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Terrestrial Storage of Biomass

Methodology for CO_2 Removal

Puro Standard

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Contents

Glossary

> **REMARK:** This glossary provides only the most important definitions for the current methodology. Please note that further definitions are listed in the Puro Standard General Rules. The glossary terms appear in *italics* in the text.

Activity A practice or ensemble of practices that take place on a delineated area resulting in emissions or removals taking place (see *Project*). An eligible activity is an activity that meets the qualification criteria in a given certification methodology or protocol.

Activity boundaries The activity boundaries determine the unit processes to be included in the *life cycle assessment* (LCA), as well as the relevant time and spatial boundaries.

Activity data Data relating to the project that quantifies activities performed, e.g. transport distances, type of truck and fuel, measurements of carbon contents, energy use, material use, and waste generation.

Carbon Carbon is a chemical element which is present in many gases and compounds. For example, carbon combines with oxygen to make carbon dioxide (CO_2), and with hydrogen to make methane (CH_4). The term "carbon" is used in a variety of ways when talking about greenhouse gas emissions, and therefore can be ambiguous and potentially confusing. "Carbon" is sometimes used as a shorthand for referring to CO_2, or greenhouse gases in general, and it can also be used to express CO_2 equivalents.

CO_2 Removal Supplier An account holder registering a *Production facility* capable of CO_2 removal according to the relevant removal method.

Dry storage A storage solution where biomass is dried and remains sufficiently dry to make it biologically stable. In this methodology, dry storage refers to an equilibrium relative humidity below 71 % in the storage chamber (i.e. water activity is below 0.71). See also *Wet storage*.

Eligible biomass *lignocellulosic biomass* (LCB) From plants mainly composed of polysaccharides (cellulose and hemicelluloses) and an aromatic polymer (lignin) making a complex assembly of polymers naturally recalcitrant to enzymatic decomposition. In simple terms, this can constitute trees and hard stemmed, lignin rich plants. For the current version of the methodology, this excludes biomass from non-tree sources such as algae, herbaceous plants and grasses.

Output Metric tonnes of CO_2 *equivalent* (CO_2e) removal within a certain time period which is eligible to receive CO_2 *Removal Certificates* (CORCs). CORCs are always issued for net CO_2 removal in the production process, which means that the total volume of output is determined by subtracting from the CO_2 removal volume the CO_2 emissions generated directly or indirectly due to the production process or materials used according to the removal method.

Production facility A facility capable of CO_2 removal according to one or several methodologies. In this context, a production facility is the end-to-end operation where storage of biomass occurs. A production facility can contain one or more individual storage chambers.

Project A collection of activities executed over time which have a start and end date. This duration often relates to the technical lifetime of a *Production facility*.

Re-emission Re-emission is the fraction (%) of sequestered carbon that can be expected to re-emit as CO_2 or other greenhouse gases within 100 years. The re-emission factor DOC_f signifies the fraction of degradable organic carbon that can decompose.

Recalcitrant biomass Biomass resistant to chemical decomposition, or decomposing extremely slowly. Biomass recalcitrance refers to the anti-degradation characteristics of native lignocellulose, which protect plant cell walls from pathogen attack or degradation by microorganisms and enzymes.

Storage chamber An enclosed chamber where predescribed parameters are controlled such that conditions that mitigate decomposition are kept constant over time. When the storage chamber reaches its maximum capacity it is sealed in a manner that ensures durable preservation of the contained biomass. This will be ensured by the CO_2 *Removal Supplier*.

Storage site In this methodology, the storage site containing the biomass corresponds to the *Production facility* of CO_2 *Removal Certificates*, as per the terminology defined in the Puro Standard General Rules. See *Production facility*.

Storage unit See *Storage chamber*.

Terrestrial storage Storage of biomass on land as opposed to e.g. marine environments

Tonne A unit of mass equivalent to 1000 kg, also known as 'metric tonne'. In this methodology, the word 'tonne' always refers to metric tonnes.

Water activity The water activity (WA) is a proxy for the fraction of water that is biologically available. It is functionally equivalent to the equilibrium relative humidity (RH), such that $WA = RH/100\,\%$. For example, an equilibrium relative humidity of 71 % corresponds to a water activity of 0.71.

Wet storage Any storage conditions that do not conform to the definition of *Dry storage*.

Acronyms

GWP_{100} Global Warming Potential over 100 years

CO_2e CO_2 equivalent

CDR Carbon Dioxide Removal

CORC CO_2 Removal Certificate

dLUC Direct Land Use Change

EIA Environmental Impact Assessment

ERA Environmental Risk Assessment

GHG Greenhouse Gas

LCA Life Cycle Assessment

LCB Lignocellulosic Biomass

PBR Plant Biomass Recalcitrance

TSB Terrestrial Storage of Biomass

WA Water Activity

Chemical species

C Carbon

CH_4 Methane

CO_2 Carbon dioxide

H_2O Water

N Nitrogen

N_2O Dinitrogen monoxide, also known as nitrous oxide

O Oxygen

Note to the reader

REMARK: This methodology provides general information as well as actual requirements which must be met by all projects seeking certification under the Puro Standard. Across the entire methodology, the requirements correspond to numbered rules with formatting conforming to the below example.

0.0.1 This is an example of a numbered rule. The requirements set within numbered rules must be followed by all projects seeking certification under the Puro Standard.

1

Introduction

1.1 Method overview

This methodology quantifies the **net CO_2 removal** achieved over one hundred (100) years[1] by the storage of *Eligible biomass* in adequate terrestrial storage systems, henceforth known as *terrestrial storage of biomass* (TSB).

Photosynthesis and subsequent plant growth removes CO_2 from the atmosphere, and locks the **carbon** (C) in lignified plant tissues. This **biomass** can then be placed in **storage** specifically designed to *inhibit decomposition* and thus prevent carbon from being returned to the atmosphere in various forms including CO_2 and CH_4 (methane).

Biomass can be **stored** in different ways to inhibit biomass decomposition. Beside different types of storage, storage sites themselves are subject to different risks, mitigation measures, and monitoring measures. Likewise, biomass sourcing is subject to different criteria for sustainable sourcing and leakage prevention.

The **goal** of this methodology is to provide **consistent requirements** across the multiple types of carbon removal solutions within this approach. Generic and consistent requirements reduce transaction costs for all market participants, foster innovation, promote *knowledge building* and enable rapid growth in the supply of CO_2 removal.

Given the differences in storage approaches as well as rapidly developing knowledge in this area, this methodology will be based on measured performance criteria including as applicable:

- Monitoring that the conditions in the storage system necessary for sustained storage are maintained.
- Measuring the sustained carbon content of storage chambers over time.
- Monitoring for methane and other *greenhouse gases* (GHGs) as part of GHG mitigation measures.

1.2 Eligible biomass

The *lignocellulosic biomass* (LCB) currently eligible in this methodology must have a rigid physical structure, a *high lignin content*, and a C:N ratio of 80 or higher (see rule 4.1.2 and glossary definition *Eligible biomass*). These chemical and physical traits make the biomass especially recalcitrant to microbial decomposition [1].

More specifically, LCB is composed of cellulose, hemicelluloses and **lignin**, resulting in a complex assembly of enduring polymers. Conversely, grasses, lichens and soft celled plants have high starch, sugar and protein content, all of which may decompose more readily [2, 3],[2] and are thus *not eligible in the present version* of this methodology.

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[1] The CO_2 must be sequestered (on a net basis) over at least 100 years.

[2] See also [4, p. 12], Table 3.0 Fraction of degradable organic carbon which decomposes (DOC_f) for different waste types.

Very simply, the focus of this version of the methodology is **naturally durable biomass**[3] and the carbon content of that biomass. Table 1 presents a basic overview of the major components of LCB in various materials and table 2 provides a basic overview of the carbon content in different types of plant. This also provides the background for rule 6.4.4 relating to the organic carbon content of the biomass.

Table 1: Major components of various lignocellulosic materials [5]

Raw material	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Grasses	25–40	25–50	10–30
Softwoods	45–50	25–35	25–35
Hardwoods	45–55	24–40	18–25

Table 2: Plant carbon content (%) in stem [6]

Type of plant	Number of samples (%)	Carbon content (%)
Herbaceous plants	162	42.4
Crop	69	43.2
Woody plants	3461	48.1
Deciduous broad-leaved	1581	47.6
Evergreen broad-leaved	1212	47.8
Conifers	502	50.5
Vine	82	46.7
Bamboo	39	49.2
All	**3754**	**47.9**

As our knowledge and understanding of biomass behavior evolves with time, *alternative types* of biomass may be considered for *inclusion in future versions* of this methodology. Although many types of biomass can potentially be durably stored under proper conditions (such as low equilibrium relative humidity), *biomass not containing lignin decays significantly faster if proper storage conditions are not maintained*. As a **re-emission precaution**, this methodology currently **only allows** the inclusion of **lignocellulosic biomass** that is naturally more recalcitrant to decomposition. This is done in part to ensure that if a storage chamber is compromised, there is enough time to restore proper storage conditions and minimize any potential reversals.

The concept of *plant biomass recalcitrance* (PBR) is complex, and is related not only to the *physical structure* and strength of the biomass matrix but also its *chemical composition*. A critically important chemical aspect of PBR is the nitrogen content of the biomass. Furthermore, PBR is also dependent on the physical and chemical features and distribution of the major components within the cell walls of the biomass: hemicellulose, cellulose, and lignin. For a comprehensive list of physical and chemical factors influencing recalcitrance of lignocellulosic biomass, see [7].

High nitrogen content promotes more rapid microbial degradation because it is required for microbial catabolic enzyme synthesis. As a result, a *carbon to nitrogen ratio* (C:N) of 25 or less promotes anaerobic or aerobic microbial conversion of biomass to volatile CO_2 or methane [8]. A C:N ratio of 25 means that there is 1 g of nitrogen for every 25 g of carbon, i.e. a

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[3] Alternatives may be considered in future versions however a fundamental in what will be allowed relates to how alternative biomass is processed to make the biomass inert. Energy used and gases produced need to be a critical consideration in this.

nitrogen content of roughly 4 % of the mass of carbon present. The C:N ratio explains why LCB has greater recalcitrance than herbaceous biomass, as it has low nitrogen content (C:N > 80, equivalent to < 1.2 % nitrogen). See figure 1 for an overview of the soil nitrogen cycle.

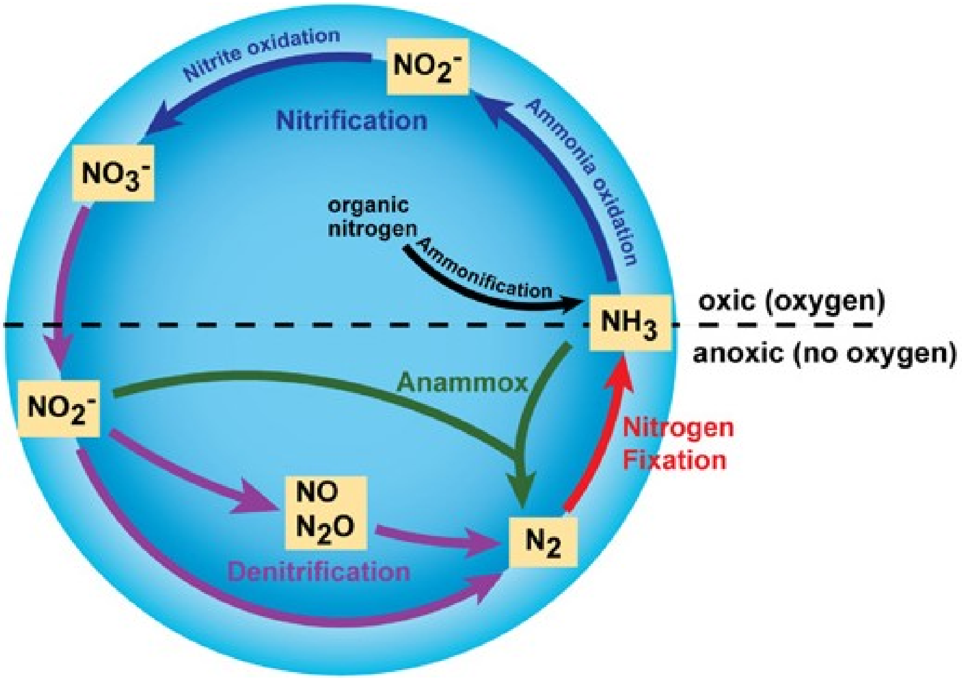

Figure 1: Soil nitrogen cycle [9].

1.3 Relevance of woody plants

In the context of this methodology, **wood/woody biomass** is an important category of LCB. However, it should be noted that *different wood types* exhibit different *decompositional characteristics* [10], and studies have attributed the observed higher levels of decay for some wood samples to differences in wood species rather than climatic conditions [11], see also tables 1 and 2.

In general, the **recalcitrance of lignin** is due to the ability of some of its structural components (guaiacyl phenolic moieties) to undergo complex branching. Under strictly anaerobic conditions, where some fractions of cellulose and hemicellulose were converted to methane and carbon dioxide, lignin remained unreacted [12].

