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Methodology: Carbon farming through short rotation forestry

Carbon farming through Paulownia trees, in order to increase the carbon sequestration capacity on former fallow, crop or pasture land.

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List of Definitions

Above Ground Biomass (AGB)	All living vegetative material above the soil including stem, stump, branches, bark, seeds, and foliage
Allometric equation	Mathematical models used to estimate a specific biological parameter (e.g., total tree biomass or volume) based on easily measurable variables (such as tree diameter at breast height or height). These equations are vital for accurately assessing biomass and carbon storage in Short rotation forestry projects.
Baseline Scenario	Hypothetical reference case that best represents the conditions most likely to occur in the absence of a proposed GHG project.
Below Ground Biomass (BGB)	It includes all living biomass of live roots. Fine roots of less than two mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Carbon Dioxide equivalent - CO_2e	A metric used to compare the emissions of various greenhouse gasses based on their Global Warming Potential (GWP). It expresses the impact of different gasses in terms of the equivalent amount of CO2, facilitating a standardized approach to assessing overall greenhouse gas emissions.
Carbon Fraction	The proportion of biomass that is composed of carbon. This value is critical in calculating the total carbon storage in tree biomass, as it allows for the translation of biomass weight into equivalent carbon content.
CDM	The Clean Development Mechanism, under the Kyoto Protocol, allows industrialized countries to invest in emission reduction projects in developing countries, contributing to sustainable development goals and emission targets
Conservativeness	Use of conservative assumptions, values, methodologies, and procedures to ensure that GHG emission reduction or removal enhancements are not over-estimated.
Diameter at Breast Height (DBH)	It is a standard method of expressing the diameter of the trunk of a standing tree. It is measured at a standardized height of 1.3 meters above ground level. DBH is often used in allometric equations and is crucial for determining the growth rate, timber volume, and carbon sequestration potential of trees in short rotation forestry projects.
Emission factors	Emission factors are coefficients that quantify the amount of greenhouse gasses released into the atmosphere per unit of activity, substance, or process. They are essential tools in calculating emissions based on fuel consumption, industrial processes, or agricultural practices, facilitating the estimation of a project's total greenhouse gas emissions.

FAO	The Food and Agriculture Organization is a UN agency leading international efforts to defeat hunger, improve agriculture, and ensure food security. FAO offers essential guidance and data on forestry through its publications, contributing significantly to global knowledge on sustainable forest management and conservation.
GHG project	Activity or activities that alter the conditions of a GHG Baseline and which cause GHG emission reductions or GHG removal enhancements. The intent of a GHG Project is to convert the GHG impact into Carbon Credits.
GHG protocol	GHG Protocol establishes comprehensive global standardized frameworks to measure and manage greenhouse gas (GHG) emissions from private and public sector operations, value chains and mitigation actions.
Harvest Cycle	The period between the planting and harvesting of trees in short rotation forestry. This cycle is characterized by the rapid growth and maturation of trees, culminating in their harvest for timber, biomass energy, or other uses.
IPCC	The Intergovernmental Panel on Climate Change is a United Nations body, assessing science related to climate change to provide policymakers with regular scientific updates.
Monitoring	The systematic observation and recording of parameters or conditions over time. In short rotation forestry projects, monitoring involves tracking tree growth, health, and other ecological factors to evaluate carbon sequestration effectiveness and overall forest health.
Specific Wood density	It is a measure of how much a certain volume of wood weighs, expressed in kilograms per cubic meter (kg/m^3). It reflects the compactness of the wood's structure, varying across different tree species and influenced by growth conditions. This density is crucial in forestry for assessing the timber quality and calculating the volume of wood material.
Sprouting	In the context of forestry, sprouting is often observed after a tree has been cut down or damaged, where new shoots grow from the stump or roots of the tree. This natural regeneration mechanism allows trees to recover from felling, ensuring survival and continued growth
Tree height	It refers to the vertical distance from the base of the tree (at ground level) to its highest point, typically the tip of the highest branch. It is a key variable in allometric equations to estimate tree biomass and volume.
Volume	In Short rotation forestry terms, volume refers to the total cubic space occupied by the tree biomass. It is a critical measure for estimating the amount of wood and biomass available in a forest stand, typically expressed in cubic meters.

