23566.0 | 23566.0 | 23566.0 | 23618.1 | 23566.0 | 23566.0 | 23618.1 | 23618.1 | 23566.0 |
| Machinery | 29977.5 | 29977.5 | 29977.5 | 29977.5 | 29977.5 | 29977.5 | 29977.5 | 29977.5 | 29977.5 |
| Energy carriers & direct emissions caused by energy carrier use | 11745.4 | 11745.4 | 11745.4 | 11745.4 | 11745.4 | 11745.4 | 11745.4 | 11745.4 | 11745.4 |
| Field work processes (machinery, fuels & direct emissions caused by fuel use) | 29248.4 | 29248.4 | 29248.4 | 29248.4 | 29248.4 | 29248.4 | 29248.4 | 29248.4 | 29248.4 |
| Land use and land use change | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Direct field emissions of C & N | 37746.0 | 37498.0 | 36468.6 | 38149.8 | 37734.2 | 37722.6 | 37886.3 | 36835.3 | 37486.1 |
| Fertilisers, mineral (purchased) | 32497.5 | 32497.5 | 32497.5 | 32497.5 | 32497.5 | 32497.5 | 32497.5 | 32497.5 | 32497.5 |
| Pesticides & direct emissions caused by pesticides use | 299.8 | 299.8 | 299.8 | 299.8 | 299.8 | 299.8 | 299.8 | 299.8 | 299.8 |
| Seeds (purchased) | 1915.9 | 1915.9 | 1915.9 | 1915.9 | 1915.9 | 1915.9 | 1915.9 | 1915.9 | 1915.9 |
| Irrigation | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| Direct animal emissions | 297125.7 | 297108.2 | 297030.0 | 296933.7 | 297125.7 | 297125.7 | 296916.4 | 296838.8 | 297108.2 |
| Animals (purchased) | 6334.1 | 6334.1 | 6334.1 | 6334.1 | 6334.1 | 6334.1 | 6334.1 | 6334.1 | 6334.1 |
| Feedstuff, roughage (purchased) | 18919.8 | 18919.8 | 18919.8 | 18919.8 | 18919.8 | 18919.8 | 18919.8 | 18919.8 | 18919.8 |
| Feedstuff, high moisture content (purchased) | 237.7 | 237.7 | 237.7 | 237.7 | 237.7 | 237.7 | 237.7 | 237.7 | 237.7 |
| Feedstuff, concentrate feeds (purchased) | 39574.6 | 39574.6 | 39574.6 | 39574.6 | 39574.6 | 39574.6 | 39574.6 | 39574.6 | 39574.6 |
| Feedstuff, others (purchased) | 268.3 | 268.3 | 268.3 | 268.3 | 268.3 | 268.3 | 268.3 | 268.3 | 268.3 |
| Other inputs | 236.6 | 637.2 | 2501.2 | 248.2 | 256.0 | 333.4 | 668.2 | 2609.7 | 656.6 |
| Total | 529702.7 | 529837.7 | 530594.1 | 529978.0 | 529710.2 | 529776.0 | 530117.2 | 530930.1 | 529845.2 |

Table C2: Difference in GWP between the scenarios and the baseline for dairy farms. Units: kg CO2-eq.

| IPCC 2021 – GWP100 | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| Direct field emissions of C & N | -248.0 | -1277.5 | 403.7 | -11.9 | -23.4 | 140.2 | -910.7 | -259.9 |
| Direct animal emissions | -17.5 | -95.7 | -192.1 | 0.0 | 0.0 | -209.4 | -286.9 | -17.5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Total difference in GWP with the baseline | -265.5 | -1373.2 | 211.7 | -11.9 | -23.4 | -69.1 | -1197.6 | -277.4 |

Table C3: Biochar amount used, emissions from biochar production and carbon sequestration per scenario for dairy farms.

| Biochar | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Amount of biochar used | kg | 4926.8 | 27851.8 | 143.0 | 238.3 | 1190.4 | 5308.1 | 29185.2 | 5165.1 |
| GWP for biochar production | | | | | | | | | |
| Biochar from wood chips | kg $CO_2$-eq | 773.2 | 4370.9 | 22.4 | 37.4 | 186.8 | 833.0 | 4580.2 | 810.6 |
| Biochar from landscape conservation wood | kg $CO_2$-eq | 364.0 | 2057.7 | 10.6 | 17.6 | 87.9 | 392.2 | 2156.3 | 381.6 |
| Biochar from straw | kg $CO_2$-eq | 1262.7 | 7138.2 | 36.6 | 61.1 | 305.1 | 1360.4 | 7479.9 | 1323.8 |
| Carbon sequestration | kg $CO_2$-eq | -12366.3 | -69908.0 | -358.9 | -598.1 | -2987.9 | -13323.3 | -73254.9 | -12964.3 |

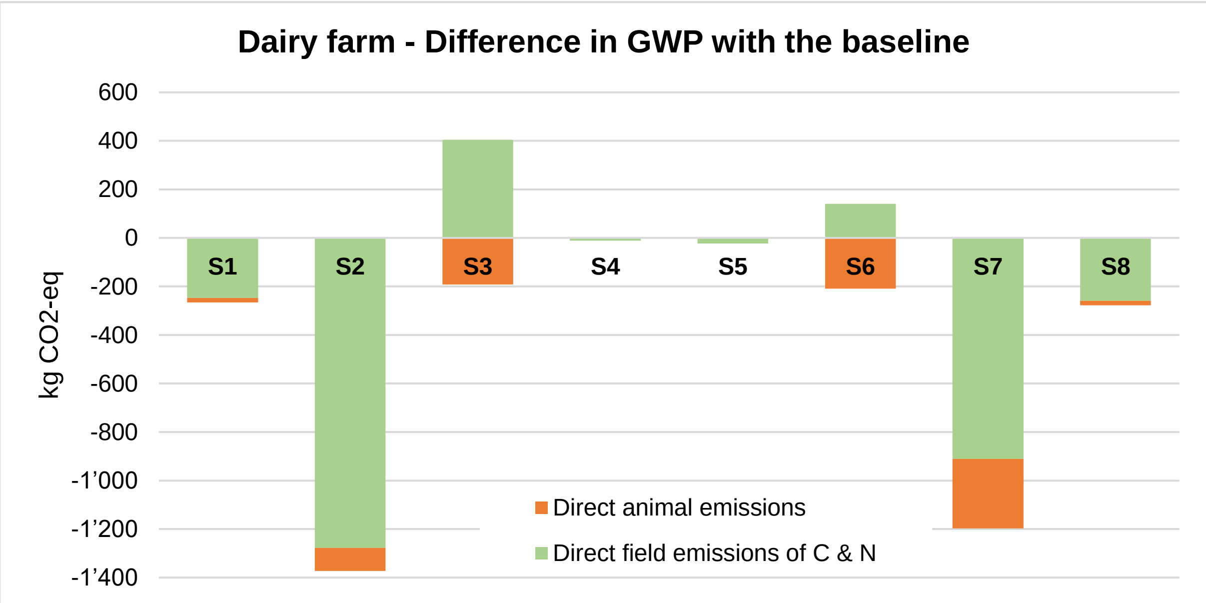



*Figure C1: Difference in GWP between each scenario and the baseline, per contribution group, for dairy farms.*

## C2: Pig Farms – GWP Results

Table C4: Impact data for the midpoint category “IPCC 2021 - GWP100 (fossil & LULUC)” for pig farms. Units: kg $CO_2$-eq.