Another key factor for recalcitrance is the high **C:N ratio** found in wood of any variety compared to leaf litter [2, 13, 14]. Leaf Litter may have a C:N of 30-80. Biomass with C:N of more than 80 has low nitrogen content and will not readily decompose without nitrogen addition. Wood chips, paper pulp and sawdust often have C:N of 150-560 or more [15]. A C:N ratio of around 25 is optimal for anaerobic digestion while a high C:N leads to rapid acidification and inhibits microbial methanogenic activity [8].

Large buried tree trunks can persist for millennia given the right conditions [16–18]. *Softwoods* with **high lignin** content and lower hemicellulose content than many hardwoods preserve well, but a variety of hardwoods (hazel, alder, oak) have also been documented to persist for over 7,000 years when buried in either fresh or saline mud [19, 20].

There is also data to illustrate the durability of sawdust as it has been purposefully placed underground in the construction of roadways. Wood chips and sawdust have been used as lightweight fill in roadway construction in the USA and northern Europe for over 50 years and are known to persist when placed beneath the water table and capped with clay [21, 22].

The absence of moisture can very effectively **inhibit decay**. In fact, wood decomposition virtually stops under highly desiccating conditions, even when oxygen is present, as evidenced by millennia-old dead wood found preserved at high altitudes [23]. In archaeology, dry wood that is protected from moisture, sunlight and insects has been preserved for several millennia, with only minor chemical and morphological changes evident upon microscopic examination [24–27]. Intact wooden artifacts obtained from the Egyptian Pyramids located in a desert with an average annual relative humidity of just 43 % have been found to be over 4,000 years old using radiocarbon dating [26]. Archeological specimens taken from excavations in the Sonoran desert (southwestern United States) where the annual relative humidity is 33 %, have revealed dry and well-preserved dead wood and charred logs, dated to be up to 1,800 years old [28].

1.4 Storage techniques and conditions

As previously outlined, the functionality and **durability** of this carbon removal category does not solely rely on the *chemical* and *physical* composition of the biomass. Thus, it is equally important to consider the solution used to effectively **store** the eligible biomass over 100+ years.

An **engineered** storage solution can further ensure the durability of the biomass against degradation. As previously outlined, biomass growth coupled with an engineered storage solution as envisaged in this methodology has the ability to capture carbon in a potentially repeatable, replicable, economic and scalable manner.

The potential of this repeatable cycle of biomass growth and storage is enhanced by embracing different techniques which exploit alternative ways of slowing or avoiding biomass decay e.g. storing LCB in engineered chambers or injecting biomass underground (see figure 2). This offers **variations** on the basic idea underpinning the potential of this category of carbon removal solution. These variations can arise in:

- Method of sourcing the eligible biomass.
- Composition of the eligible biomass.
- Condition of the eligible biomass at the point of storage (e.g. dry storage).
- Specific engineered design of the storage chamber.
- Specific approach to inhibiting decomposition of the biomass.
- Ecological, social and economic setting in which a specific project takes place.

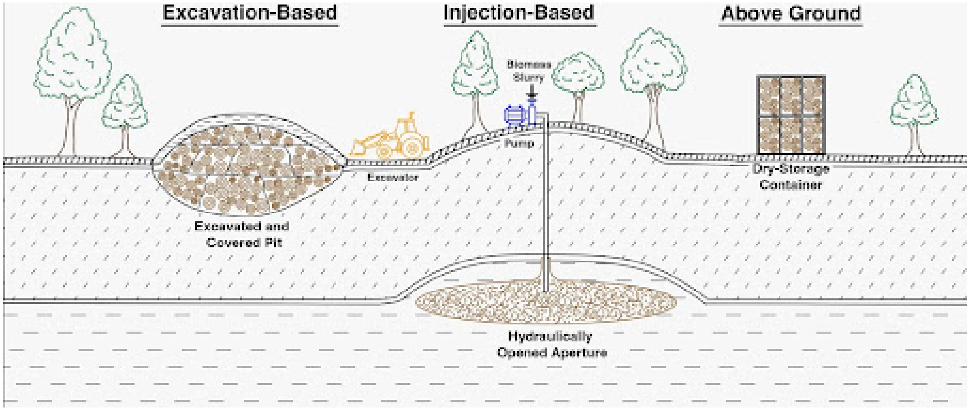

Figure 2: Examples of techniques for Terrestrial Storage of Biomass.

The function of the **storage chamber** is to *sustain the conditions* that inhibit the migration of carbon from the stored biomass back to the atmosphere, or *prevent decomposition entirely* (e.g., equilibrium relative humidity below 71 %). Even though terrestrial storage of biomass offers the potential for very long periods of carbon storage (much greater than 100 years), the stored carbon remains to some degree at risk of return to the atmosphere.

While the **conditions** necessary to sustain the containment of carbon in biomass and storage chambers are well understood, the conditions need to be *maintained* for the carbon to be contained for correspondingly long periods of time [29].

The **design**, **engineering** and **construction** of the chamber to achieve and maintain the targeted conditions is solution specific. This methodology currently includes **three broad categories** of biomass storage:

1. **Above ground storage chambers**: purpose-built covered structures that are typically ventilated or otherwise constructed to maintain a low relative equilibrium humidity (dry storage), and shield stored biomass from UV radiation, pests, and other external factors promoting decomposition.
2. **Below ground storage chambers**: purpose-built and covered storage pits that can be constructed to maintain either an anoxic environment or a dry, oxic environment such as in above ground storage chambers.
3. **Below ground subterranean injection**: a layer of biomass particles that is formed by the subterranean injection of a slurry containing wood or other eligible biomass [30]. The storage chamber is formed by the injection process itself and not otherwise pre-engineered (e.g. lined or ventilated). The storage occurs in an anoxic environment, and the chamber does not require active maintenance.

   Note that for subterranean injection, the water used to transport the biomass as a slurry may be removed and reused or allowed to leak out into the surrounding soil. Thus the moisture level in the biomass will soon approach the ambient moisture level of the surrounding soil. The mass of the overburdening soil will compact the biomass particles, reducing the void space between them. The density of the biomass layer may approach that of solid wood with injection depths beyond 10 meters. There is no known upper limit to the particle size that may be injected: as the technology matures, particles up to several centimeters in size might be placed with larger scale equipment.

Each of the above-mentioned storage options and their design/s will be associated with different **monitoring approaches** to demonstrate that biomass decomposition is not occurring. This methodology details **conditions** that *may be relevant* for a specific engineered storage chamber design, but does not exhaustively detail all conditions that are *relevant for every approach*, as these will be project specific.

Importantly, all storage chamber designs require the **optimization and monitoring** of certain external and internal parameters (e.g. humidity, temperature, water/gas conductivity) to maintain proper storage conditions. For some of these parameters, the optimal values and precise operational limits are still being discussed in the scientific literature and will be refined with experimentation and time. Therefore, this methodology cites specific parameter values or ranges where such are available from long term empirical calibration. In cases where more ambiguity exists, a more neutral term such as high or low is used. The purpose of this approach is to encourage more projects to start, promoting the progress of scientific research and a more thorough understanding of the behavior of the many factors and variables possessing a material impact in this field.

Numerous possible **conditions** and engineering approaches may eliminate, slow, inhibit or hinder the major biomass decomposition pathways and eliminate or limit the migration of organic gases to the atmosphere [31]. To **ensure biomass durability**, various feature combinations of can be employed in the design and intended functionality of storage chambers, such as:

- **Anoxic conditions** determined by soil redox potential $< -100\,\mathrm{mV}$ [32].
- **Absence of moisture** in the stored biomass, determined by a *Water activity* below 0.71 in the storage chamber [24, 33], see further discussion below.
- **Absence of liquid water** e.g. through permanently frozen conditions.
- **Absence of light and UV radiation** in the storage chamber.
- **Mineral occlusion** of the wood substrates or decomposition products [13, 34].
- **Tightly compacted biomass**.
- **Low to extremely low two-way water and gas conductivity**.
- **Hyper-saline environment**.
- **Chamber pH** below 5 or above 9 [35].
- **Chamber temperature** below 20 °C.

As an example, **anoxic conditions** (no oxygen) can greatly slow the decomposition of biomass. Such conditions may be the result of natural storage in permanently saturated fine grained soil or sediment, whether in a marsh, a forest, or when biomass is delivered down rivers to ocean floor environments. Partially saturated fine-grain compacted soil is also an excellent barrier to prevent oxygen intrusion.

Anoxic conditions both reduce the energy yield[4] of wood degradation for microbes and also result in production of *microbial necromass*[5] which without oxygen may be even more resistant to degradation than lignin [34, 37]. Overall, naturally occurring anoxic storage conditions are responsible for at least one third of long-term terrestrially-sourced carbon storage on Earth [38–40].

Other conditions can also efficiently prevent decomposition. LCB resists decay when it is sufficiently dried and kept sufficiently **dry** and protected from environmental stressors such as sunlight (UV), insects, and excessive moisture [24, 25, 27].

If sufficient **moisture is present**, LCB can decay into CO_2 and water under aerobic conditions, and (more slowly) into methane under anaerobic conditions. In temperate environments, the aerobic decay process for LCB is driven primarily by the growth of fungi and molds and to a lesser extent bacteria, which tend to colonize LCB in aquatic environments or buried in saturated soils [41].

Nearly all molds and fungi (the primary organisms responsible for aerobic decay of LCB) require a *water activity* (WA) > 0.75 to grow [42–44]. The *water activity* (WA) is functionally equivalent to the equilibrium relative humidity (RH), where $\mathrm{WA} = \mathrm{RH}/100\,\%$, and is a proxy

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[4] Aerobic decomposition of glucose ($C_6H_{10}O_5$), the monomer of cellulose, yields $2812\,\mathrm{kJ\,mol^{-1}}$, while anaerobic decomposition yields only 271kJ/mol, i.e. less than 10 % the energy. Additionally, around 72 % of the energy provided by anaerobic decomposition comes from the acidogenesis (acid-forming) stage leaving only 28 % for the final formation of methane and CO_2. Thus production of methane by archaea yields only 2.8 % the energy of aerobic decomposition of glucose [36].

[5] Microbial necromass includes lipids and other molecular structures. It is a large, dynamic and persistent component of soil organic carbon, the dominant terrestrial carbon pool.

for the fraction of water that is biologically available [45]. The lower limit on WA for most mold growth is 0.80 (RH = 80 %), although a few known molds can grow at WA as low as 0.75 [46, 47]. The lower limit on WA for most bacteria is 0.98 (RH = 98 %), although certain specific strains can survive at lower WA in saline environments [46]. There are very few reports of microbial growth of any kind for WA < 0.71 [33].

A handful of microorganisms have been found to grow *in vitro* at WA as low as 0.605 in the presence of certain solutes, but such growth has not been observed on LCB. Fungi isolated from decaying LCB were not observed to grow *in vitro* below WA = 0.71, and even so-called "dry-rot" fungi, which can digest dry LCB, require the ability to draw from a nearby water source, often the soil [24, 46–48].

Allowing for some limited fungal growth down to WA = 0.71, dry LCB preserved below an equilibrium RH of 71 % will not decay by biological routes. However, **UV light** and **wet-dry cycling** can slowly break down exposed LCB over time [28, 49], necessitating the avoidance of light exposure and the persistence of dry conditions for durable preservation of LCB.

1.5 Biomass decomposition and methane emissions

It is important to note that when sufficient moisture is present, even in anoxic conditions, and despite effective storage chamber design, naturally recalcitrant biomass can undergo some **initial decomposition**, fueled by the consumption of labile organic molecules. However, the rate of decomposition is expected to significantly decline as such molecules are exhausted, unless breaches of the storage chamber enable additional lignocellulosic degradation.

One method to **quantify** the overall **biomass decomposition** over time is via the *fraction of degradable organic carbon that can decompose* (DOC_f). This quantity is an estimate of the fraction of carbon that is ultimately degraded,[6] and reflects the fact that most of the degradable organic carbon does not, in fact, degrade under effective storage conditions (or degrades exceedingly slowly).

For wood, wood products, wood waste and tree branches stored in municipal landfills, the IPCC guidelines for national carbon accounting suggest a DOC_f of 8.8 % [4].[7] This value is also adopted for the present methodology, even though the purposely engineered chambers or injection of particulate wood into the deep, anoxic sub-soil will likely significantly outperform municipal landfills in limiting the return of terrestrial biomass carbon to the atmosphere. This methodology further assumes that half (50 %) of the above-mentioned carbon loss is *attributed to methane*, in agreement with the IPCC default value for the fraction of CH_4 in landfill gas [4].

It should be noted that a portion of the **methane generated** may **oxidize in the soil** or cover material, with the overall rate of oxidation being affected by many factors such as soil pH, moisture, temperature, and nutrient levels [50]. The oxidation process can also be facilitated by the construction of various types of **engineered microbial methane oxidation systems** [51, 52].

As a simple example, such a system could consist of a *methane oxidation layer*, i.e. a soil cover layer composed of gas permeable, bioactive materials (such as coarse soil or compost), underlain by a *gas distribution layer* of e.g. gravel or crushed glass to promote the even distribution of

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[6] Note that the decomposition, conversion to GHGs, and the escape of gas into the atmosphere are distinct processes. For example, methane produced during decomposition can subsequently be partially oxidized in the soil before reaching the atmosphere.