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List of Abbreviations

AGB: Above Ground Biomass

BEF: Biomass Expansion Factor

BGB: Below Ground Biomass

DBH: Diameter at Breast Height

GHG: Greenhouse Gas/Gasses

SRF: Short Rotation Forestry

SSRs: Sources, Sinks, and Reservoirs

SHT: Stem Height of the Tree (without crown)

THT: Total Height of the Tree (including crown)

IPCC: Intergovernmental Panel of Climate Change

FAO: Food and Agriculture Organization of the United Nations

CDM: Carbon Development Mechanism

Summary

This methodology document serves as a comprehensive guide for evaluating the impact of short-rotation forestry using Paulownia trees on greenhouse gas (GHG) emissions, reductions, and removals, achieved through detailed measurements and calculations.

This document aims to offer clarity and coherence in understanding the process of establishing baseline carbon stocks and evaluating the role of Paulownia trees as a long-term carbon sink through the use of their wood in various applications. It is based on rigorous research, established methodologies, and standard values outlined in scientific literature and Climate Change and Carbon Management Frameworks' (IPCC, CDM, FAO, GHG protocol) reports, and databases. Each step is meticulously outlined, offering a clear path to measure, monitor, and quantify CO2 sequestration.

Through systematic data collection, assessment methodologies, and utilization considerations, this document aims to assist project developers in comprehensively evaluating the carbon sequestration potential of Paulownia tree plantations.

1. Introduction

1.1. Paulownia characteristics

Paulownia, known for its rapid growth and adaptability to various environmental conditions, is emerging as a significant species in biomass production and carbon sequestration efforts (Jakubowski, 2022). Recognized as one of the fastest-growing tree species globally, Paulownia's capacity for quick growth and high biomass yield make it ideal for short-rotation forestry (Yadav et al., 2013) . This characteristic is particularly valuable in the context of climate change, as it can sequester large amounts of atmospheric CO2 in both its above-ground and below-ground parts (Joshi, 2015). Native to China and found in diverse regions worldwide (Europe, the USA, and Australia), Paulownia exhibits traits such as resistance to rot, dimensional stability, and a high ignition point, enhancing its timber's market value (Jakubowski, 2022). Its versatility and the increasing demand for wood and wood-based materials position Paulownia as a vital resource for sustainable forestry and renewable energy sources. Some examples of Paulownia wood products are veneers, blockboards, engineered wood, plywood, furniture, kitchen items, and instruments (Jakubowski, 2022). Lastly, Paulownia's unique ability to regenerate through sprouting is a key component of this process. After each harvest, new shoots emerge from the stumps, utilizing the established root system to rapidly grow, thereby enabling continuous carbon absorption without the need for replanting. This cycle of growth, harvest, and regeneration allows for ongoing carbon sequestration, efficiently reducing atmospheric CO2 levels.

1.2. Applicability of methodology

This methodology applies to GHG projects that want to cultivate fast-growing Paulownia trees for their carbon sequestration abilities, capturing carbon in both their above-ground and below-ground (root systems) biomass. These Paulownia plantation projects can be regarded as a sequence of activities in which Paulownia based products will be monitored from cultivation until the fabrication of end products in terms of construction material.

A project can consist of multiple harvest cycles since the harvesting can be repeated multiple times as it is mentioned based on the physiology of Paulownia species. In accordance with the Proba Standards, this methodology applies exclusively to projects where harvested timber is utilized in construction, ensuring the sequestration of carbon for at least 40 years. It is necessary for project developers to establish a specific procedure or process that verifies the use of harvested timber as construction material, thereby securing the long-term storage of the carbon. Reductions in GHG emissions that are the result of using Paulownia timber instead of more conventional construction materials will not be included in this methodology.

The goal of this methodology document is to provide a well-founded calculation method for carbon sequestration in Paulownia trees that form the basis for issuing high-integrity carbon credits, which can help financing these carbon removal initiatives. Additionally this methodology document aims to increase the cooperation of parties like landowners, farmers, building material processors, area developers and construction companies.

Applicability of this methodology, in terms of geographical boundaries, is limited to the European Union.

The methodology is not applicable under the following conditions:

- Land use change to cultivating Paulownia involves deforestation
- Plantations meant to harvest biomass for biofuels, or wood pellets for the biomass energy generation
- Plantations occuring in protected areas (e.g. Natura 2000, National Parks)

This methodology document has been written in line with the Proba Standard[1],.

1.3. Co-benefits

This methodology doesn't prescribe any calculation methods for quantifying additional benefits resulting from Paulownia plantation projects. Proba expects that every Paulownia plantation projects contribute to at least one or more UN Sustainable Development Goals[2], and expects that project developers, farmers or landowners will take these into account when preparing and designing a project.

1.4. Additionality

Paulownia plantation projects that wish to issue credits under the Proba Standard and wish to use this methodology, must be able to demonstrate additionality. Projects must adhere to at least one of three additionality definitions: regulatory, financial or prevalence as explained in the Proba Standard.