| Impact category | Baseline | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Buildings & equipment | 14353.2 | 14353.2 | 14353.2 | 14425.6 | 14353.2 | 14353.2 | 14425.6 | 14425.6 | 14353.2 |
| Machinery | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 |
| Energy carriers & direct emissions caused by energy carrier use | 29571.0 | 29571.0 | 29571.0 | 29571.0 | 29571.0 | 29571.0 | 29571.0 | 29571.0 | 29571.0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Field work processes (machinery, fuels & direct emissions caused by fuel use) | 53894.3 | 53894.3 | 53894.3 | 53894.3 | 53894.3 | 53894.3 | 53894.3 | 53894.3 | 53894.3 |
| Land use and land use change | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Direct field emissions of C & N | 71575.2 | 71444.0 | 71365.7 | 72328.4 | 71561.2 | 71546.8 | 72180.0 | 72085.5 | 71430.0 |
| Fertilisers, mineral (purchased) | 102245.4 | 102245.4 | 102245.4 | 102245.4 | 102245.4 | 102245.4 | 102245.4 | 102245.4 | 102245.4 |
| Pesticides & direct emissions caused by pesticides use | 647.0 | 647.0 | 647.0 | 647.0 | 647.0 | 647.0 | 647.0 | 647.0 | 647.0 |
| Seeds (purchased) | 4104.4 | 4104.4 | 4104.4 | 4104.4 | 4104.4 | 4104.4 | 4104.4 | 4104.4 | 4104.4 |
| Irrigation | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 |
| Direct animal emissions | 138621.4 | 138599.5 | 138590.6 | 138281.0 | 138621.4 | 138621.4 | 138259.3 | 138250.4 | 138599.5 |
| Animals (purchased) | 38059.3 | 38059.3 | 38059.3 | 38059.3 | 38059.3 | 38059.3 | 38059.3 | 38059.3 | 38059.3 |
| Feedstuff, roughage (purchased) | 2133.1 | 2133.1 | 2133.1 | 2133.1 | 2133.1 | 2133.1 | 2133.1 | 2133.1 | 2133.1 |
| Feedstuff, high moisture content (purchased) | 54947.9 | 54947.9 | 54947.9 | 54947.9 | 54947.9 | 54947.9 | 54947.9 | 54947.9 | 54947.9 |
| Feedstuff, concentrate feeds (purchased) | 165030.5 | 165030.5 | 165030.5 | 165030.5 | 165030.5 | 165030.5 | 165030.5 | 165030.5 | 165030.5 |
| Feedstuff, others (purchased) | 47259.1 | 47259.1 | 47259.1 | 47259.1 | 47259.1 | 47259.1 | 47259.1 | 47259.1 | 47259.1 |
| Other inputs | 234.4 | 1066.7 | 1610.0 | 265.6 | 281.0 | 467.3 | 1144.6 | 1874.1 | 1113.3 |
| Total | 753114.7 | 753793.9 | 754249.9 | 753631.2 | 753147.3 | 753206.9 | 754340.0 | 754176.0 | 753403.0 |

Table C5: Difference in GWP between the scenarios and the baseline for pig farms.

| IPCC 2021 – GWP100 | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Direct field emissions of C & N | kg $CO_2$-eq | -131.2 | -209.6 | 753.2 | -14.0 | -28.4 | 604.8 | 510.3 | -145.2 |
| Direct animal emissions | kg $CO_2$-eq | -22.0 | -30.9 | -340.4 | 0.0 | 0.0 | -362.2 | -371.1 | -22.0 |
| Total difference in GWP with the baseline | kg $CO_2$-eq | -153.1 | -240.4 | 412.8 | -14.0 | -28.4 | 242.7 | 139.3 | -167.2 |

Table C6: Biochar amount used, emissions from biochar production and carbon sequestration per scenario for pig farms.

| Biochar | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Amount of biochar used | kg | 5303.6 | 8765.5 | 199.1 | 297.0 | 1483.9 | 5799.8 | 10448.5 | 5600.7 |
| GWP for biochar production | | | | | | | | | |
| Biochar from wood chips | kg $CO_2$-eq | 832.3 | 1375.6 | 31.2 | 46.6 | 232.9 | 910.2 | 1639.7 | 878.9 |
| Biochar from landscape conservation wood | kg $CO_2$-eq | 391.8 | 647.6 | 14.7 | 21.9 | 109.6 | 428.5 | 772.0 | 413.8 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Biochar from straw | kg $CO_2$-eq | 1359.3 | 2246.5 | 51.0 | 76.1 | 380.3 | 1486.4 | 2677.9 | 1435.4 |
| Carbon sequestration | kg $CO_2$-eq | -13312.1 | -22001.4 | -499.8 | -745.5 | -3724.7 | -14557.5 | -26225.9 | -14057.7 |

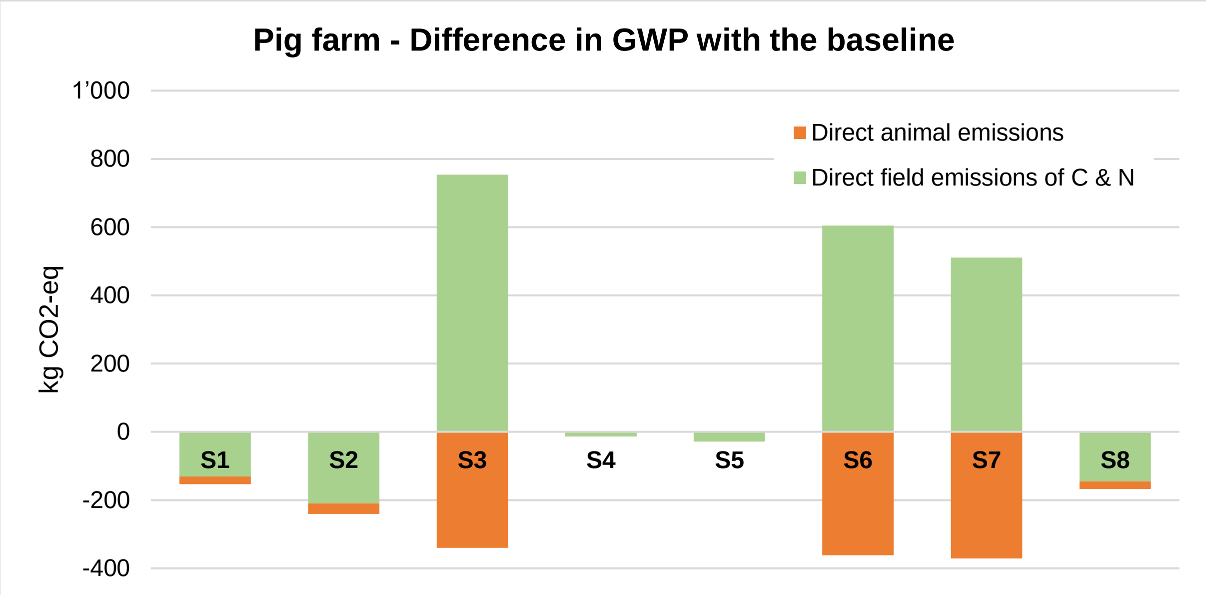



*Figure C2: Difference in GWP between each scenario and the baseline, per contribution group, for pig farms.*

## C3: Vegetable Farms – GWP Results

Table C7: Impact data for the midpoint category “IPCC 2021 - GWP100 (fossil & LULUC)” for vegetable farms. Units: kg $CO_2$-eq.