[7] See [4, p. 12], Table 3.0: "Fraction of degradable organic carbon which decomposes (DOC_f) for different waste types".

gases from the biomass to the oxidation layer, where bacteria will oxidize methane into carbon dioxide and water (see figure 3).

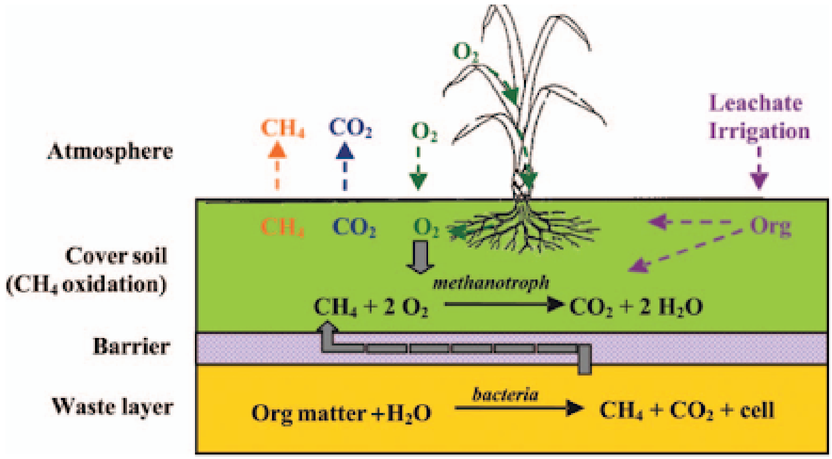

Figure 3: Microbial methane oxidation in the soil [53].

A **uniform spatial distribution** of CH_4 to the oxidation layer is particularly important, as unequal distribution can lead to preferential flow pathways with local CH_4 fluxes exceeding the oxidation capacity of the medium. In fact, studies of landfill soils have shown that the oxidation efficiency (% CH_4 oxidized) is exponentially dependent on the total CH_4 flux rate into the oxidation layer [50]. On the other hand, ensuring an even distribution of the CH_4 loading greatly improves performance, with CH_4 oxidation rates nearing 100 % in some cases.[8]

Methane oxidation rates can vary significantly, and even the performance of purpose-built systems relies heavily on factors such as the choice of adequate materials, gas transport and water retention characteristics of the cover layer [51]. Landfill studies have shown that methane oxidation can range between 0–100 % of internally produced CH_4 [54]. A later review of methane oxidation rate across a variety of soil types and landfill covers found that the means for the fraction of methane oxidized in the soil covers ranged between 22–55 % from clayey to sandy material, with an overall mean of 36 % ± 6 % [55].

Several methods can be utilized to *measure methane emissions* and oxidation rates both in laboratory and in-field conditions [51, 55, 56]. For example, fugitive emissions from the soil can be measured e.g. with a surface flux chamber and compared to estimated CH_4 flux based on decay rates. It is also possible to directly quantify biologically oxidized methane in a soil cover by utilizing e.g. the stable isotope technique[9] [50, 57]. It is however worth pointing out that while surface flux measurements are instructive, a significant portion of methane may instead escape through cracks and fissures or through lateral diffusion.

Acceptable values of landfill methane oxidation fractions are regulated for example by the United States Code of Federal Regulations (40 CFR 98.343).[10] The accepted oxidation fractions

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[8] See [51, p. 2] and references therein.

[9] The stable isotope technique refers to the determination of the isotopic composition of the methane emitted from the soil. Methanotropic bacteria in the soil have a tendency to preferentially consume the methane molecules containing the lighter isotope of carbon ($^{12}CH_4$) over the heavier isotope ($^{13}CH_4$), resulting in a shift in the isotopic composition of the gas as it passes through the cover soil layer.

[10] See equation HH-5 of the United States Code of Federal Regulations, Title 40, Chapter I, Subchapter C, Part 98, Subpart HH, §98.343, `https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98/subpart-HH/section-98.343`, as well as Table HH-4 of Part 98, Subpart HH, `https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98/subpart-HH/appendix-Table%20HH-4%20to%20Subpart%20HH%20of%20Part%2098`

range from 0–35 % depending on various factors such as the cover type and methane flux. As a result of the significant variance in the reported fractions of methane oxidation in soil, it is conservatively assumed that oxidation does not occur unless the storage site meets the criteria outlined in this methodology, or the oxidation rate is explicitly measured on-site.

Due to the particularly *deleterious near term impact of methane emissions on the net negativity of projects* [58], this methodology includes *prescriptive requirements* to **protect specifically against methane re-emission**.

> “Expressing methane emissions as CO_2 equivalent emissions using GWP_{100} overstates the effect of constant methane emissions on global surface temperature by a factor of 3–4 . . . while understating the effect of any new methane emission source by a factor of 4–5 over the 20 years following the introduction of the new source [59, 60].”

In other words, any **new source of methane** needs to be avoided given its short term impact. In a sealed chamber, monitoring the quantity and attributes of gases produced (or temperature and humidity for a dry chamber) is a way to monitor the performance of the chamber.

In a storage chamber where sufficient moisture is present such that decomposition can occur, **sampling gases** that might be produced allows the accurate measurement of carbon loss from the biomass and provides assurance that while carbon has migrated from the biomass, it remains contained within the sealed chamber.

Subterranean injection systems may incorporate **methane testing** via soil probes which enable periodic soil vapor removal and sampling with pumps or alternatively with sealed methane accumulation piping in communication with subterranean apertures to enable accumulation and testing of vapor space from the surface.

1.6 Summary

The *multiple solution types* of TSB may individually scale and collectively combine to provide very large volumes of carbon removal. Furthermore, the amplification of established natural processes suggests that affordable solutions with low risk of harm to the environment may be developed [61]. For example, the risk of re-emission with this method may be lower than gaseous or liquid underground storage mechanisms given the slow nature and easy detectability of any carbon leak occurring in a storage chamber. Also, if degradation is detected, the project developer can take relatively straightforward measures to rectify the issue before significant amounts of carbon are lost to the atmosphere.

The following sections of the methodology will detail the requirements to be met by a project seeking to utilize this methodology for CORC certification purposes. Any project attempting to apply this methodology should adhere to our broad philosophy: to **measure meaningfully**, and where possible to build data sets that both enhance the knowledge required to better understand the decomposition behavior of biomass under certain conditions, and improve the accuracy of any associated carbon accounting. This enhances the endeavors for carbon removal in general. Without measurement, we only have theoretical approximations from which it is difficult to meaningfully learn more. Anecdotal observation is not a substitute for scientific and experimental rigor.

2

Principles of verifiable CO_2 removals in Puro Standard

2.1 Guiding Principles

The methodology document is the protocol that sets the requirements for **verification** and **quantification** of **CO_2 removal projects**. The development of methodologies into the **Puro Standard** is done in an open and transparent manner with an expert working group, public consultation and review by an **Advisory Board**.

As a **scientific community** there is still a lot we don't know and in order to learn we have to try new things safely and record the results. Over time we will then be able to calibrate our models of understanding and incrementally improve the accuracy of any **measurement** related to carbon removal projects. This will take time and given the excess quantity of CO_2 already in our atmosphere we need to start work now.

The guiding principles are:

1. Transparency
2. Application of evidence
3. Monitoring, Reporting, and Verification (MRV)
4. Refinement over time

Transparency

Transparency by all parties fosters trust and reduces transaction costs in the operation of markets. This helps markets operate effectively and deliver desirable outcomes. Transparency is critical to building a high level of assurance for the buyers and sellers of CORCs (certified carbon removal). The public registry and the verification process is at its essence an exercise in delivering transparency and confidence to market participants.

Application of evidence

Application of evidence and wherever possible **direct measurements** of carbon removed throughout the duration of the project/s is preferred and encouraged in methodologies rather than relying only on estimates from simulated processes. The use and incorporation of **robust evidence** and *field measurements* in the design and operation of methodologies is good practice and particularly important in developing accuracy and scientific understanding.

Monitoring, reporting and verification (MRV)

Monitoring, reporting and verification (MRV) requirements are set in each methodology outlining the required monitoring and record keeping of the project/s for the purposes of performance (CO_2 removal output) reporting. This involves developing and adhering to a plan for long-term monitoring of the project. Carbon accounting and MRV are linked.

Each project reports the **performance** (CO_2 removal volumes), and submits it at designated intervals for **third-party verification**. This will also significantly enhance data sets associated with carbon removal methods to build certainty, confidence and allow for calibration with time. Improving scientific understanding with time is an essential aspect of any measurement carried out. Measurement for measurement sake has little value in the long run.

Project-level carbon accounting reports all greenhouse gas emissions associated with a *carbon dioxide removal* (CDR) project using repeatable and verifiable GHG quantification methods. In general, this requires the use of cradle-to-grave LCAs and/or models that accurately estimate net CDR, calibrated by periodic direct measurement.

In line with **Microsoft's criteria** [62] for *high quality carbon dioxide removal* project developers should:

- Develop a credible *MRV plan* prior to the start of the project.
- *Adapt the MRV* plan throughout the project by incorporating the best available science and evolving industry practices.
- Use *peer-reviewed and scientifically supported carbon accounting methods* to quantify the net volume of removals claimed, and disclose the specific methods used.
- Where an LCA is provided, use a *cradle-to-grave* LCA and specify the use of either attributional or consequential LCA.
- *Incorporate uncertainty conservatively* to avoid overstating the estimated CDR from a project.
- Separately quantify *removed, reduced, and avoided emissions*, including delineating by greenhouse gas type.
- If applicable, use models that are *calibrated and validated* for the *specific conditions* in which the project will operate.
- *Specify model assumptions* that cannot be calibrated or revised due to practice constraints.
- Developers should *periodically review MRV measurements and other scientific advancements* to revise all other assumptions.

Refinement over time

This methodology will be **refined** and **improved over time** based upon the **best available science** and the **measured performance** of TSB projects. As more field data becomes available the scientific knowledge base of this carbon removal category will be improved. Indeed, this principle of calibration based on new field data is central to the progressive improvement of any quantification method. Over time, the TSB projects will collectively develop large data sets that will allow for the **refinement** and **validation** of approaches to calculate removals, along with many other of the core aspects of this methodology.

2.2 Alignment with Core Carbon Principles

The *Integrity Council for the Voluntary Carbon Market* (**ICVCM**), is an independent governance body for the voluntary carbon market. Their objective is to build integrity, so that high-quality carbon credits efficiently mobilize finance towards urgently needed mitigation and climate resilient activities. The **Puro Standard** is following the **Core Carbon Principles (CCPs)** issued by the ICVCM [63].

Principles for carbon-crediting programs

1. **Effective governance (CCP 01)**

The carbon-crediting program shall have *effective program* governance to ensure *transparency*, accountability, continuous *improvement* and the overall *quality* of carbon credits.

2. **Tracking (CCP 02)**

The carbon-crediting program shall operate or make use of a *registry* to uniquely identify, record and track mitigation activities and carbon credits issued to ensure credits can be identified securely and unambiguously.

3. **Transparency (CCP 03)**

The carbon-crediting program shall provide *comprehensive* and *transparent* information on all credited mitigation activities. The information shall be publicly available in electronic format and shall be accessible to non-specialised audiences, to enable scrutiny of mitigation activities.

4. **Robust independent third-party validation and verification (CCP 04)**

The carbon-crediting program shall have program-level requirements for robust *independent third-party validation* and *verification* of mitigation activities.

5. **Sustainable development benefits and safeguards (CCP 09)**

The carbon-crediting program shall have clear guidance, tools and compliance procedures to ensure mitigation activities conform with or go beyond widely established industry best practices on *social and environmental safeguards* while delivering positive sustainable development impacts.

Principles for projects (mitigation activities)

6. **Additionality (CCP 05)**

The greenhouse gas (GHG) emission reductions or removals from the mitigation activity shall be *additional*, i.e., they *would not have occurred in the absence of the incentive created by carbon credit revenues*.[11]

7. **Permanence (CCP 06)**

The GHG emission reductions or removals from the mitigation activity shall be *permanent* or, where there is a risk of reversal, there shall be measures in place to address those risks and *compensate for reversals*.

8. **Robust quantification of emission reductions and removals (CCP 07)**

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[11] There are multiple approaches for additionality that, depending on the type of mitigation activity, can provide strong assurances without the need for an investment analysis.

The GHG emission reductions or removals from the mitigation activity shall be *robustly quantified*, based on *conservative approaches*, *completeness* and *sound scientific methods*.

9. No double counting (CCP 08)

The GHG emission reductions or removals from the mitigation activity *shall not be double counted*, i.e., they shall only be *counted once* towards achieving mitigation targets or goals. Double counting covers double issuance, double claiming, and double use.

10. Contribution to net zero transition (CCP 10)

The mitigation activity shall *avoid locking-in levels of GHG emissions, technologies or carbon-intensive practices* that are *incompatible* with the objective of achieving *net zero* GHG emissions by *mid-century*.

3

Point of creation of the CO_2 *Removal Certificate* (CORC)

3.1 The CO_2 *Removal Supplier*

3.1.1 The CO_2 *Removal Supplier* is the authorized party to represent the end-to-end supply chain of the activities associated with the *terrestrial storage of biomass* (TSB).