[1] https://proba.earth/hubfs/Product/The_Proba_standard.pdf?hsLang=en

[2] https://sdgs.un.org/goals

It is crucial for a project developer to assess the regional and national regulatory environment on a project-by-project basis.

The Project Developer should be able to prove that the project wouldn't be achievable without the financial support from carbon credits, solidifying its alignment with the Proba Standard's additionality criteria. An investment analysis calculating costs and benefits, helps comparing financial aspects between a GHG project, the chosen baseline and possible alternative scenarios. Where appropriate, project developers can use the CDM: "Combined tool to identify the baseline scenario and demonstrate additionality"[3] for this purpose.

The Project Developer must provide a barrier analysis to identify and document obstacles that prevent the project from being realized without carbon finance. The CDM "Guidelines for objective demonstration and assessment of barriers"[4] provide help for identifying and assessing barriers.

1.5. Risks

For every Paulownia-forestry project, the Project Developer should at least assess and address the following risks that can affect the calculations of the carbon estimations and measurements.

- Risk of overestimation of carbon stocks
- Risk of the occurrence of human activities that reduce product volumes
- Risk of regulatory changes
- Reversal risk of fire
- Reversal risk of other weather events (eg. frost and storms)
- Reversal risk of water availability
- Reversal risk of pests and diseases
- Risk of leakage

1.6. Crediting Period

Every GHG project must define a Crediting Period. The crediting period is the timeframe within which the GHG program can issue credits for the project. Various projects may have Crediting Periods from different durations, based on project length, intervention type or harvest cycles. The

[3] https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-02-v7.0.pdf

[4] https://cdm.unfccc.int/EB/050/eb50_repan13.pdf

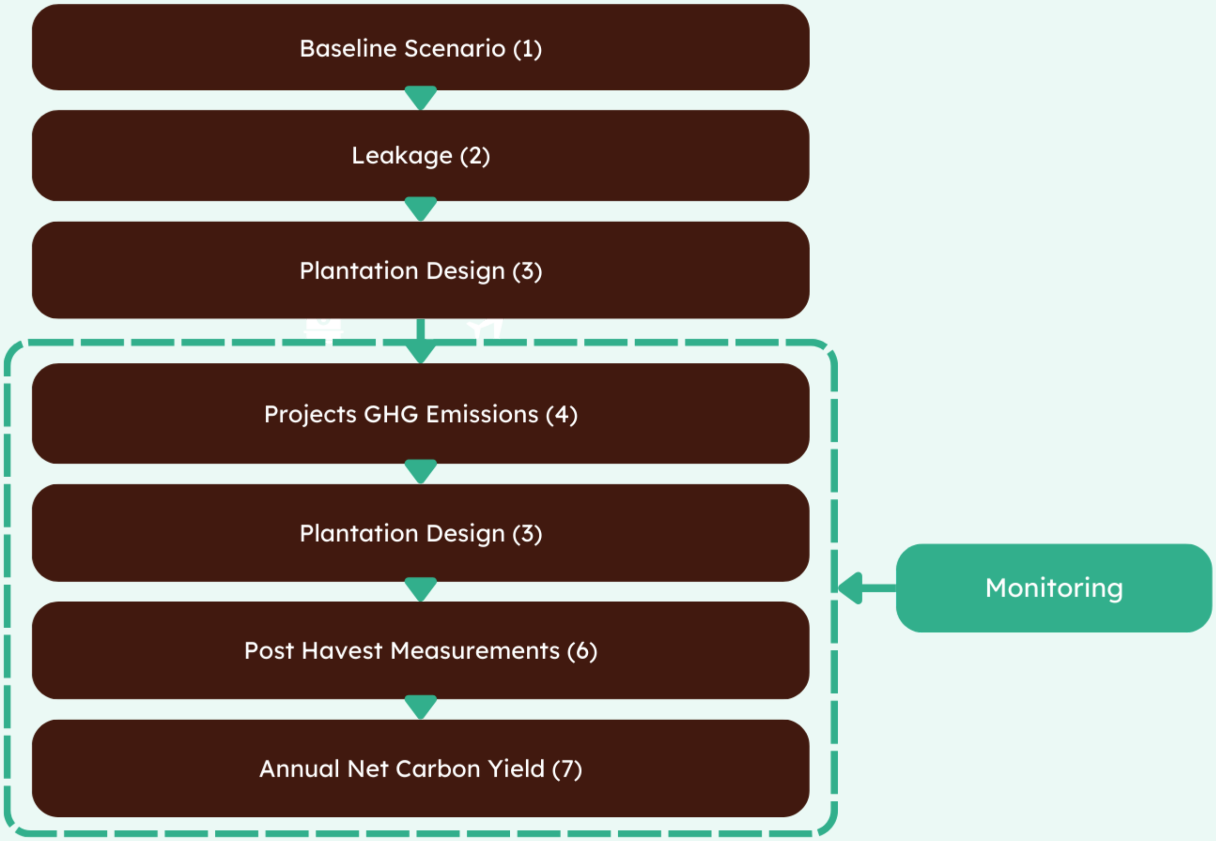
Crediting Period can be renewed within the total project duration, providing it complies with the criteria defined in *Section 3.2* of the Proba Standard[5].