| Impact category | Baseline | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Buildings & equipment | 7037.9 | 7037.9 | 7037.9 | 7061.8 | 7037.9 | 7037.9 | 7061.8 | 7061.8 | 7037.9 |
| Machinery | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 | 30427.4 |
| Energy carriers & direct emissions caused by energy carrier use | 11327.2 | 11327.2 | 11327.2 | 11327.2 | 11327.2 | 11327.2 | 11327.2 | 11327.2 | 11327.2 |
| Field work processes (machinery, fuels & direct emissions caused by fuel use) | 28753.8 | 28753.8 | 28753.8 | 28753.8 | 28753.8 | 28753.8 | 28753.8 | 28753.8 | 28753.8 |
| Land use and land use change | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Direct field emissions of C & N | 20134.5 | 20101.2 | 19940.2 | 20187.4 | 19600.3 | 19011.0 | 19623.1 | 18871.9 | 19570.4 |
| Fertilisers, mineral (purchased) | 29974.4 | 29974.4 | 29974.4 | 29974.4 | 29974.4 | 29974.4 | 29974.4 | 29974.4 | 29974.4 |
| Pesticides & direct emissions caused by pesticides use | 708.8 | 708.8 | 708.8 | 708.8 | 708.8 | 708.8 | 708.8 | 708.8 | 708.8 |
| Seeds (purchased) | 22959.6 | 22959.6 | 22959.6 | 22959.6 | 22959.6 | 22959.6 | 22959.6 | 22959.6 | 22959.6 |
| Irrigation | 334.2 | 334.2 | 334.2 | 334.2 | 334.2 | 334.2 | 334.2 | 334.2 | 334.2 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Direct animal emissions | 32210.7 | 32208.1 | 32195.8 | 32184.5 | 32210.7 | 32210.7 | 32181.9 | 32169.7 | 32208.1 |
| Animals (purchased) | 1341.6 | 1341.6 | 1341.6 | 1341.6 | 1341.6 | 1341.6 | 1341.6 | 1341.6 | 1341.6 |
| Feedstuff, roughage (purchased) | 643.3 | 643.3 | 643.3 | 643.3 | 643.3 | 643.3 | 643.3 | 643.3 | 643.3 |
| Feedstuff, high moisture content (purchased) | 1088.8 | 1088.8 | 1088.8 | 1088.8 | 1088.8 | 1088.8 | 1088.8 | 1088.8 | 1088.8 |
| Feedstuff, concentrate feeds (purchased) | 12197.8 | 12197.8 | 12197.8 | 12197.8 | 12197.8 | 12197.8 | 12197.8 | 12197.8 | 12197.8 |
| Feedstuff, others (purchased) | 1561.4 | 1561.4 | 1561.4 | 1561.4 | 1561.4 | 1561.4 | 1561.4 | 1561.4 | 1561.4 |
| Other inputs | 33.3 | 80.8 | 329.3 | 37.1 | 735.5 | 3541.6 | 786.8 | 3841.3 | 783.0 |
| Total | 200734.6 | 200746.3 | 200821.4 | 200789.0 | 200902.6 | 203119.4 | 200971.9 | 203262.9 | 202205.0 |

Table C8: Difference in GWP between the scenarios and the baseline for vegetable farms.

| IPCC 2021 – GWP100 | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Direct field emissions of C & N | kg $CO_2$-eq | -33.3 | -194.3 | 52.9 | -534.2 | -1123.5 | -511.4 | -1262.6 | -564.1 |
| Direct animal emissions | kg $CO_2$-eq | -2.6 | -14.9 | -26.2 | 0.0 | 0.0 | -28.8 | -41.0 | -2.6 |
| Total difference in GWP with the baseline | kg $CO_2$-eq | -35.9 | -209.1 | 26.7 | -534.2 | -1123.5 | -540.2 | -1303.6 | -566.7 |

Table C9: Biochar amount used, emissions from the biochar production and carbon sequestration per scenario for vegetable farms.

| Biochar | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Amount of biochar used | kg | 822.4 | 5123.7 | 65.8 | 12157.7 | 60739.7 | 13045.8 | 65929.2 | 12980.0 |
| GWP for biochar production | | | | | | | | | |
| Biochar from wood chips | kg $CO_2$-eq | 129.1 | 804.1 | 10.3 | 1907.9 | 9532.1 | 2047.3 | 10346.5 | 2037.0 |
| Biochar from landscape conservation wood | kg $CO_2$-eq | 60.8 | 378.6 | 4.9 | 898.2 | 4487.6 | 963.8 | 4871.0 | 959.0 |
| Biochar from straw | kg $CO_2$-eq | 210.8 | 1313.2 | 16.9 | 3115.9 | 15567.1 | 3343.5 | 16897.1 | 3326.7 |
| Carbon sequestration | kg $CO_2$-eq | -2064.1 | -12860.6 | -165.1 | -30515.7 | -152456.6 | -32745.0 | -165482.3 | -32579.9 |

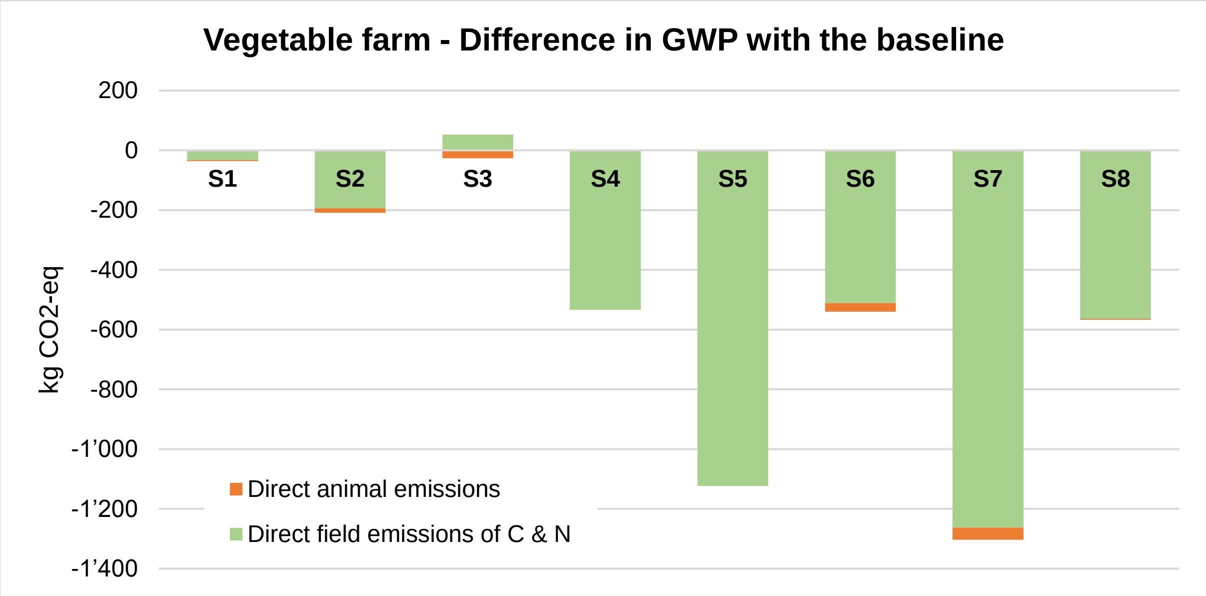



*Figure C3: Difference in GWP between each scenario and the baseline, per contribution group, for vegetable farms.*

## C4: Difference in GWP Between a Combined Scenario and the Sum of Individual Scenarios

Tables C10–C12 show the difference in GWP between a combined scenario (Scenarios 6, 7, or 8) and the sum of the individual scenarios comprising the combined scenarios.