3.1.2 The CO_2 *Removal Supplier* is responsible for making end-to-end data available and accessible for 3rd party verification. This includes delivering data needed to assess the **eligibility** of the activities, quantify the predicted **net carbon removal**, and monitor the actual rate of decomposition, if any exists.

3.2 Point of creation

3.2.1 The *point of creation* of the CO_2 *Removal Certificate* (CORC) is when the *eligible biomass is enclosed within the storage chamber*. What a storage chamber exactly constitutes depends upon the design specifications of the individual project (see rule 4.3.2).

3.2.2 Proven **stable storage conditions** of a filled and completed chamber are a prerequisite for issuing CORCs. Evidence of the stability of such conditions needs to be provided by the supplier to a high degree of confidence. Additional data may be required by Puro.earth to evidence the stability of storage conditions. Issuance of CORCs may be delayed until such time that the stability of the storage conditions can be proven by the supplier.

4

Eligibility requirements and verification

4.1 Requirements for general eligibility and sustainability

4.1.1 An **eligible activity** is an activity where eligible biomass is sustainably sourced and subsequently stored in a terrestrial storage site under conditions that inhibit biomass decomposition, maintaining such conditions for at least 100 years.

4.1.2 **Eligible biomass** consists of *lignocellulosic biomass* (LCB) from plants mainly composed of polysaccharides (cellulose and hemicelluloses) and an aromatic polymer (lignin), forming a complex assembly of polymers naturally recalcitrant to enzymatic decomposition. In simple terms this constitutes trees and hard stemmed, lignin rich plants.[12] More specifically, the eligible biomass must possess the following properties:

- A **rigid physical structure** and **high lignin content** that make it very recalcitrant to microbial destruction such as, trees, bark, twigs, forestry residues, thinnings, chippings, sawdust, wood shavings, wood residues, or timber damaged by fires, storms or drought.[13]
- A **carbon to nitrogen ratio**[14] (C:N) higher than 80, unless the storage reliably excludes liquid water, such as under permanently frozen or dry (xeric) conditions, as availability of nitrogen encourages decomposition.

At this stage in this methodology's evolution, the definition of eligible biomass **excludes biomass from non-tree sources** such as algae, herbaceous plants and grasses.

4.1.3 The CO_2 *Removal Supplier* must provide proof of the eligibility of the biomass, excluding impurities from harvesting. This may take the form of a list of the **individual species**[15] of biomass being stored or other documentation that demonstrates the eligibility of the biomass in accordance with rule 4.1.2. This is important because different types of biomass may behave differently in terms of decomposition profiles through time.

4.1.4 The CO_2 *Removal Supplier* shall provide a **chemical analysis** of the biomass to be stored. This analysis must cover at least:

- A determination of the carbon to nitrogen ratio (**C:N**) of the stored biomass.

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[12] The use of entire such plants is permitted, as when all the above ground biomass of the plants are harvested for storage.

[13] In the case that the biomass has been impacted by disease or pests, care must be taken to make certain that these are not introduced to the biomass storage.

[14] The carbon to nitrogen ratio (C:N ratio) is a ratio of the mass of carbon to the mass of nitrogen in organic residue. A laboratory can measure the C:N ratio of a sample using devices such as a CHN analyzer.

[15] For unknown wood samples, examining the cellular structure of wood is one method of identifying tree species. Another method is to analyze the chemical composition of the wood using techniques such as mass spectrometry or infrared spectroscopy. These techniques can provide information about the chemical compounds present in the wood, which can help to identify the tree species.

- A determination of the **quantity** and **composition** of the major structural components of the biomass (*cellulose*, *hemicellulose* and *lignin*).

This analysis must be performed for a **statistically representative sample** of the entire stored biomass. In lieu of an experimental determination, values from peer-reviewed scientific literature can be utilized if available for the particular species of biomass being stored [64, 65].

4.1.5 The CO_2 *Removal Supplier* must demonstrate that the biomass is **sourced sustainably** in accordance with local regulations and other requirements detailed in this methodology (see rule 4.1.6) or the Puro Standard. Any land use right, environmental permits, as well as certification of operations, shall be part of the proof.

4.1.6 For the biomass to be considered **sustainably sourced**, for the carbon storage to be **additional** relative to the baseline, and for **economic leakage** to be adequately addressed, the following rules apply for the different categories of biomass sources described in subrules (a)–(e) below.

The biomass used in a given project can be a *mix of the below-listed categories*. However, evidence must be provided separately for each category of biomass used.

(a) If the biomass is sourced from **forest land** that is **managed** for production of materials or energy (managed forests):

- This *category includes* any biomass types arising from forestry operations such as trunks, stumps, branches, and tops. It also includes wood from thinning operations, fire prevention operations, as well as wood chips, wood shavings or sawdust from wood processing operations.
- Carbon storage *additionality* relative to baseline: biomass is left unharvested or disposed on forest land or nearby in conditions that do not guarantee secure long-term carbon storage. The baseline carbon storage is in that case set to 0.
- Economic leakage prevention:
  - The biomass cannot be merchantable wood, unless demonstrated by the project that there is a local oversupply of wood in the project area.
  - The biomass cannot be energy-grade wood, unless demonstrated by the project that there is a local oversupply of wood in the project area.
  - Local oversupply shall be demonstrated by demonstrating that the total quantity of biomass of this type annually available in the project region (defined as within a 250 km radius around the project activity) is at least 25 % larger than the quantity of biomass which is utilized annually (for storage by the project and other material and energy uses) in the project region.[16]
  - If local oversupply is demonstrated, emissions from economic leakage can be set to 0.

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[16] This definition of local oversupply is in line with the CDM tool for determination of economic leakage `https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-16-v5.0.pdf`

  - Certification of operations: forestry operations must possess a certification of sound socio-environmental practices (e.g. FSC, RSB, PEFC and similar).

  In summary, biomass in subrule (a) is eligible provided that i) forestry operations are certified, and ii) local oversupply of biomass is demonstrated.

(b) If the biomass is sourced from **forests that are not managed** for production of materials or energy (natural forests):

  - This category only includes wood salvaged as part of fire risk mitigation, or forest restoration works (e.g. replantation after fire or disease). On a given area of forest land, salvaged wood only represents a small fraction of the stock of biomass.
  - Carbon storage additionality relative to baseline: in the baseline, it is assumed that the biomass would remain in the forest, putting at risk a large carbon stock, although simultaneously contributing to forest carbon stocks. In this specific context, the baseline carbon storage is set to 0.
  - Economic leakage: in the context of salvage wood from natural forests, economic leakage is deemed not relevant and is set to 0.
  - Authorisation of operations: the collection of wood in a natural forest must be authorized by local authority, for the specific purpose of fire prevention or forest restoration.

  In summary, biomass in subrule (b) is eligible provided that an authorisation for collection of wood is granted by a local authority.

(c) If the biomass is **purpose-grown** on land that is **not forest land**:

  - This category only includes at this stage land that is cultivated as part of a land restoration activity. In particular, cultivation on marginal land or agricultural land with low productivity is permitted.
  - Carbon storage additionality relative to baseline: in the baseline, the land is assumed to be not productive or marginally productive (e.g. for food production). In that context, the baseline carbon storage is set to 0.
  - Economic leakage: economic leakage is deemed not relevant or marginal and is set to 0.
  - Authorisation of operations: the land restoration activity must be authorized by a local authority.

  In summary, biomass in subrule (c) is eligible provided that the land restoration activity is authorized by a local authority.

(d) If the biomass is a waste from industrial or post-consumer activities:

  - This category includes biomass waste such as wood from construction and demolition works, wood from urban landscaping, urban wood waste.

- The biomass waste must not be hazardous or have been chemically treated (e.g. this excludes wood of Class D from the UK PAS 111:2012 classification).[17]
- Carbon storage additionality relative to baseline: to determine eligibility, the historical baseline of the biomass must be known. Several cases are then distinguished:
    1. Biomass was sent to an anaerobic landfill meeting IPCC requirements with respect to long-term carbon storage from wood waste. The biomass does not contribute to additional carbon storage and is therefore not eligible in the general case. An exception is made if it is demonstrated that the designated local landfill has closed or has banned disposal of wood. The biomass is eligible only under that exception, and the baseline carbon storage is then set to 0.
    2. Biomass was sent to an aerobic landfill, dumped in field, stockpiled, or burnt without energy recovery. No long-term carbon storage is secured. The baseline carbon storage is set to 0.
    3. Biomass was sent to incineration with energy recovery, or used for any material use (e.g. mulch). No long-term carbon storage is secured. The baseline carbon storage is set to 0.
    4. Historical fate is unknown or cannot be determined with sufficient confidence. Then, the biomass is not eligible.
- Economic leakage: economic leakage is here dependent on the historical baseline identified above.
    1. Landfills may produce energy from landfill gas. However, wood waste contributes only marginally to this production. Leakage is deemed not relevant and is set to 0.
    2. The biomass is disposed of without any apparent valuable use. Leakage is deemed not relevant and is set to 0.
    3. The biomass was used either for energy or material use. Material and energy leakage are relevant and must be quantified conservatively in the life cycle assessment.

In summary, biomass in subrule (d) is eligible provided that i) the biomass is demonstrated to not be hazardous waste, ii) the historical fate of the waste is known and eligible as outlined above, and iii) whenever relevant, economic leakage is quantified.

(e) If the biomass is sourced from **land clearing** in construction projects:

- This category only includes at this stage wood from land clearing in construction projects.

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[17] UK PAS 111:2012 wood waste classification `https://wrap.org.uk/sites/default/files/2020-08/WRAP-PAS111.pdf`

- The land use change and related emissions are attributed to the construction project. The biomass arising from land clearing is technically classified as non-renewable.
- Carbon storage additionality relative to baseline: the baseline assumes that the construction project would take place in any case, and that the biomass is treated as a waste product similar to biomass of type D. Depending on the local context, it is likely that a fraction of the biomass is economical to use as material (e.g. timber, plywood) or energy, while another fraction is not suited for any use and can be either burnt or disposed of.
- Economic leakage prevention: only the fractions not suited or not economic to use as material and energy are eligible.
- Authorisation of operations: the construction project must have a valid construction permit that allows land clearing.

In summary, biomass in subrule (e) is eligible provided that i) the construction project has a valid permit, and ii) the economically usable fractions of the cleared biomass are not used for storage.

4.2 Requirements for the production facility audit

4.2.1 In this methodology, the **storage site** containing the biomass corresponds to the *Production facility* of CO_2 *Removal Certificates*, as per the terminology defined in the Puro Standard General Rules.

4.2.2 A *Production facility* and the associated *Activity* is determined as eligible for issuance of CO_2 *Removal Certificates*, once the *Production facility* has undergone a process of **third-party verification** by a duly appointed auditor performing a Production Facility Audit. The Production Facility Auditor verifies the *Production facility* conformity to the requirements for activities under this methodology, and the evidence required from the CO_2 *Removal Supplier*.

4.2.3 The **Production Facility Auditor** collects and checks the **standing data** of the CO_2 *Removal Supplier* and the *Production facility*. The standing data, in *digital format*, to be collected by the Auditor includes:

- A **certified trade registry extract** or similar official document stating that the CO_2 *Removal Supplier*'s *organization legitimately exists*.
- The CO_2 *Removal Supplier* registering the *Production facility* in the *Puro Registry*.
- **Locations** of the terrestrial storage sites forming the *Production facility*.
- A statement detailing whether the *Production facility* has benefited from **public financial support**.
- **Date** on which the *Production facility* becomes *eligible to issue* CORCs.

4.3 Requirements for storage site design

4.3.1 To be eligible, the **storage site** and **chamber/s** must create *conditions that inhibit biomass decomposition*. The control of these factors must be achieved by engineered design. More specifically, the storage site:

- May be made of **several storage chamber/s**, each storage chamber being uniquely identified and characterized (location, volume stored, measures implemented to inhibit and monitor potential decomposition, technical drawings of each storage chamber).
- Must be **specifically engineered** to inhibit the decomposition of biomass into greenhouse gases (CO_2 or CH_4).
- Must implement measures to **inhibit and monitor** potential decomposition of biomass.

4.3.2 The following general storage chamber designs are eligible under this methodology:

- **Above ground storage chambers**: purpose-built covered structures that are typically ventilated or otherwise constructed to maintain a low equilibrium relative humidity (dry storage), and shield stored biomass from UV radiation, pests, and other external factors promoting decomposition.
- **Below ground storage chambers**: purpose-built and covered storage pits that can be constructed to maintain either an anoxic environment or a dry, oxic environment, such as in above ground storage chambers.
- **Subterranean injection**: a hydraulically opened aperture below ground that is formed by the subterranean injection of a slurry containing wood or other eligible biomass. The storage chamber is formed by the injection process itself and not otherwise pre-engineered (e.g. lined or ventilated). The storage occurs in an anoxic environment, and the chamber does not require active maintenance. In this methodology, the *minimum eligible injection depth* is **3 meters**.

In this methodology, the terms *dry storage* and *dry conditions* mean that the equilibrium relative humidity in the storage chamber is **below** 71 % (i.e. the water activity is below 0.71).