Table C10: Dairy farms – Difference in GWP between the baseline and the indicated scenario.

| Contribution group | Unit | S1 + S3 + S4 | S6 | S2 + S3 + S5 | S7 | S1 + S4 | S8 |
|---|---|---|---|---|---|---|---|
| Direct field emissions of C & N | kg $CO_2$-eq | 143.80 | 140.25 | -897.18 | -910.73 | -259.92 | -259.92 |
| Direct animal emissions | kg $CO_2$-eq | -209.54 | -209.38 | -287.75 | -286.89 | -17.48 | -17.48 |
| Total change in GWP due to biochar | kg $CO_2$-eq | -65.74 | -69.13 | -1184.92 | -1197.63 | -277.40 | -277.40 |

Table C11: Pig farms – Difference in GWP between the baseline and the indicated scenario.

| Contribution group | Unit | S1 + S3 + S4 | S6 | S2 + S3 + S5 | S7 | S1 + S4 | S8 |
|---|---|---|---|---|---|---|---|
| Direct field emissions of C & N | kg $CO_2$-eq | 607.99 | 604.83 | 515.20 | 510.30 | -145.21 | -145.21 |
| Direct animal emissions | kg $CO_2$-eq | -362.39 | -362.17 | -371.29 | -371.05 | -21.96 | -21.96 |
| Total change in GWP due to biochar | kg $CO_2$-eq | 245.59 | 242.66 | 143.91 | 139.25 | -167.17 | -167.17 |

Table C12: Vegetable Farms – Difference in GWP between the baseline and the indicated scenario.

| Contribution group | Unit | S1 + S3 + S4 | S6 | S2 + S3 + S5 | S7 | S1 + S4 | S8 |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Direct field emissions of C & N | kg $CO_2$-eq | -514.62 | -511.42 | -1264.86 | -1262.60 | -567.49 | -564.08 |
| Direct animal emissions | kg $CO_2$-eq | -28.79 | -28.77 | -41.07 | -40.97 | -2.59 | -2.59 |
| Total change in GWP due to biochar | kg $CO_2$-eq | -543.41 | -540.19 | -1305.93 | -1303.58 | -570.08 | -566.67 |

## C5: Extrapolation to Switzerland

Table C13: Total emission reduction from the extrapolation of dairy farms (i.e. multiplication of results from tables C2 and C3 by 4,096). The total emission reduction is the sum of the three first lines in the table (biochar production, biochar cascade use, and carbon sequestration).

| Scenario | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Total GWP from biochar production | kg $CO_2$-eq | 3 166 957 | 17 903 196 | 91 921 | 153 160 | 765 192 | 3 412 039 | 18 760 308 | 3 320 118 |
| Total GWP from biochar cascade use | kg $CO_2$-eq | -1 087 589 | -5 624 484 | 866 966 | -48 631 | -95 931 | -283 149 | -4 905 485 | -1 136 220 |
| Total carbon sequestration | kg $CO_2$-eq | -50 652 234 | -286 343 242 | -1 470 178 | -2 449 644 | -12 238 455 | -54 572 056 | -300 051 875 | -53 101 878 |
| **Total emission reduction** | kg $CO_2$-eq | -48 572 866 | -274 064 530 | -511 292 | -2 345 115 | -11 569 194 | -51 443 167 | -286 197 051 | -50 917 980 |
| Emission reduction per kg biochar | kg $CO_2$-eq/kg biochar | -2.41 | -2.40 | -0.87 | -2.40 | -2.37 | -2.37 | -2.39 | -2.41 |

Table C14: Total emission reduction from the extrapolation of pig farms (i.e. multiplication of results from Tables C5 and C6 by 939). The total emission reduction is the sum of the three first rows in the table (biochar production, biochar cascade use, and carbon sequestration).

| Scenario | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|
| Total GWP from biochar production | kg $CO_2$-eq | 781 550 | 1 291 691 | 29 343 | 43 770 | 218 676 | 854 663 | 1 539 710 | 825 321 |
| Total GWP from biochar cascade use | kg $CO_2$-eq | -143 786 | -225 748 | 387 582 | -13 185 | -26 702 | 227 860 | 130 757 | -156 971 |
| Total carbon sequestration | kg $CO_2$-eq | -12 500 096 | -20 659 272 | -469 308 | -700 059 | -3 497 496 | -13 669 463 | -24 626 076 | -13 200 155 |
| **Total emission reduction** | kg $CO_2$-eq | -11 862 332 | -19 593 329 | -52 383 | -669 473 | -3 305 522 | -12 586 939 | -22 955 610 | -12 531 805 |
| Emission reduction per kg biochar | kg $CO_2$-eq/kg biochar | -2.38 | -2.38 | -0.28 | -2.40 | -2.37 | -2.31 | -2.34 | -2.38 |

Table C15: Total emission reduction from the extrapolation of vegetable farms (i.e. multiplication by 654 of results from Tables C8 and C9). The total emission reduction is the sum of the three first rows in the table (biochar production, biochar cascade use, and carbon sequestration).

| Scenario | Unit | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Total GWP from biochar production | kg $CO_2$-eq | 84 404 | 525 875 | 6 751 | 1 247 799 | 6 234 012 | 1 338 954 | 6 766 638 | 1 332 203 |
| Total GWP from biochar cascade use | kg $CO_2$-eq | -23 448 | -136 779 | 17 444 | -349 386 | -734 742 | -353 282 | -852 538 | -370 605 |
| Total carbon sequestration | kg $CO_2$-eq | -1 349 953 | -8 410 824 | -107 981 | -19 957 269 | -99 706 631 | -21 415 203 | -108 225 435 | -21 307 222 |
| **Total emission reduction** | kg $CO_2$-eq | -1 288 998 | -8 021 729 | -83 785 | -19 058 856 | -94 207 360 | -20 429 530 | -102 311 335 | -20 345 624 |
| Emission reduction per kg biochar | kg $CO_2$-eq/kg biochar | -2.40 | -2.39 | -1.95 | -2.40 | -2.37 | -2.39 | -2.37 | -2.40 |

Table C16: Total emission reduction for Switzerland based on the biochar feedstock. Unit = t $CO_2$-eq.

| **Scenario** | **S1** | **S2** | **S3** | **S4** | **S5** | **S6** | **S7** | **S8** |
|---|---|---|---|---|---|---|---|---|
| Wood chips | -61 724 | -301 680 | -647 | -22 073 | -109 082 | -84 460 | -411 464 | -83 795 |
| Landscape conservation wood | -63 858 | -312 116 | -715 | -22 838 | -112 902 | -87 426 | -425 788 | -86 694 |
| Straw | -49 149 | -240 186 | -248 | -17 568 | -86 575 | -66 980 | -327 064 | -66 715 |

## C6: Ecological Scarcity Method for the Biochar Application Scenarios

Table C17: Contributions of the endpoint category "Ecological Scarcity" to the cascade use of biochar for the modelled dairy farms. The results are shown for wood chip biochar, not accounting for biochar production. Unit = UBP.

| **Model farm** | **Dairy farm – Without biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **1** | **2** | **3** | **4** | **5** | **7** | **8** | **9** |
| **Impact category** | | | | | | | | |
| **Water resources, net balance** | 0.0 | 0.0 | 1264.1 | 0.0 | 0.0 | 1264.1 | 1264.1 | 0.0 |
| **Energy resources** | 0.0 | 0.0 | 5920.6 | 0.0 | 0.0 | 5920.6 | 5920.6 | 0.0 |
| **Mineral resources** | 0.0 | 0.0 | 628.1 | 0.0 | 0.0 | 628.1 | 628.1 | 0.0 |
| **Land use** | 0.0 | 0.0 | 257.6 | 0.0 | 0.0 | 257.6 | 257.6 | 0.0 |
| **Global warming** | -262607.2 | -1358075.7 | 261437.2 | -11742.6 | -23163.6 | -16267.0 | -1132365.9 | -274349.5 |
| **Ozone layer depletion** | 0.0 | 0.0 | 103.8 | 0.0 | 0.0 | 103.8 | 103.8 | 0.0 |
| **Main air pollutants and particulates** | -52396.0 | -289664.5 | -2056436.0 | -0.1 | -0.1 | -2107051.6 | -2336916.2 | -52396.0 |
| **Carcinogenic substances into air** | 0.0 | 0.0 | 1280.6 | 0.0 | 0.0 | 1280.6 | 1280.6 | 0.0 |
| **Heavy metals into air** | 0.0 | 0.0 | 2590.7 | 0.0 | 0.0 | 2590.7 | 2590.7 | 0.0 |
| **Water pollutants** | -5110426.7 | -26182722.0 | 2613456.5 | -262930.5 | -262930.5 | -2831207.5 | -24092994.9 | -5373357.2 |
| **Persistent organic pollutants into water** | 0.0 | 0.0 | 263.5 | 0.0 | 0.0 | 263.5 | 263.5 | 0.0 |
| **Heavy metals into water** | 0.0 | 0.0 | 340.8 | 0.0 | 0.0 | 340.8 | 340.8 | 0.0 |
| **Pesticides into soil** | 0.0 | 0.0 | 221.5 | 0.0 | 0.0 | 221.5 | 221.5 | 0.0 |
| **Heavy metals into soil** | 0.0 | 0.0 | 40.9 | 0.0 | 0.0 | 40.9 | 40.9 | 0.0 |
| **Radioactive substances into air** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Radioactive substances into water** | 0.0 | 0.0 | 32.6 | 0.0 | 0.0 | 32.6 | 32.6 | 0.0 |
| **Noise** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Waste, non-radioactive** | 0.0 | 0.0 | 2607.7 | 0.0 | 0.0 | 2607.7 | 2607.7 | 0.0 |
| **Radioactive waste to deposit** | 0.0 | 0.0 | 1590.3 | 0.0 | 0.0 | 1590.3 | 1590.3 | 0.0 |
| **Biotic resources** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table C18: Contributions of the endpoint category "Ecological Scarcity" to the cascade use of biochar for the modelled dairy farms. The results are shown for wood chip biochar, accounting for biochar production. Unit = UBP.

| **Model farm** | **Dairy farm – With biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **1** | **2** | **3** | **4** | **5** | **7** | **8** | **9** |
| **Impact category** | | | | | | | | |
| **Water resources, net balance** | 5402.4 | 30540.7 | 1420.9 | 261.3 | 1305.6 | 7084.6 | 33267.3 | 5663.7 |
| **Energy resources** | 538904.0 | 3046498.0 | 21562.3 | 26062.5 | 130234.7 | 586528.9 | 3198295.1 | 564966.5 |
| **Mineral resources** | 34305.3 | 193932.7 | 1623.8 | 1659.0 | 8290.4 | 37588.2 | 203846.9 | 35964.4 |
| **Land use** | 188941.6 | 1068112.5 | 5741.7 | 9137.6 | 45660.7 | 203820.9 | 1119514.9 | 198079.2 |
| **Global warming** | 395338.2 | 2361379.4 | 280533.9 | 20077.1 | 135839.5 | 692594.8 | 2765189.0 | 415415.6 |
| **Ozone layer depletion** | 252.3 | 1426.0 | 111.1 | 12.2 | 61.0 | 375.5 | 1598.1 | 264.5 |
| **Main air pollutants and particulates** | 138438.9 | 789151.3 | -2050897.0 | 9229.1 | 46118.2 | -1901448.6 | -1206443.2 | 147668.1 |
| **Carcinogenic substances into air** | 17362.1 | 98150.5 | 1784.6 | 839.7 | 4195.8 | 19986.4 | 104130.9 | 18201.8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Heavy metals into air** | 31522.3 | 178200.1 | 3505.6 | 1524.4 | 7617.8 | 36552.4 | 189323.7 | 33046.8 |
| **Water pollutants** | -4857598.4 | -24753449.0 | 2620794.8 | -250703.2 | -201830.5 | -2558813.5 | -22595283.6 | -5108301.6 |
| **Persistent organic pollutants into water** | 2214.3 | 12517.7 | 327.7 | 107.1 | 535.1 | 2649.1 | 13380.5 | 2321.4 |
| **Heavy metals into water** | 6145.6 | 34742.1 | 519.2 | 297.2 | 1485.2 | 6962.1 | 36746.5 | 6442.9 |
| **Pesticides into soil** | 47133.2 | 266450.6 | 1589.5 | 2279.5 | 11390.5 | 51002.2 | 279430.6 | 49412.7 |
| **Heavy metals into soil** | 4925.3 | 27843.5 | 183.8 | 238.2 | 1190.3 | 5347.3 | 29217.6 | 5163.5 |
| **Radioactive substances into air** | 0.1 | 0.5 | 0.0 | 0.0 | 0.0 | 0.1 | 0.5 | 0.1 |
| **Radioactive substances into water** | 206.3 | 1166.1 | 38.6 | 10.0 | 49.8 | 254.8 | 1254.5 | 216.2 |
| **Noise** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Waste, non-radioactive** | 13936.9 | 78787.4 | 3012.2 | 674.0 | 3368.1 | 17623.2 | 85167.8 | 14611.0 |
| **Radioactive waste to deposit** | 10069.8 | 56925.8 | 1882.6 | 487.0 | 2433.5 | 12439.4 | 61242.0 | 10556.8 |
| **Biotic resources** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table C19: Contributions of the endpoint category “Ecological Scarcity” to the cascade use of biochar for the modelled pig farms. The results are shown for wood chip biochar, not accounting for biochar production. Unit = UBP.