4.3.3 The CO_2 *Removal Supplier shall consider* the effect of the following **general design principles** during the design and construction of any storage chamber:

- The *absence of light* in the storage chambers.
- *Absence of biomass disturbance* over 100 years by e.g. mixing or agitation of the contained biomass.
- *Temperature, gas and moisture monitoring and control*, to detect any potential decomposition or change of conditions.
- *Consistent* chamber moisture conditions.
- Limiting any external risk factors such as insect incursion or structural damage (see section 7).

Note that the exhaustive *implementation* of all the above-mentioned criteria is not required as long as durable storage conditions are ensured (see also rules 4.3.1, 4.3.2

and 4.3.4. However, they serve as an important and useful list of key considerations when conceptualizing the design of storage chamber/s and sites.

4.3.4 In storage system designs where fire can occur in the stored biomass (including but not limited to dry ventilated storage conditions), the CO_2 *Removal Supplier* must implement measures to limit the **risk of fire** and management of any occurrence with appropriate detection and suppression systems.

4.3.5 In addition to the general design principles listed in rule 4.3.3, the CO_2 *Removal Supplier shall consider* the effect of the following **conditions** in the context of the selected storage design:

(a) For a storage chamber where **sufficient moisture** is present to affect biological decay (i.e., the water activity is 0.71 or higher), the following important factors must be considered:

- **Physical separation** of the stored biomass from the atmosphere to maintain anoxic conditions utilizing either 2 meters or more of fine grain well-compacted soil or polymer barriers with comparably low gas permeability whose integrity is ensured for a 100 year horizon.
- Very **low oxygen** levels in the storage chambers.[18]
- **Hydraulic conductivity** at the boundaries of the chamber which have been designed and demonstrated to restrict ground water flow into and out of the chamber.
- Utilization of a **microbial methane oxidation system** to reduce emissions [51]. In simple terms, this consists of a **methane oxidation layer**, i.e. a soil cover layer composed of gas permeable, bioactive materials (such as coarse soil or compost), underlain by a **gas distribution layer** of e.g. gravel to ensure even distribution of gases from the biomass to the oxidation layer, where bacteria will oxidize methane into carbon dioxide and water.

(b) For a storage chamber designed to maintain **dry conditions** (water activity below 0.71) that eliminate decomposition, the following important factors must be considered:

- **Physical integrity** of the storage chamber (e.g., absence of water leaks).
- **Drying biomass** below the moisture content at which any form of *microbial decomposition* can take place (including, but not limited to methanogenesis) and maintaining dry conditions over time.

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[18] The oxygen levels in storage environments are determined by the isolation from oxygen entry in combination with consumption chemistry for the infinitesimal oxygen levels that exist in storage. Thus "anoxic" functionally means that no oxygen is available to react but the anoxic threshold can be reached at different (very low) oxygen levels depending on how low the chamber specific chemistry drives the equilibrium oxygen level.

4.4 Requirements for storage site monitoring

4.4.1 The CO_2 *Removal Supplier* must prepare a **monitoring plan** for the stored biomass. The monitoring plan must specify and detail the measures in place to ascertain that consistent storage conditions are being maintained through time. This includes but is not limited to detailing the experimental determination of the storage conditions.

4.4.2 The CO_2 *Removal Supplier* must detail and implement a **systematized approach** for **timely detection of compromised storage conditions**. This includes an approach for detection and, where relevant, **oxidation** of any significant methane emissions to the atmosphere (see also rules 4.3.5 and 4.4.3).

4.4.3 **All storage sites** must be equipped to **monitor** and **quantify** the release of greenhouse gases (CO_2 or CH_4). The precise instrumentation specifications for greenhouse gas monitoring can be chosen by the CO_2 *Removal Supplier*. However, any monitoring approach must fulfill at least the following requirements:

- The CO_2 *Removal Supplier* must be able to experimentally measure the concentration of greenhouse gases released from the storage chambers to the atmosphere.
- The instrument(s) utilized to monitor methane release must be **accurate** and **precise enough to reliably quantify CH_4 concentrations** of at least 2 ppmv (parts per million by volume).[19]

The CO_2 *Removal Supplier* must periodically perform these measurements, in line with the monitoring plan (see rule 4.4.1), to ensure that proper storage conditions are being maintained over time. Continuous (on-line) measurements are not required.

4.4.4 **Storage chambers designed to maintain dry conditions** (water activity below 0.71) to eliminate decomposition must be equipped to:

- Monitor relative humidity and temperature.
- Remove excess moisture from the chamber (e.g. by using forced air) to restore acceptable storage conditions in the event that water activity exceeds the threshold of 0.71 for decomposition.
- Detect and suppress fire, if oxygen is present in the storage chamber (i.e. the chamber is not anoxic). Furthermore, the CO_2 *Removal Supplier* shall create and periodically update a systematic plan for fire risk management and prevention. See also rule 4.3.4.

4.4.5 **Storage chambers** created by **subterranean injection** (see rule 4.3.2) must be equipped to enable the monitoring of GHGs by a soil vapor probe or a vapor accumulation pipe in communication with injected biomass. Alternatively, monitoring of surface emissions through flux measurements using a static chamber, or a methane survey[20] can be utilized. Monitoring must continue at least until conditions in the chamber have stabilized as demonstrated by methane levels equivalent to background soil. Additionally, the CO_2 *Removal Supplier* must periodically perform these measurements, in

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[19] For example, this can be achieved by laser spectroscopy (e.g. cavity ringdown spectroscopy or off-axis integrated cavity output spectroscopy) or (micro) gas chromatography. A low limit of quantification is required due to the expected slow rate of decomposition.

[20] A methane survey refers to the utilization of grid sampling of soil methane emissions (by means of e.g. a portable gas probe) above the subterranean storage chamber to produce a statistically representative geographical distribution of soil methane emissions.

line with the monitoring plan (see rule 4.4.1), to ensure that proper storage conditions are being maintained over time.

4.5 Requirements for property management and liabilities

4.5.1 The CO_2 *Removal Supplier* shall present either the **property title** and proof of ownership, or the **right or authorisation** to use the land as a storage site, such as a lease or other agreement between the landowner and the CO_2 *Removal Supplier*.[21]

4.5.2 The CO_2 *Removal Supplier* shall present proof of the **right or authorisation to harvest or collect the biomass** stored according to this methodology. In instances where the biomass is sourced from a third-party, the CO_2 *Removal Supplier* shall present proof of purchase or a recorded change of ownership if no payment is made.

4.5.3 The CO_2 *Removal Supplier* must present relevant legal documentation such as an **easement** which ensures the associated land use for 100 years and guard against risk of a potential new owner not maintaining such conditions.

This requirement *does not apply* to storage techniques based on *subterranean injection* at depths in excess of 3 meters (see rule 4.3.2) because the disturbance of the storage is not possible in any reasonably foreseeable circumstance. In particular, the presence of injection-based storage chamber(s) does not exclude the utilization of the land area above the chamber(s) for most purposes such as construction of buildings, re-vegetation or recreation facilities which will not compromise the integrity of the storage chamber(s).

4.5.4 The CO_2 *Removal Supplier* is **liable for any greenhouse gas emissions** from the stored biomass during the lifetime of the project, or at least for 100 years in total from the point when CORCs are issued.

4.5.5 The CO_2 *Removal Supplier* shall demonstrate the creation of a binding **contractual framework** securing the storage site against any unexpected re-emissions,[22] and enabling storage chamber maintenance to comply with applicable regulatory requirements and standard-based carbon confinement for at least 100 years. Examples of *eligible contractual frameworks* include:

- A **trust fund** or similar under the laws of the host country.
- An **insurance policy** securing the CORCs against the damage of unexpected re-emissions.
- **Contracts** between the CO_2 *Removal Supplier* and the buyer of CORCs.

The contractual framework must demonstrate that in cases of unexpected re-emissions *sufficient commercial arrangements and funds* are available for at least:

- The **determination** and **quantification** of the extent of biomass loss and the associated climate impact.
- **Repair** of any compromised storage chambers without delay to prevent

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[21] For subterranean injection this could be a signed contract with the property owner describing the sequestration process to be undertaken and the terms of post closure monitoring for greenhouse gas re-emissions that the property owner must acknowledge and consent to allow.

[22] In this rule, *unexpected re-emissions* refer to any re-emissions of greenhouse gases from the storage site that have not been accounted for in any previous issuance of CORCs.

biomass loss and to ensure restoration of effective and durable storage conditions.

- Long term storage site **monitoring** and **management** (including potential remediation).
- **Compensation** for involved stakeholders suffering financial damages.

Furthermore, the contractual framework must be formulated in such a way that the aforementioned requirements can be **fulfilled even in cases where**:

- The CO_2 *Removal Supplier ceases to exist as a legal entity*.
- The *ownership of the storage site and/or the stored biomass is transferred* to a third party.
- The storage site is *destroyed or decommissioned*.

4.5.6 The CO_2 *Removal Supplier* shall provide a detailed written estimate, in current prices, of the funding required for the purposes detailed in rule 4.5.5. The estimate shall be based upon the nature of the contractual framework employed.

4.6 Requirements for additionality

4.6.1 The CO_2 *Removal Supplier* shall be able to demonstrate **additionality**,[23] meaning that the *greenhouse gas* (GHG) emission reductions or removals from the mitigation activity shall be additional, i.e., they would not have occurred in the absence of the incentive created by carbon credit revenues.

4.6.2 To demonstrate additionality, the CO_2 *Removal Supplier* must show that the project is **not required by existing laws**, regulations, or other binding obligations.

4.6.3 To demonstrate additionality, the CO_2 *Removal Supplier* must provide full project financials and **counter-factual** analysis based on baselines that shall be project-specific, conservative and periodically updated.

4.7 Requirements for prevention of double-counting

4.7.1 The CO_2 *Removal Supplier* shall ensure that the CO_2 removals from the terrestrial storage of biomass shall not be **double-counted** nor **double-claimed**. The carbon removal credit must solely be registered in Puro.earth's carbon removal registry. The upstream and downstream commercial relationships between the supply-chain partners shall prevent double-counting and double-claiming of the carbon removal.

4.7.2 To demonstrate no double-counting, the CO_2 *Removal Supplier* must evidence with documents that the **biomass suppliers** are prevented from making claims to include the carbon net-negativity, carbon removal, carbon drawdown or carbon sequestration performed by the CO_2 *Removal Supplier*.

4.7.3 To demonstrate no double-counting, the CO_2 *Removal Supplier* must also evidence with documents that the **land-owners** or **land-users** receiving the biomass material beneath their soil are prevented from making claims to include the carbon net-negativity, carbon removal, carbon drawdown or carbon sequestration performed by the removal supplier.

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[23] Removals are **additional** if they would not have occurred without carbon finance. Developers must measure the removals claimed against a baseline which should represent a conservative scenario for what would likely have happened without carbon finance (the "counterfactual").

4.7.4 The resulting carbon removal shall **not be used in marketing** of any products arising as a part of the supply-chain (e.g. forestry products). However, supply-chain partners can **claim their affiliation** to the removal activity, in coordination with the CO_2 *Removal Supplier*. A signed commitment from counter-parties that they will not make unpermitted claims may be required depending upon the individual circumstances.

4.8 Requirements for environmental safeguards

4.8.1 The CO_2 *Removal Supplier* is responsible for following any existing regulation in general and especially any **environmental regulation** in the jurisdiction where the harvesting and storage of the biomass takes place.

4.8.2 The CO_2 *Removal Supplier* must demonstrate that the activities related to the storage of biomass pose no significant threat to the surrounding natural environment. This is done by assessing the **environmental risks** associated with the project. For example, the assessment can include:

- *Environmental impact assessment* (EIA).
- *Environmental risk assessment* (ERA).
- Environmental **permits**.
- Other documentation on the analysis and management of the environmental impacts.

4.8.3 The CO_2 *Removal Supplier* is the entity responsible for assessing the **environmental risks** associated with the project, and **implementing the measures** to effectively manage these risks.

4.8.4 The assessment of **environmental impacts** such as an *environmental risk assessment* (ERA) or *environmental impact assessment* (EIA) shall be completed before biomass is harvested or sourced, and before any significant ground works are implemented to establish the storage site.

4.8.5 The assessment of **environmental impacts** shall focus on the prevention of environmental risks and must consider all relevant risks, including but not necessarily limited to the risks associated with:

- *Sourcing* of the biomass (considering the potentially contained toxins in any material and any potential biosecurity risks such as spread of pest, disease or foreign species).
- *Transport or harvesting* of the biomass.
- The activity relating to *creating the storage chamber/s*.
- *Site selection* for storage.
- *Design* of the storage chamber/s.
- Long term *monitoring* of consistent chamber conditions.

4.8.6 The assessment of environmental impacts shall be **conservative** and **precautionary** in its assumptions and calculations.

4.8.7 The assessment of environmental impacts shall be **reviewed** by an **independent third-party**, with relevant expertise.

4.8.8 The **assessment** of **environmental impacts** and its supporting evidence shall be submitted to Puro.earth for internal screening.

4.8.9 The CO_2 *Removal Supplier* shall make information about the environmental risks associated with the project available to all involved stakeholders (e.g. local community, land owner, local municipality, investors, credit buyers).