| **Model farm** | **Pig farm – Without biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **1** | **2** | **3** | **4** | **5** | **7** | **8** | **9** |
| **Impact category** | | | | | | | | |
| **Water resources, net balance** | 0.0 | 0.0 | 1760.2 | 0.0 | 0.0 | 1760.2 | 1760.2 | 0.0 |
| **Energy resources** | 0.1 | 0.1 | 8244.1 | 0.1 | 0.1 | 8244.1 | 8244.1 | 0.1 |
| **Mineral resources** | 0.0 | 0.0 | 874.6 | 0.0 | 0.0 | 874.6 | 874.6 | 0.0 |
| **Land use** | 0.0 | 0.0 | 358.8 | 0.0 | 0.0 | 358.8 | 358.8 | 0.0 |
| **Global warming** | -151444.1 | -237771.8 | 480773.1 | -13887.2 | -28124.6 | 312544.3 | 210269.1 | -165331.2 |
| **Ozone layer depletion** | 0.0 | 0.0 | 144.5 | 0.0 | 0.0 | 144.5 | 144.5 | 0.0 |
| **Main air pollutants and particulates** | -73372.7 | -115887.2 | -3502739.9 | -0.2 | -0.2 | -3573765.5 | -3616136.8 | -73372.7 |
| **Carcinogenic substances into air** | 0.0 | 0.0 | 1783.3 | 0.0 | 0.0 | 1783.3 | 1783.3 | 0.0 |
| **Heavy metals into air** | -0.1 | -0.1 | 3607.4 | -0.1 | -0.1 | 3607.4 | 3607.4 | -0.1 |
| **Water pollutants** | -2426351.0 | -3993464.5 | 5217929.8 | -310956.0 | -310956.0 | 2420381.6 | 816080.3 | -2737307.0 |
| **Persistent organic pollutants into water** | 0.0 | 0.0 | 366.9 | 0.0 | 0.0 | 367.0 | 366.9 | 0.0 |
| **Heavy metals into water** | 0.0 | 0.0 | 474.6 | 0.0 | 0.0 | 474.6 | 474.6 | 0.0 |
| **Pesticides into soil** | 0.1 | 0.1 | 308.4 | 0.1 | 0.1 | 308.0 | 308.4 | 0.1 |
| **Heavy metals into soil** | 0.0 | 0.0 | 56.9 | 0.0 | 0.0 | 56.9 | 56.9 | 0.0 |
| **Radioactive substances into air** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Radioactive substances into water** | 0.0 | 0.0 | 45.4 | 0.0 | 0.0 | 45.4 | 45.4 | 0.0 |
| **Noise** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Waste, non-radioactive** | 0.0 | 0.0 | 3631.1 | 0.0 | 0.0 | 3631.1 | 3631.1 | 0.0 |
| **Radioactive waste to deposit** | -0.1 | -0.1 | 2214.5 | -0.1 | -0.1 | 2214.5 | 2214.5 | -0.1 |
| **Biotic resources** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table C20: Contributions of the endpoint category "Ecological Scarcity" to the cascade use of biochar for the modelled pig farms. The results are shown for wood chip biochar, and accounting for biochar production. Unit = UBP.

| Model farm | Pig farm – With biochar production | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Scenario | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 9 |
| Impact category | | | | | | | | |
| Water resources, net balance | 5815.6 | 9611.7 | 1978.5 | 325.6 | 1627.1 | 8120.0 | 13217.6 | 6141.3 |
| Energy resources | 580125.4 | 958790.4 | 30024.7 | 32489.5 | 162317.7 | 642639.6 | 1151132.8 | 612614.9 |
| Mineral resources | 36929.3 | 61034.2 | 2261.0 | 2068.2 | 10332.7 | 41258.6 | 73628.0 | 38997.5 |
| Land use | 203393.9 | 336155.1 | 7995.1 | 11391.0 | 56909.2 | 222779.9 | 401059.3 | 214784.9 |
| Global warming | 556826.6 | 932809.2 | 507364.8 | 25777.4 | 170046.7 | 1087074.8 | 1605616.5 | 582605.9 |
| Ozone layer depletion | 271.5 | 448.8 | 154.7 | 15.2 | 76.0 | 441.4 | 679.5 | 286.8 |
| Main air pollutants and particulates | 132059.1 | 223636.2 | -3495027.3 | 11504.6 | 57478.9 | -3349115.7 | -3211421.1 | 143564.2 |
| Carcinogenic substances into air | 18690.1 | 30889.7 | 2484.9 | 1046.7 | 5229.4 | 22221.8 | 38604.2 | 19736.8 |
| Heavy metals into air | 33933.3 | 56082.7 | 4881.3 | 1900.2 | 9494.3 | 40715.2 | 70458.8 | 35833.7 |
| Water pollutants | -2154183.5 | -3543645.3 | 5228148.1 | -295713.5 | -234804.2 | 2718009.9 | 1352269.7 | -2449897.0 |
| Persistent organic pollutants into water | 2383.7 | 3939.5 | 456.4 | 133.5 | 666.9 | 2973.6 | 5062.9 | 2517.2 |
| Heavy metals into water | 6615.7 | 10934.0 | 723.0 | 370.5 | 1851.0 | 7709.2 | 13508.0 | 6986.2 |
| Pesticides into soil | 50738.6 | 83857.1 | 2213.4 | 2841.6 | 14196.6 | 55793.1 | 100266.9 | 53580.1 |
| Heavy metals into soil | 5302.0 | 8762.9 | 256.0 | 296.9 | 1483.5 | 5855.0 | 10502.3 | 5599.0 |
| Radioactive substances into air | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.1 |
| Radioactive substances into water | 222.0 | 367.0 | 53.7 | 12.4 | 62.1 | 288.2 | 482.8 | 234.5 |
| Noise | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Waste, non-radioactive | 15002.9 | 24795.8 | 4194.3 | 840.2 | 4197.7 | 20037.6 | 33188.0 | 15843.2 |
| Radioactive waste to deposit | 10840.0 | 17915.6 | 2621.5 | 607.1 | 3033.0 | 14068.6 | 23570.2 | 11447.1 |
| Biotic resources | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table C21: Contributions of the endpoint category "Ecological Scarcity" to the cascade use of biochar for the modelled vegetable farms. The results are shown for wood chip biochar, not accounting for biochar production. Unit = UBP.

| Model farm | Vegetable farm – Without biochar production | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Scenario | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 9 |
| Impact category | | | | | | | | |
| Water resources, net balance | 0.0 | 0.1 | 581.6 | 0.1 | 0.1 | 581.6 | 581.6 | 0.1 |
| Energy resources | -0.1 | 3.4 | 2726.8 | 3.4 | 3.4 | 2726.8 | 2726.8 | 3.4 |
| Mineral resources | 0.0 | 3.3 | 292.2 | 3.3 | 3.3 | 292.2 | 292.2 | 3.3 |
| Land use | 0.0 | 70.2 | 188.7 | 70.2 | 70.2 | 188.7 | 188.7 | 70.2 |
| Global warming | -35459.8 | -206826.3 | 50363.3 | -528341.2 | -1111095.2 | -510266.5 | -1265266.9 | -560428.5 |
| Ozone layer depletion | 0.0 | 1.1 | 48.8 | 1.1 | 1.1 | 48.8 | 48.8 | 1.1 |
| Main air pollutants and particulates | 58526.2 | 16343.1 | -195461.7 | 67337.8 | 67337.8 | -204054.8 | -245465.5 | -8717.3 |
| Carcinogenic substances into air | 0.0 | 1.3 | 590.3 | 1.3 | 1.3 | 590.3 | 590.3 | 1.3 |
| Heavy metals into air | 0.0 | 1.9 | 1193.6 | 1.9 | 1.9 | 1193.6 | 1193.6 | 1.9 |
| Water pollutants | -800338.6 | -4113852.1 | 137906.3 | -11950736.6 | -11950736.6 | -12301718.9 | -15632493.2 | -12436256.5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Persistent organic pollutants into water** | 0.0 | 0.5 | 121.7 | 0.5 | 0.5 | 121.7 | 121.7 | 0.5 |
| **Heavy metals into water** | 0.0 | 0.5 | 157.2 | 0.5 | 0.5 | 157.2 | 157.2 | 0.5 |
| **Pesticides into soil** | 0.0 | -4774.1 | -4672.2 | -4774.1 | -4774.1 | -4672.2 | -4672.2 | -4773.4 |
| **Heavy metals into soil** | 0.0 | -62.2 | -43.4 | -62.2 | -62.2 | -43.4 | -43.4 | -62.2 |
| **Radioactive substances into air** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Radioactive substances into water** | 0.0 | 0.0 | 15.0 | 0.0 | 0.0 | 15.0 | 15.0 | 0.0 |
| **Noise** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Waste, non-radioactive** | 0.0 | 26.4 | 1225.9 | 26.4 | 26.4 | 1225.9 | 1225.9 | 26.4 |
| **Radioactive waste to deposit** | 0.0 | 0.6 | 732.2 | 0.6 | 0.6 | 732.2 | 732.2 | 0.7 |
| **Biotic resources** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table C22: Contributions of the endpoint category “Ecological Scarcity” to the cascade use of biochar for the modelled vegetable farms. The results are shown for wood chip biochar, and accounting for biochar production. Unit = UBP.