4.9 Requirements for social safeguards

4.9.1 The CO_2 *Removal Supplier* shall be able to demonstrate the impact on communities of the terrestrial storage activity. Where applicable, documented information on the effects on local communities, indigenous people, land tenure, local employment, food production, user safety, cultural and religious sites, *inter alia* shall be provided.

4.9.2 To demonstrate **local stakeholder consultation**, the CO_2 *Removal Supplier* shall provide documented evidence on how they informed and acquired consent from local communities and other affected stakeholders. The documented information shall detail the procedures for continued dialogue with the local community over the entire operational time of the storage site. The CO_2 *Removal Supplier* shall demonstrate with documents the policy and procedures in place to address potential grievances.

4.9.3 The CO_2 *Removal Supplier* is able to present measures taken for **occupational health** and **safety** hazards management and mitigation during its operations. The activities (e.g. biomass transport, biomass chipping, biomass and soil handling) shall be performed in accordance with local regulations (e.g. noise limits, dust emission limits, occupational health and safety).

5

Assessment of life cycle greenhouse gas emissions

5.1 Generic life cycle assessment requirements

5.1.1 The CO_2 *Removal Supplier* must conduct a *life cycle assessment* (LCA) for the terrestrial storage activity. The LCA must follow the general principles defined in ISO 14040/44 and the scope defined in sections 5 and 6 of this methodology.

5.1.2 The LCA must include a report, which explains and justifies the **data and modeling choices** made, as well as supporting calculation files, which will be used for calculation of CORCs.

5.1.3 The LCA must quantify the **climate change impact of the activity**, using 100-year global warming potentials (GWP_{100}). Environmental impact categories other than climate change may be included but are not required.

5.1.4 For transparency and interpretability, the climate change impact calculated in the LCA **must be presented in a disaggregated** way exhibiting the contribution of the different life cycle stages described in figure 4, as well as the contribution of major greenhouse gases (i.e. providing the total in CO_2e but also the contributions of CO_2-fossil, CH_4, N_2O, and other greenhouse gases to this total climate impact).

5.1.5 In the event that **waste, recycled or secondary resources** are used as input to the activity (e.g. recycled steel or plastic), it is permissible and recommended to apply in the LCA the cut-approach[24] for waste, recycled and secondary products. Specifically, the environmental burdens from production of e.g. secondary resources can be excluded from the **system boundary**, but the supply, transformation and handling of the secondary resources must be included.

5.1.6 In the event that **by-products** are generated during the activity and that these by-products have a useful use outside of the process boundaries, then an allocation of the relevant life cycle stages between the co-products may be applied. Determination of an appropriate allocation rule shall follow principles from ISO 14040/44.

5.2 Specific life cycle assessment requirements

5.2.1 The **functional unit** of the LCA shall be “the sourcing and storage of 1 dry metric tonne of biomass in a specific terrestrial storage site”. Results of the LCA are expressed per dry metric tonne of biomass put in terrestrial storage.

5.2.2 The **activity boundaries** that must be included in the LCA to represent terrestrial storage of biomass are defined in figure 4, from establishment of a terrestrial storage site up to its decommissioning and rehabilitation.

5.2.3 Each stage included in the **activity boundaries** represents a complete life cycle, for which the full scope of emissions must be included. A full scope of emissions im-

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[24] Description of the cut-off system model is available on the website of the ecoinvent life cycle database: `https://ecoinvent.org/the-ecoinvent-database/system-models/#!/allocation-cut-of`

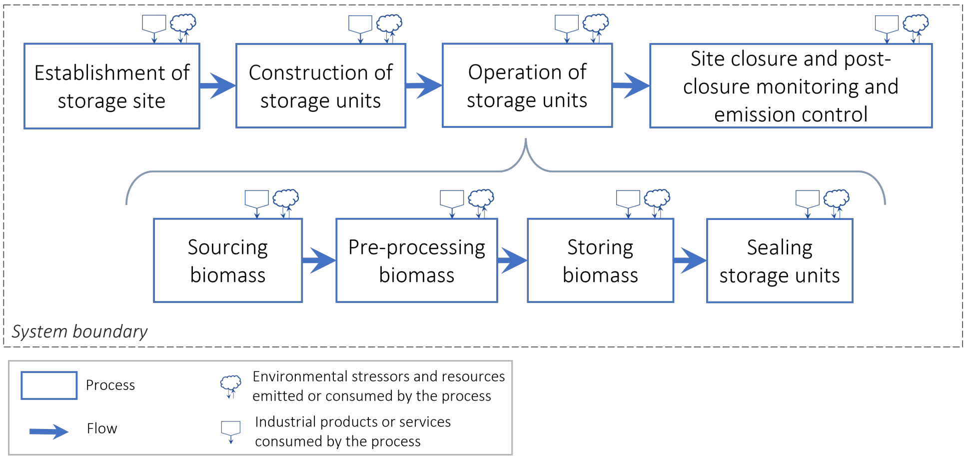

Figure 4: Process boundaries for the *life cycle assessment* (LCA)

ply that infrastructure requirements, material and energy consumption, as well as treatment of waste materials must be included. The *stages* are briefly described below:

- **Establishment** of **storage** site refers to all operations required for establishing the terrestrial storage site where biomass will be added. This includes construction works e.g. terrassing, fencing, buildings, soil disturbance (land clearing and associated land use change emissions, see rule 5.2.6). This stage terminates with an *established storage site*.
- **Construction** of **storage chambers** refers to all operations required for building the individual storage chambers (or cells) in which biomass will be stored. This includes e.g. excavation, lining, installation of monitoring equipment. This stage terminates with *built storage chambers*.
- **Operation** of **storage chambers** refers to all the activities taking place during the sourcing of biomass and the filling of the storage chambers. These can be split further into the following sub-stages:
  - *Sourcing of biomass*: refers to the production and supply of biomass, including e.g. cultivation of biomass, harvesting of biomass, transport, leakage and land use change (see rule 5.2.7). This stage terminates with *biomass supplied to the storage site*.
  - *Pre-processing of biomass*: refers to any handling operations of the biomass, including e.g. conveying, storage, drying, chipping, mixing with additives, baling. This stage terminates with *biomass prepared for storage*.
  - *Storing of biomass*: refers to the actual placement of the prepared biomass in the storage chambers, including e.g. use of machinery for handling and compaction of the biomass, use of materials as intermediary layers in the storage cells. This stage terminates with *biomass in storage*.
  - *Sealing of storage chambers* refers to activities performed to close a given storage chamber, e.g. via the installation of a final cap. This stage terminates with *sealed storage chambers*.
- **Site closure**, **post-closure monitoring** and **emission control** refers to all

activities required for closing the storage site, such as rehabilitation of its land cover and other construction, as well as post-closure monitoring activities over the required time period of monitoring. Further details on monitoring requirements are presented in section 4.4.

5.2.4 The **spatial boundaries** of the LCA must be defined. This includes: the location of the storage site and the areas from which biomass is sourced.

5.2.5 The **time boundaries** of the LCA must be defined. This includes specifying the timing of the establishment of the storage site, the expected lifetime of the storage site, and the extent of the decommissioning, rehabilitation and subsequent monitoring phase of the site. Timing here refers to durations and dates, e.g. establishment of storage site in year 2023 (6 months of work), operation of site for 10 years, and post-closure monitoring of 25 years.

5.2.6 **Emissions** from *direct land use change* (dLUC) at the storage site must be considered and included in the LCA, as part of the emissions related to the *establishment of the storage site*. dLUC must be assessed relative to the land area remaining in its historical state, i.e prior to use as a terrestrial storage site of biomass. dLUC must include any loss of aboveground and belowground biogenic carbon stocks, relative to the historical state of the land. dLUC must also include any greenhouse emissions arising during the land conversion, e.g. emissions associated with land clearing by fire may include significant amounts of methane (CH_4) and dinitrogen monoxide (N_2O).

5.2.7 **Economic leakage**: indirect increase in emissions or decrease in carbon stocks related to changes in the historical fate of the biomass or the land on which biomass is produced must be considered and included in the LCA, as part of the emissions related to *sourcing of the biomass*:

- In the case of *purpose-grown biomass*, whether on forest or agricultural land, the historical fate or use of the land must be known. Economic leakage must be quantified relative to this historical baseline. This typically includes direct land use change (i.e. any loss of aboveground and belowground biogenic carbon stocks, and any greenhouse emissions arising during the land conversion) as well as replacements for crops and products no longer-produced, if any.
- In all *other cases*, the historical fate or use of the biomass feedstock must be known with a reasonable estimate. Economic leakage must be quantified relative to this historical baseline. This typically includes biomass previously used for bioenergy services, requiring a replacement by another energy source.
- Note that so-called "reversed" or "positive" leakage, i.e. whenever the reallocation of biomass or land resources leads to avoided emissions or gains in biogenic carbon stocks, are not included in the calculation of CORCs as CORCs solely focus on certifying removals with a given durability. Such avoided emissions however constitute co-benefits worth pursuing.

6

Calculation methodology for the quantification of CO_2 *Removal Certificates* (CORCs)

6.1 General principles

In general, a CORC represents **net 1 tonne CO_2e** removed from the atmosphere. In the specific case of terrestrial storage of biomass, the CO_2 removal results from the interruption of a short-term carbon cycle by preventing biomass decomposition through *engineered storage techniques*.

The overall principle of the CORC calculation is that the CO_2 *Removal Supplier* first determines the **gross** amount (in metric tonnes) of carbon sequestered in the biomass that has been stored over a given reporting period. Various deductions are then made such as supply chain **emissions** and potential GHG *re-emissions*. The resulting **net amount** of **carbon sequestered** is converted to CO_2 equivalents and credited as CORCs. More details on the method of calculation are given in this section.

6.2 Requirements for robust quantification of carbon removal and net-negativity

6.2.1 The length of the **reporting period** can be decided by the CO_2 *Removal Supplier*, but shall not exceed **one (1) year**.

6.2.2 The CO_2 *Removal Supplier* must be capable of **metering**, **quantifying**, and **keeping records** of the parameters needed to quantify the CO_2 removal. This includes, but is not limited to, the quantity and composition of the biomass used, the direct use of energy and fuels, and other greenhouse gas emissions from the process.

6.2.3 The CO_2 *Removal Supplier* must follow robust and auditable measurement practices and protocols for the **data** needed for the calculation of the quantity of CORCs resulting from biomass storage.

6.2.4 The CO_2 *Removal Supplier* must provide a *life cycle assessment* (LCA) quantifying the greenhouse gas emissions related to the terrestrial storage activity, as per the scope and system boundaries defined in section 5, and following the general LCA guidelines described in ISO 14040/44.

6.2.5 The CO_2 *Removal Supplier* must **calculate** the amount of sequestered carbon in the form of CO_2 *Removal Certificates* (CORCs) for each reporting period, as per the requirements detailed in section 6.

6.2.6 In cases where the storage chamber water activity is 0.71 or higher (i.e. **dry conditions** are **not maintained**), the CO_2 *Removal Supplier* must present an analysis of a stress test where the CORCs have been calculated according to the requirements of rule 6.2.5, but utilizing the 20-year global warming potential of methane ($GWP_{CH_4,20} = 81.2$) instead of the default $GWP_{CH_4,100} = 27.9$ value mentioned in rule 6.5.3.

In the event that the **stress test** results in a negative value for CORCs, the CO_2 removal activity is **not eligible** due to introducing a new methane source, having the potential to increase the rate of global warming in the short term.

Note that this requirement *does not apply to cases where dry storage conditions (water activity below 0.71) are maintained*, as in such cases methane generation is likely insignificant for the purposes of the stress test.

6.2.7 The CO_2 *Removal Supplier* must have an **information system** in place to keep records of the construction of storage chambers, the filling of storage chambers, and sealing of the storage chambers, with eligible biomass. These records must include time stamped events, quantitative information, as well as photographic records. These records must be available to the auditor, for the Production Facility Audit and Output Audits.

6.2.8 The CO_2 *Removal Supplier* must ensure that any **instrumentation** used for data collection is in place and adequately calibrated at all times. The data records shall be kept in a **reliable data system**.

6.3 Overall equation

The **overall equation** to calculate the number of CORCs is illustrated in figure 5. It includes three variables:

- E_{stored} describes the **gross** amount of CO_2 sequestered by the biomass over a 100 year time horizon. Guidelines for calculation of E_{stored} are given in section 6.4.
- $E_{\text{supply chain}}$ describes the life cycle greenhouse gas emissions arising from the entire supply chain of the biomass storage activity, as defined by the LCA process boundaries (see figure 4). Guidelines for the calculation of $E_{\text{supplychain}}$ are given in section 6.6.
- $E_{\text{re-emission}}$ describes the amount of greenhouse gases **re-emitted** during storage, if any. Guidelines for the calculation of $E_{\text{re-emission}}$ are given in section 6.5.

$$\underbrace{\text{CORCs}} = \underbrace{E_{\text{stored}}} - \underbrace{E_{\text{supply chain}}} - \underbrace{E_{\text{re-emission}}}$$

Description	Amount of net CO_2e removed by the terrestrial storage of biomass over the reporting period	Gross amount of CO_2 sequestered in the stored biomass by the project over the reporting period	Life cycle emissions arising from the whole supply chain of the terrestrial storage activity	Amount of greenhouse gases re-emitted during storage, if any
Units	Tonnes of CO_2e	Tonnes of CO_2	Tonnes of CO_2e	Tonnes of CO_2e

Figure 5: CORC calculation equation

6.4 Determining carbon stored (E_{stored})

6.4.1 For each reporting period, the gross amount of CO_2 sequestered in the stored biomass (E_{stored}) is calculated as follows (for a numerical example, see section 6.5).

$$E_{\text{stored}} = M \times DM \times C_{\text{org}} \times \frac{44}{12} \quad (1)$$

Where:

- M is the **total mass** of the biomass placed in storage over the reporting period (in metric tonnes, based on the wet weight).
- DM is the **dry matter** content of the biomass placed in storage over the reporting period (in percentage of the wet weight). See rule 6.4.3.
- C_{org} is the **organic carbon content**, in percentage of the dry weight, of the biomass placed in storage (48 % by default, see rule 6.4.4).
- $\frac{44}{12}$ is the **mass conversion factor** from elemental carbon to a corresponding amount of carbon dioxide, calculated as the ratio between the molar masses of carbon dioxide and carbon (unitless).