| **Model farm** | **Vegetable farm – With biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **1** | **2** | **3** | **4** | **5** | **7** | **8** | **9** |
| **Impact category** | | | | | | | | |
| **Water resources, net balance** | 901.8 | 5618.5 | 653.7 | 13331.5 | 66604.0 | 14886.9 | 72876.0 | 14233.3 |
| **Energy resources** | 89952.7 | 560451.0 | 9921.6 | 1329838.9 | 6643866.9 | 1429709.8 | 7214232.6 | 1419791.6 |
| **Mineral resources** | 5726.2 | 35680.0 | 750.2 | 84657.4 | 422935.5 | 91130.5 | 459359.2 | 90383.6 |
| **Land use** | 31537.7 | 196565.0 | 2711.2 | 466315.0 | 2329431.0 | 500493.7 | 2528566.8 | 497852.7 |
| **Global warming** | 74363.0 | 477421.5 | 59147.3 | 1095248.6 | 7000366.4 | 1231930.4 | 7539226.7 | 1172984.1 |
| **Ozone layer depletion** | 42.1 | 263.4 | 52.2 | 623.6 | 3111.0 | 716.8 | 3424.4 | 665.7 |
| **Main air pollutants and particulates** | 90379.8 | 214806.8 | -192914.0 | 538254.7 | 2420040.6 | 301263.7 | 2308248.9 | 494053.3 |
| **Carcinogenic substances into air** | 2898.0 | 18057.4 | 822.1 | 42845.2 | 214049.8 | 46564.1 | 232926.9 | 45743.2 |
| **Heavy metals into air** | 5261.6 | 32784.4 | 1614.5 | 77788.5 | 388624.2 | 84662.7 | 423019.2 | 83050.2 |
| **Water pollutants** | -758137.1 | -3850916.6 | 141281.8 | -11326840.7 | -8833749.8 | -11632245.8 | -12249195.4 | -11770159.0 |
| **Persistent organic pollutants into water** | 369.6 | 2303.3 | 151.3 | 5464.6 | 27299.3 | 5985.0 | 29752.9 | 5834.2 |
| **Heavy metals into water** | 1025.8 | 6391.8 | 239.3 | 15165.8 | 75766.7 | 16430.5 | 82396.9 | 16191.7 |
| **Pesticides into soil** | 7867.4 | 44243.4 | -4042.9 | 111535.0 | 576306.6 | 120133.5 | 626055.2 | 119403.0 |
| **Heavy metals into soil** | 822.1 | 5060.0 | 22.4 | 12091.8 | 60659.4 | 12998.5 | 65866.1 | 12914.0 |
| **Radioactive substances into air** | 0.0 | 0.1 | 0.0 | 0.2 | 1.0 | 0.2 | 1.1 | 0.2 |
| **Radioactive substances into water** | 34.4 | 214.5 | 17.8 | 509.0 | 2543.0 | 561.2 | 2775.3 | 543.4 |
| **Noise** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Waste, non-radioactive** | 2326.3 | 14520.5 | 1412.0 | 34418.2 | 171847.6 | 38130.1 | 187727.3 | 36744.5 |
| **Radioactive waste to deposit** | 1680.8 | 10473.0 | 866.6 | 24849.5 | 124145.6 | 27396.3 | 135483.9 | 26530.3 |
| **Biotic resources** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

## C7: Environmental Impacts of the Cascade Use of Biochar for the Model Farms

We provide the percentage differences between the eight scenarios and the baseline for the cascade use of biochar, that is:

$$\text{Percentage difference } [\%] = \frac{Value_{scenario} - Value_{baseline}}{Value_{baseline}} \cdot 100\%$$

The percentage differences are displayed separately for each of the three model farms. Furthermore, to allow for more insight into the results, we list the percentage differences for (i) solely the cascade use of biochar and (ii) the cascade use of biochar plus the production of biochar. The first case is displayed in Tables C23, C25, and C27, while the latter case is presented in Tables C24, C26, and C28.

The percentage differences of the biochar cascade use with and without considering the production of biochar are closely related to the quantity of biochar used in each scenario.

Table C23: Percentage differences in the environmental impacts on the modelled dairy farms from the biochar cascade use. The results are shown for wood chip biochar, not accounting for biochar production.

| **Model farm** | | **Dairy farm – Without biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Impact category** | **Unit** | | | | | | | | |
| **CML – Abiotic depletion potential** | kg Sb-eq | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Water scarcity – AWARE** | $m^3$ | 0.00% | 0.00% | 0.03% | 0.00% | 0.00% | 0.03% | 0.03% | 0.00% |
| **Water use – from LCI** | $m^3$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Land transformation – Deforestation** | $m^2$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Land occupation – Total** | $m^2a$ | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| **IPCC 2021 – GWP100 (fossil & LULUC)** | kg $CO_2$-eq | -0.05% | -0.26% | 0.05% | 0.00% | 0.00% | 0.00% | -0.22% | -0.05% |
| **Eutrophication – Marine** | kg N-eq | -1.63% | -8.35% | 0.83% | -0.08% | -0.08% | -0.90% | -7.69% | -1.71% |
| **Eutrophication – Freshwater** | kg P-eq | 0.00% | 0.00% | 0.02% | 0.00% | 0.00% | 0.02% | 0.02% | 0.00% |
| **Eutrophication – Terrestrial** | mol N-eq | -0.04% | -0.24% | -1.86% | 0.00% | 0.00% | -1.90% | -2.09% | -0.04% |
| **Acidification – Terrestrial** | kg $SO_2$-eq | -0.04% | -0.23% | -1.84% | 0.00% | 0.00% | -1.88% | -2.06% | -0.04% |

Table C24: Percentage differences in the environmental impacts on the modelled dairy farms from the biochar cascade use. The results are shown for wood chip biochar, and accounting for biochar production.

| **Model farm** | | **Dairy farm – With biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Impact category** | **Unit** | | | | | | | | |
| **CML – Abiotic depletion potential** | kg Sb-eq | 0.06% | 0.35% | 0.01% | 0.00% | 0.01% | 0.08% | 0.38% | 0.07% |
| **Water scarcity – AWARE** | $m^3$ | 0.14% | 0.77% | 0.03% | 0.01% | 0.03% | 0.18% | 0.83% | 0.14% |
| **Water use – from LCI** | $m^3$ | 0.06% | 0.34% | 0.01% | 0.00% | 0.01% | 0.08% | 0.37% | 0.06% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Land transformation – Deforestation** | $m^2$ | 0.38% | 2.16% | 0.02% | 0.02% | 0.09% | 0.42% | 2.27% | 0.40% |
| **Land occupation – Total** | $m^2a$ | 2.65% | 15.00% | 0.08% | 0.13% | 0.64% | 2.86% | 15.71% | 2.78% |
| **IPCC 2021 – GWP100 (fossil & LULUC)** | kg $CO_2$-eq | 0.07% | 0.43% | 0.05% | 0.00% | 0.02% | 0.13% | 0.50% | 0.08% |
| **Eutrophication – Marine** | kg N-eq | -1.63% | -8.34% | 0.83% | -0.08% | -0.08% | -0.90% | -7.67% | -1.71% |
| **Eutrophication – Freshwater** | kg P-eq | 1.66% | 9.38% | 0.07% | 0.08% | 0.40% | 1.81% | 9.85% | 1.74% |
| **Eutrophication – Terrestrial** | mol N-eq | -0.02% | -0.08% | -1.86% | 0.00% | 0.01% | -1.87% | -1.93% | -0.01% |
| **Acidification – Terrestrial** | kg $SO_2$-eq | -0.01% | -0.08% | -1.84% | 0.00% | 0.01% | -1.85% | -1.90% | -0.01% |