6.4.2 The **mass of biomass** placed in storage must be measured and accounted for. This can be determined via direct on-site measurements with reliable and calibrated weight measurement equipment, such as load cells or weighbridges. The total mass of the biomass placed in storage in the reporting period must be known.

6.4.3 The **dry matter content** (DM) of the biomass must be determined via direct on-site measurements.[25] Reliable and calibrated moisture measurement equipment must be used. The sample used to determine the dry matter content must be representative of the actual composition of the biomass deposited in the storage chamber. This includes, but is not limited to, cases where several types of biomass are deposited in the same storage chamber.

6.4.4 The default value for the **organic carbon content** (C_{org}) of the biomass is set to be 48 %. The carbon content of any biomass is in a very narrow range (48–50 %) and woody plants even more narrow. For variations and determinants of carbon content in plants, see [6] for a global synthesis. Alternatively, the CO_2 *Removal Supplier* may utilize an experimentally determined value for C_{org} provided that its value is determined from a statistically representative sample of the stored biomass, and the analysis performed in a suitably accredited laboratory.

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[25] For example, there are handheld devices that can be used to measure moisture content. Pin-type moisture meters have two pins that are used to penetrate the test surface and measure the moisture content at the depth of the head of the contact pins. These meters use the principle of electrical resistance to measure moisture content by measuring the conductivity between the pins.

6.5 Re-emissions ($E_{\text{re-emission}}$)

Carbon lost due to decomposition over time can be re-emitted as **carbon dioxide** or **methane**. In anaerobic processes methane and carbon dioxide are re-emitted to the atmosphere in equal parts unless methane is e.g. trapped in the storage unit or oxidized in the soil column.

6.5.1 For each reporting period, the amount of CO_2 equivalents **re-emitted** from the stored biomass ($E_{\text{re-emission}}$) is calculated as follows.

$$E_{\text{re-emission}} = E_{CO_2} + E_{CH_4} \tag{2}$$

Where:

- E_{CO_2} describes the amount of CO_2 re-emitted from the stored biomass. The calculation of E_{CO_2} is defined in rule 6.5.2.
- E_{CH_4} describes the CO_2 equivalent amount re-emitted as methane from the stored biomass. The calculation of E_{CH_4} is defined in rule 6.5.3.

6.5.2 The amount of CO_2 **re-emitted** from the stored biomass (E_{CO_2}) is calculated as follows.

$$E_{CO_2} = M \times DM \times C_{\text{org}} \times \frac{44}{12} \times \left(F_{CO_2} \times DOC_f + F_{CH_4} \times DOC_f \times O_x\right) \tag{3}$$

Where:

- M, DM, C_{org}, and $\frac{44}{12}$ are as defined in rule rule 6.4.1.
- $F_{CO_2} \times DOC_f$ describes the **fraction of stored carbon re-emitted as CO_2**, where:
  - F_{CO_2} is the **fraction** of re-emitted carbon lost as CO_2 (50 % by default, see rule 6.5.6).
  - DOC_f is the 100 year **re-emission factor** (8.8 % by default) for the terrestrial storage of biomass (see rules 6.5.4 and 6.5.7).
- $F_{CH_4} \times DOC_f \times O_x$ describes the **fraction** of **stored carbon initially re-emitted as CH_4, but oxidized** in the soil or cover above the storage site (see also rule 6.5.1), where:
  - F_{CH_4} is the **fraction** of **re-emitted** carbon lost as CH_4 (50 % by default, see rules 6.5.5 and 6.5.8).
  - O_x is the **oxidation factor**, or the percent of methane that is oxidized in the soil or cover above the storage site. The default value for the oxidation factor is conservatively set to 0 %, unless otherwise evidenced by the CO_2 *Removal Supplier* (see rules 6.5.9–6.5.11).

6.5.3 The CO_2 equivalent amount of re-emitted methane from the stored biomass (E_{CH_4}) is calculated as follows.

$$E_{CH_4} = M \times DM \times C_{\text{org}} \times \frac{16}{12} \times F_{CH_4} \times DOC_f \times GWP_{CH_4,100} \times (1 - O_x) \tag{4}$$

Where:

- M, DM, and C_{org} are as defined in rule rule 6.4.1.
- $\frac{16}{12}$ is the **mass conversion factor** from elemental carbon to a corresponding amount of methane, calculated as the ratio between the molar masses of methane and carbon (unitless).

- $F_{\mathrm{CH_4}}$, DOC_f and O_x are as defined in rule 6.5.2
- $GWP_{\mathrm{CH_4},100} = 27.9$ is the **100-year global warming potential of methane**

6.5.4 The **default value** for the 100-year re-emission factor DOC_f is set to 8.8 % (see also rule 6.5.7). This factor is obtained from the IPCC 2019 guidelines for less decomposable wastes e.g. wood, engineered wood products, or tree branches deposited in solid waste landfills.[26]

Note that as the value of the re-emission factor depends on the type of biomass used and its storage conditions, the value applied in this methodology is *likely to evolve as the evidence and science on terrestrial storage of biomass advances*.

6.5.5 The **default value** for $F_{\mathrm{CH_4}}$, the **fraction** of **re-emitted** carbon lost as CH_4, is set to 50 % (see also rule 6.5.8). This factor is obtained from the IPCC default value for the fraction of CH_4 in landfill gas.[27]

6.5.6 The sum of the parameters $F_{\mathrm{CO_2}}$ and $F_{\mathrm{CH_4}}$ (the fraction of re-emitted carbon lost as CO_2 and CH_4, respectively) utilized in this methodology must always equal 100 %, i.e. $F_{\mathrm{CO_2}} + F_{\mathrm{CH_4}} = 100\,\%$. More specifically, as consequences of this rule:

- The default value of $F_{\mathrm{CO_2}}$ is also equal to 50 %, due to the default value set for $F_{\mathrm{CH_4}}$ in rule 6.5.5
- Any change to $F_{\mathrm{CH_4}}$ that might occur as a result of applying rule 6.5.8 will automatically lead to a corresponding change in the value of $F_{\mathrm{CO_2}}$ to $F_{\mathrm{CO_2}} = 100\,\% - F_{\mathrm{CH_4}}$

6.5.7 In cases where a storage chamber is designed to maintain **dry conditions** (water activity below 0.71) that eliminate decomposition, the CO_2 *Removal Supplier* can present evidence for a project specific re-emission factor DOC_f to be adopted instead of the default value of 8.8 % defined in rule 6.5.4. The process for adopting a **project specific re-emission factor** shall be conducted according to the following guidelines:

- The **decision** to accept or reject the proposal for the utilization of a project specific re-emission factor DOC_f shall be made by **Puro.earth** in its sole discretion.
- Proposal for a new DOC_f value shall be based on applicable peer-reviewed scientific research, as well as field trials and/or laboratory testing. The **evidence** shall contain data sourced directly from the storage chambers over a period of at least **12 months**, as well as an estimation of the biomass decomposition for up to 100 years after storage.
- Proposal for a new DOC_f value can be submitted in a Production Facility Audit or Output Audit, accompanied by sufficient evidence.
- Should the utilization of a project specific DOC_f value be approved, it shall replace the default value in rule 6.5.4 (8.8 %) in all calculations.
- In the case that, during previous reporting periods, CORCs have already been issued utilizing a higher DOC_f value, the CO_2 *Removal Supplier* can request the retroactive issuance of additional CORCs to reflect the difference in the re-emission factor. However, the CO_2 *Removal Supplier* must present

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[26] See [4, p. 12], Table 3.0 Fraction of degradable organic carbon which decomposes (DOC_f) for different waste types.

[27] See [4, p. 14], section "FRACTION OF CH_4 GENERATED IN LANDFILL GAS (F)".

evidence to prove that the conditions justifying the adoption of the new DOC_f value had persisted for the entire duration of the reporting period(s) for which the retroactive issuance is claimed.

At present, the possibility to suggest a *project specific value* for the re-emission factor DOC_f is **limited to projects utilizing dry storage** due to the fact that the IPCC 2019 guidelines, referenced in rule 6.5.4 as the basis for the adoption of the default DOC_f value, are derived from studies of landfilled waste, where the storage conditions are poorly applicable to dry storage of biomass.

6.5.8 In cases where a storage chamber is designed to maintain aerobic and dry conditions (see below), the CO_2 *Removal Supplier* can present evidence for a project specific value for F_{CH_4} (the fraction of re-emitted carbon lost as CH_4) to be adopted instead of the default value $F_{CH_4} = 50\,\%$ defined in rule 6.5.5.

For this rule to be applicable, the design of the storage chamber must satisfy **both** of the following conditions:

- The storage chamber is designed to **maintain dry conditions** (water activity below 0.71) that eliminate decomposition.
- The storage chamber is equipped with a **ventilation system** or otherwise designed to maintain an oxic environment in the stored biomass that prevents anaerobic decomposition.

The process for adopting a project specific values for F_{CH_4} shall be conducted according to the following guidelines:

- The decision to accept or reject the proposal for the utilization of a project specific F_{CH_4} value shall be made by **Puro.earth** in its sole discretion.
- Proposal for a new F_{CH_4} value shall be based on *applicable peer-reviewed scientific research*, as well as *field trials* and/or *laboratory testing*. The **evidence** shall include data from GHG emissions monitoring in line with rule 4.4.3, sourced directly from the storage chambers over a period of at least **12 months**.
- Proposal for a new F_{CH_4} value can be submitted in a Production Facility Audit or Output Audit, accompanied by sufficient evidence.
- Should the utilization of a project specific F_{CH_4} value be approved, it shall replace the default value (50 %) defined in rule 6.5.5 in all calculations.
- Should the utilization of a project specific F_{CH_4} value be approved, the value of F_{CO_2} (the fraction of re-emitted carbon lost as CO_2) will be automatically changed to $F_{CO_2} = 100\,\% - F_{CH_4}$ (see rule 6.5.6).
- In the case that, during previous reporting periods, CORCs have already been issued utilizing a higher F_{CH_4} value, the CO_2 *Removal Supplier* can request the retroactive issuance of additional CORCs to reflect the difference in the F_{CH_4} value. However, the CO_2 *Removal Supplier* must present evidence to prove that the conditions justifying the adoption of the new F_{CH_4} value had persisted for the entire duration of the reporting period(s) for which the retroactive issuance is claimed.

At present, the possibility to suggest a project specific F_{CH_4} value **limited to projects utilizing aerobic dry storage** due to the fact that the IPCC 2019 guidelines, referenced in rule 6.5.5 as the basis for the adoption of the default F_{CH_4} value, are derived from studies of landfilled waste, where the storage conditions are poorly applicable to aerobic dry storage of biomass in which methane generation is very unlikely. This is due to the fact that (i) dry storage conditions inhibit microbial decomposition in general and, more importantly, (ii) methane producing microorganisms are very sensitive to the presence of oxygen and are not active in aerobic conditions.

6.5.9 The **default value** for the methane **oxidation factor** O_x (the percentage of methane that is oxidized in the soil or cover above the storage site) is set to be 0 % (see also rules 6.5.10 and 6.5.11). This default value is adopted due to the high variability in the efficiency of *methane oxidation* in different storage solutions.

6.5.10 The CO_2 *Removal Supplier* may utilize an oxidation factor O_x value from table 3, provided that the storage site meets the corresponding requirements.

In cases where the requirements of table 3 necessitate the determination of the methane flux, the CO_2 *Removal Supplier* must **present evidence** of its quantitative empirical determination using on-site measurements. The flux measurements must be performed using established scientific methods.[28]

This rule is **only applicable for below ground storage chambers** (see rule 4.3.2) without any such ventilation system that would enable methane to escape to the atmosphere without going through a soil cover layer.

6.5.11 The CO_2 *Removal Supplier* may, subject to approval from Puro.earth, utilize a **project specific value** for the oxidation factor O_x provided that its value is **empirically measured** at the storage site, utilizing a technique able to directly quantify the percentage of methane oxidized in the soil cover, such as the stable isotope method, see e.g. [50, 57]. The CO_2 *Removal Supplier* must present the **scientific evidence** for the determination of the oxidation factor to Puro.earth experts for review and approval.