Table C25: Percentage differences in the environmental impacts on the modelled pig farms from the biochar cascade use. The results are shown for wood chip biochar, not accounting for biochar production.

| **Model farm** | | **Pig farm – Without biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Impact category** | **Unit** | | | | | | | | |
| **CML – Abiotic depletion potential** | kg Sb-eq | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Water scarcity – AWARE** | $m^3$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Water use – from LCI** | $m^3$ | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| **Land transformation – Deforestation** | $m^2$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Land occupation – Total** | $m^2a$ | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| **IPCC 2021 – GWP100 (fossil & LULUC)** | kg $CO_2$-eq | -0.02% | -0.03% | 0.06% | 0.00% | 0.00% | 0.04% | 0.03% | -0.02% |
| **Eutrophication – Marine** | kg N-eq | -0.34% | -0.56% | 0.73% | -0.04% | -0.04% | 0.34% | 0.11% | -0.38% |
| **Eutrophication – Freshwater** | kg P-eq | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Eutrophication – Terrestrial** | mol N-eq | -0.03% | -0.04% | -1.40% | 0.00% | 0.00% | -1.42% | -1.44% | -0.03% |
| **Acidification – Terrestrial** | kg $SO_2$-eq | -0.03% | -0.04% | -1.37% | 0.00% | 0.00% | -1.39% | -1.41% | -0.03% |

Table C26: Percentage differences in the environmental impacts on the modelled pig farms from the biochar cascade use. The results are shown for wood chip biochar, and accounting for biochar production.

| **Model farm** | | **Pig farm – With biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Impact category** | **Unit** | | | | | | | | |
| **CML – Abiotic depletion potential** | kg Sb-eq | 0.03% | 0.05% | 0.01% | 0.00% | 0.01% | 0.04% | 0.07% | 0.03% |
| **Water scarcity – AWARE** | $m^3$ | 0.05% | 0.08% | 0.01% | 0.00% | 0.01% | 0.06% | 0.10% | 0.05% |
| **Water use – from LCI** | $m^3$ | 0.02% | 0.04% | 0.01% | 0.00% | 0.01% | 0.03% | 0.05% | 0.02% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Land transformation – Deforestation** | $m^2$ | 0.21% | 0.35% | 0.01% | 0.01% | 0.06% | 0.24% | 0.42% | 0.22% |
| **Land occupation – Total** | $m^2a$ | 1.04% | 1.73% | 0.04% | 0.06% | 0.29% | 1.14% | 2.06% | 1.10% |
| **IPCC 2021 – GWP100 (fossil & LULUC)** | kg $CO_2$-eq | 0.07% | 0.12% | 0.07% | 0.00% | 0.02% | 0.14% | 0.21% | 0.08% |
| **Eutrophication – Marine** | kg N-eq | -0.34% | -0.55% | 0.73% | -0.04% | -0.04% | 0.34% | 0.12% | -0.38% |
| **Eutrophication – Freshwater** | kg P-eq | 0.58% | 0.95% | 0.03% | 0.03% | 0.16% | 0.64% | 1.14% | 0.61% |
| **Eutrophication – Terrestrial** | mol N-eq | -0.01% | -0.02% | -1.40% | 0.00% | 0.00% | -1.41% | -1.41% | -0.01% |
| **Acidification – Terrestrial** | kg $SO_2$-eq | -0.01% | -0.02% | -1.37% | 0.00% | 0.00% | -1.38% | -1.38% | -0.01% |

Table C27: Percentage differences in the environmental impacts on the modelled vegetable farms from the biochar cascade use. The results are shown for wood chip biochar, not accounting for biochar production.

| **Model farm** | | **Vegetable farm – Without biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Impact category** | **Unit** | | | | | | | | |
| **CML – Abiotic depletion potential** | kg Sb-eq | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Water scarcity – AWARE** | $m^3$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Water use – from LCI** | $m^3$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Land transformation – Deforestation** | $m^2$ | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Land occupation – Total** | $m^2a$ | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| **IPCC 2021 – GWP100 (fossil & LULUC)** | kg $CO_2$-eq | -0.02% | -0.10% | 0.03% | -0.27% | -0.56% | -0.26% | -0.64% | -0.28% |
| **Eutrophication – Marine** | kg N-eq | -0.41% | -2.10% | 0.07% | -6.11% | -6.11% | -6.29% | -7.99% | -6.36% |
| **Eutrophication – Freshwater** | kg P-eq | 0.00% | 0.00% | 0.01% | 0.00% | 0.00% | 0.01% | 0.01% | 0.00% |
| **Eutrophication – Terrestrial** | mol N-eq | 0.17% | 0.05% | -0.58% | 0.19% | 0.19% | -0.60% | -0.71% | -0.02% |
| **Acidification – Terrestrial** | kg $SO_2$-eq | 0.16% | 0.05% | -0.55% | 0.18% | 0.18% | -0.57% | -0.67% | -0.02% |

Table C28: Percentage differences in the environmental impacts on the modelled vegetable farms from the biochar cascade use. Results are shown for wood chip biochar, and accounting for biochar production.

| **Model farm** | | **Vegetable farm – With biochar production** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
| **Impact category** | **Unit** | | | | | | | | |
| **CML – Abiotic depletion potential** | kg Sb-eq | 0.01% | 0.09% | 0.01% | 0.22% | 1.08% | 0.24% | 1.18% | 0.23% |
| **Water scarcity – AWARE** | $m^3$ | 0.02% | 0.13% | 0.01% | 0.31% | 1.56% | 0.35% | 1.70% | 0.33% |
| **Water use – from LCI** | $m^3$ | 0.01% | 0.07% | 0.01% | 0.16% | 0.80% | 0.18% | 0.88% | 0.17% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Land transformation – Deforestation** | $m^2$ | 0.22% | 1.35% | 0.03% | 3.21% | 16.06% | 3.46% | 17.45% | 3.43% |
| **Land occupation – Total** | $m^2a$ | 0.73% | 4.55% | 0.06% | 10.79% | 53.93% | 11.58% | 58.54% | 11.52% |
| **IPCC 2021 – GWP100 (fossil & LULUC)** | kg $CO_2$-eq | 0.04% | 0.23% | 0.03% | 0.53% | 3.40% | 0.59% | 3.66% | 0.56% |
| **Eutrophication – Marine** | kg N-eq | -0.41% | -2.10% | 0.07% | -6.10% | -6.05% | -6.28% | -7.93% | -6.34% |
| **Eutrophication – Freshwater** | kg P-eq | 0.32% | 1.99% | 0.04% | 4.72% | 23.60% | 5.08% | 25.62% | 5.04% |
| **Eutrophication – Terrestrial** | mol N-eq | -0.02% | -0.08% | -1.86% | 0.00% | 0.01% | -1.87% | -1.93% | -0.01% |
| **Acidification – Terrestrial** | kg $SO_2$-eq | -0.01% | -0.08% | -1.84% | 0.00% | 0.01% | -1.85% | -1.90% | -0.01% |