This rule is **only applicable for below ground storage chambers** (see rule 4.3.2) without any such ventilation system that would enable methane to escape to the atmosphere without going through a soil cover layer.

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[28] For example, surface flux chambers are often utilized. Other potential methods include eddy covariance or stationary mass balance, see e.g. [56]

NUMERICAL EXAMPLE

A CO_2 *Removal Supplier* stores **20.000 metric tonnes** (wet weight) of wood waste over the course of one (1) reporting period. The dry matter content has been determined by on-site measurements to be 61 % of the wet weight, and a laboratory analysis shows that the organic carbon content of the biomass is 48 % of the dry weight. To estimate the re-emissions from the biomass during storage, the default re-emission factor $DOC_f = 8.8\,\%$ is used, as well as the default values $F_{CO_2} = F_{CH_4} = 50\,\%$ for the fraction of re-emitted carbon lost as CO_2 and CH_4. It has furthermore been evidenced by the supplier that 25 % of the re-emitted methane is oxidized in the soil cover above the storage chamber (i.e.$O_x = 25\,\%$)

Now:

$$M = 20\,000\,\text{t} \qquad DM = 61\,\% \qquad C_{org} = 48\,\% \qquad DOC_f = 8.8\,\%$$
$$F_{CO_2} = 50\,\% \qquad F_{CH_4} = 50\,\% \qquad O_x = 25\,\%$$

And therefore:

$$\begin{aligned}
E_{\text{stored}} &= 20\,000\,\text{t} \times 0.61 \times 0.48 \times \frac{44}{12} = \underline{21\,472\,\text{t}} \\
E_{CO_2} &= 20\,000\,\text{t} \times 0.61 \times 0.48 \times \frac{44}{12} \times (0.5 \times 0.088 + 0.5 \times 0.088 \times 0.25) \approx \underline{1181\,\text{t}} \\
E_{CH_4} &= 20\,000\,\text{t} \times 0.61 \times 0.48 \times \frac{16}{12} \times 0.5 \times 0.088 \times 27.9 \times (1 - 0.25) \approx \underline{7189\,\text{t}} \\
E_{\text{re-emissions}} &= E_{CO_2} + E_{CH_4} \approx \underline{8370\,\text{t}}
\end{aligned}$$

6.6 Supply-chain emissions over a reporting period ($E_{\text{supply chain}}$)

6.6.1 The term $E_{\text{supply chain}}$ must be derived from a life cycle assessment of the terrestrial storage activity, according to the system boundaries defined in section 5 of this methodology, excluding the emissions and removals already accounted for under $E_{\text{re-emissions}}$ and E_{stored}.

6.6.2 For each reporting period, the calculated supply-chain emissions must be updated with actual activity data, which has been measured and recorded. This includes e.g. transport distances, fuel, energy, material consumption.

> **REMARK:** The currently adopted approach to CO_2 sequestration and emissions was chosen to build confidence in the certification process among buyers and foster trust in the carbon market, not to prevent project developers from starting biomass storage projects. As in most carbon removal technologies, there is an evolving scientific competence in this area. This approach advocates for projects to collect performance data, which can lead to new scientific analysis of re-emissions factors for terrestrial storage of biomass. The purpose is to promote, not constrain, innovative action on climate change, and to develop durable and sustainable solutions to decrease the concentration of CO_2 in our atmosphere.

Table 3: Flux dependent methane oxidation rates in the soil, adapted from [66] and US EPA greenhouse gas reporting program (GHGRP).[a]

Condition	**Min CH_4 flux**[b] ($g/m^2/d$)	**Max CH_4 flux** ($g/m^2/d$)	O_x	**Requirement**
C1	–	–	0 %	For storage chambers that have a geomembrane (synthetic) cover or other non-soil barrier, and with less than 30 cm cover soil for the majority (> 50 %) of the storage chamber containing the biomass
C2	–	–	10 %	For storage chambers that do not meet the conditions in C1 and elect not to determine the methane flux
C3	–	–	10 %	For storage chambers that do not meet the conditions in C1 and do not have a soil cover of at least 60 cm for a majority (> 50 %) of the storage chamber containing the biomass
C4	0	10	35 %	For storage chambers that have a soil cover of at least 60 cm for a majority (> 50 %) of the landfill area containing the biomass and for which the methane flux rate is less than 10 $g/m^2/d$
C5	10	70	25 %	For storage chambers that have soil cover of at least 60 cm for a majority (> 50 %) of the landfill area containing the biomass and for which methane flux rate is 10–70 $g/m^2/d$
C6	70	–	10 %	For storage chambers that have soil cover of at least 60 cm for a majority (> 50 %) of the landfill area containing the biomass and for which methane flux rate is greater than 70 $g/m^2/d$

[a] United States Code of Federal Regulations, Title 40, Chapter I, Subchapter C, Part 98, Subpart HH, Table HH-4 `https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98/subpart-HH/appendix-Table%20HH-4%20to%20Subpart%20HH%20of%20Part%2098`

[b] Methane flux rate (in grams per square meter per day; $g/m^2/d$) is the mass flow rate of methane per unit area at the bottom of the surface soil prior to any oxidation.

7

Management of re-emission risks

7.1 Overview of risks and management options

Re-emission risks refers to the **loss** of **carbon storage** due to either human activities (e.g. deliberate destruction of carbon storage) or natural events (e.g. fires, storms, earthquakes). Re-emission risks **do not include** the expected re-emissions that are already accounted for in the calculation of CORCs for certain storage conditions.

These **risks** must be assessed and mitigation measures must be deployed. It is important to note that the *relevance of certain risks varies with the type of biomass storage*, and that **mitigation measures** must be implemented over the full liability period of the project, namely **100 years**.

In the context of *terrestrial storage of biomass* (TSB), the following **risks** have been identified:

- **Fire** at the storage site and/or in its surroundings: if fire reaches the stored biomass, large amounts of stored carbon can be re-emitted.
- **Structural damage** to storage units, due to:
    - natural events (e.g. earthquakes, floods, droughts): natural events can damage storage units and possibly lead to a breach in storage conditions that are meant to inhibit biomass decomposition.
    - human activity: humans having access to or passing by the storage sites can affect the physical structure of storage units, e.g. via digging, whether deliberately or not.
    - fauna and flora: animals in the surroundings of storage sites can do minor damage to storage units, possibly adversely affecting storage conditions. Likewise, plants allowed to grow on top of storage units can, with their roots, damage the storage units. Finally, pests and insects may reach stored biomass.
- Deliberate human **excavation** of stored biomass and use for other purposes: humans can decide to deliberately excavate the stored biomass for use as fuel.
- **Construction faults** or **design error**: unforeseen construction or design faults may lead to storage units underperforming, and leading to higher re-emissions than expected.
- **Equipment failure**: storage systems that require technical components to maintain storage conditions (e.g. solar-powered drying, mechanical venting systems) or to monitor the systems are exposed to equipment failure. If equipment is not replaced in a timely fashion, the storage can be put at risk.

7.2 Relevance of risks for different storage conditions

The risks identified above have different relevance for the different storage systems considered in this methodology. Table 4 provides a reasoning on what risks are relevant to consider for each type of storage.

Table 4: Relevance of different risks for the three storage types considered in the methodology.

Risk	**Above-ground** storage, in dry conditions	**Below-ground** storage, in anoxic, anaerobic, or dry conditions	**Subterranean injection**, in anoxic or anaerobic conditions
Fire	Should be considered[a]	Should be considered[b]	Not relevant[c]
Structural damage: Natural events	Should be considered	Should be considered	Not relevant
Structural damage: Flora and fauna	Should be considered	Should be considered	Not relevant
Structural damage: Human activity	Should be considered	Should be considered	Not relevant
Deliberate human excavation	Should be considered	Should be considered	Not relevant
Construction and design faults	Should be considered	Should be considered	Should be considered
Equipment failure	Should be considered	Should be considered	Not relevant

[a] Fire can propagate to biomass stored in above-ground structures, pits or containers, with access to air. However, stored biomass is unlikely to ignite.

[b] Fire is unlikely to propagate to biomass stored in below-ground structures, provided depth is sufficient. Heat might damage storage units.

[c] Fire is unlikely to propagate or damage subterranean injection sites.

The **identified risks** can however to a large extent be **prevented or mitigated** by adequate measures, resulting in **low** or very low risk of re-emission from these sources. First, some general key measures are presented. Then, measures specific to certain risks are presented in table 5.

The mitigation of the risks is performed both preventively before (**ex-ante**) the adverse event and after (**ex-post**) the adverse event. Preventive **risk mitigations** include:

- **Limiting eligible biomass** in this methodology to only allow inherently recalcitrant biomass with high carbon to nitrogen ratio.
- Storage sites must have a **modular design** with multiple separate storage units, compartmentalizing any potential impact in one or a limited number of cells. *This applies to above-ground and below-ground storage, but not to subterranean injection.*
- Storage units must be designed such that they are **accessible for maintenance and repair**, should the storage conditions be compromised. *This applies to above-ground and below-ground storage, but not to subterranean injection.*
- **Land title** for 100 + years with an appropriate easement.
- **Optimal site selection** with regards to hydrology, topology, geography to reduce risk of flood, earthquakes and other natural disasters.

- **Storage chamber design** and construction to control the conditions so that decay and re-emission does not occur.
- **Geographically dispersed** set of storage Production Facilities each with multiple separate storage chambers.
- A **monitoring plan** for early detection of compromised storage chambers.
- Pre-defined **maintenance** responsibilities and **corrective action plan**.

Table 5: Possible preventive and corrective measures to address the specific risks.

Risk	Preventive measures	Corrective measures
Fire	• Storage chamber design • Storage chamber separation from any likely fire source • Monitoring of fire activity and alert systems in place. • Fire risk mitigation training for staff. • On-site equipment to extinguish fire or intervention firefighters.	In case stored biomass was lost: • Quantify wood loss. • Activate compensation mechanism
Structural damage: Natural events	• Selection of site with adequate hydrology, topology, geography.	Repair the affected storage units.
Structural damage: Flora and fauna	• Design of storage units to minimize root penetration. • Continuous maintenance of any vegetation cover. • Fencing to prevent wildlife from entering storage sites, when relevant. • Design of storage units to minimize penetration of pests and insects, when relevant	Repair the affected storage units.
Structural damage: Human activity	• Obtain legal right to exclude prevent unauthorized access • Police access • Remote monitoring • Visible presence • Fencing to prevent humans from entering storage sites, when relevant.	Repair the affected storage units.

Continued on next page

Table 5: Possible preventive and corrective measures to address the specific risks. (Continued)

Risk	Preventive measures	Corrective measures
Deliberate human excavation	• Obtain legal right to exclude prevent unauthorized access • Police access • Remote monitoring • Visible presence • Fencing to prevent humans from entering storage sites, when relevant. • Monitoring • Land lease	Repair the affected storage units.
Construction and design faults	• Third-party inspection of constructed sites, to verify that works meet the declared specifications. • Active program to incorporate lessons from faults into future design and construction practice • Pre-defined maintenance and repair program and responsibilities.	Repair the affected storage units.

With the above preventive mitigations in place as appropriate the re-emission risks are very low to extremely low, with low consequence, slow impact, remediable and all limited by compartmentalization and geographic dispersal of chambers.

7.3 Illustrative risk matrix

Removal suppliers should conduct formal risk assessments for their entire businesses and their biomass storage approach in particular. Such an assessment should at least include:

1. An initial risk assessment covering both likelihood and consequences of each risk
2. A specification of the mitigations to be applied
3. A residual risk assessment

A standard approach is illustrated below in tables 6–8 notionally in connection with an above ground storage solution. The ratings provided are indicative only and will certainly be different for each location and each specific type of above ground storage. Mitigations are not included in the table as they have already been discussed above. Explanations are provided in separate tables of risk likelihood and consequence levels, and risk scoring.

Table 6: Illustrative risk matrix for an above ground storage solution[a]

Risk	Pre-mitigation risk assessment			Post mitigation risk assessment		
	Likelihood rating	Consequence rating	Risk assessment	Likelihood rating	Consequence rating	Residual risk
	A	B	C	D	E	F
			$A + B = C$			$D + E = F$
Fire	4	5	9	1	2	3
Structural damage: Natural events	3	4	7	2	1	3
Structural damage: Flora and fauna	1	2	3	1	1	2
Structural damage: Human activity	2	2	4	1	1	2
Deliberate human excavation	2	3	5	1	2	3
Construction and design faults	2	4	6	2	2	4

[a] The risk ratings are for illustrative purposes only.

Table 7: Likelihood level and description

Level	Likelihood	Description
1	Rare	Event may only occur in exceptional circumstances
2	Unlikely	Event could occur at some time
3	Possible	Event might possibly occur at some time
4	Likely	Event will probably occur in most circumstances
5	Almost certain	Event is expected to occur in most circumstances—regular occurrence

Table 8: Consequence level and description

Level	Likelihood	Description
1	Insignificant	Consequences dealt with by routine operations
2	Minimal	Efficiency or effectiveness of some aspects of the project threatened but can be dealt with acceptably
3	Moderate	Project could be subject to significant review or modification
4	Substantial	Continued delivery of the project is threatened
5	Severe	Viability of the project is threatened, financial loss is high

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