For Paulownia plantation projects, the Crediting Period must cover at least one full harvest cycle, typically 7 to 10 years (but can vary based on the project's specific intervention). After the determined harvest year, the Project Developer can apply for a Renewal of the Crediting Period, as described in the Proba Standard Section 3.2. The project Developer must re-assess the baseline scenario and project emissions with the new context, and where possible update the carbon sequestration potential of the plantation based on the project's characteristics.

2. Process Overview

The flowchart below demonstrates each phase in the process of estimating and measuring carbon storage in short rotation forestry projects. It shows each step, from the start of the plantation to the end calculations of the carbon storage (net carbon yield).

[5] https://proba.earth/hubfs/Product/The_Proba_standard.pdf?hsLang=en



Below, the summarized description of the steps involved in the methodology for estimating and monitoring carbon sequestration in a Paulownia plantation can be seen. This structured approach encompasses a range of critical phases, from the initial design of the plantation to the final assessment of the project's Net Carbon Yield.

Phase 1: Defining Baseline Scenario

- Establish baseline scenarios considering land's prior use
- Based on the above, a few scenarios describing what would happen with the land in the absence of the project, on a similar timeframe to the project should be defined. The most likely scenario should be chosen.
- Estimate the GHG emissions sources and sinks of the chosen scenario over the project period
- Document pre-project conditions for future comparisons and impact assessments.

Phase 2: Calculation of Leakage

- Identify potential displacement of emissions due to project activities and quantify the impact (direct and indirect GHG emissions)
- Establish a system for ongoing evaluation of leakage effects and the effectiveness of mitigation measures
- Estimate the GHG emissions sources based on the referenced methodology and databases that are provided in Appendix 1

Phase 3: Plantation Design

- Select the optimum Paulownia species variety, total area to be planted, plot organization, tree density, spacing, and locations for plantation.
- Develop comprehensive irrigation and fertilization strategies, implement continuous monitoring for an effective control of the plantation (e.g. pest diseases)
- Different locations may have varying soil properties and baseline conditions, affecting factors like growth rate, biomass accumulation, and baseline carbon stocks.

Phase 4: Determine project emissions

Based on the above plantation design:

- Assess emissions during pre-planting, planting, maintenance, and harvesting stages.
- Focus on machinery operation, transportation, and maintenance activities for GHG source evaluation.

Phase 5: Estimation of Carbon Sequestration volume

- Utilize allometric equations derived from scientific literature data, assumptions, measurements, and wood density for initial carbon storage estimates.
- Regular monitoring to track growth and carbon sequestration, with emphasis on early detection of deviations.
- Tree growth monitoring must happen at least once per calendar year through measurements (DBH, Total Tree Height, Tree Stem Height)
- Evaluating assumptions against on field data in carbon sequestration potential.

Phase 6: Post-harvest measurements of Paulownia trees

- The trees will be harvested (timber), and the project developer will proceed to actual measurements by destructive sampling (volume may be measured)

- Validate carbon sequestration estimates with direct measurements of volume during the initial harvest
- "Employing scientifically derived formulas for the calculation of tree stem volume"

Phase 7: Net Carbon Yield Calculation

- Convert measured biomass to carbon stored in trees.
- Calculate total carbon sequestered in the project, subtracting baseline, potential leakage, and project emissions to determine the net carbon yield.
- .Apply a Buffer (%) percentage to enhance conservativeness and reliability in the calculations

2.1. Defining baseline scenario

Before initiating the planting process, it is crucial to establish a comprehensive understanding of the baseline carbon stocks. This initial step involves an examination of sinks, sources, and reservoirs (SSRs). SSRs encompass the dynamic elements influencing carbon fluxes within the ecosystem, including the capacity of the land to sequester carbon (sinks), factors contributing to carbon emissions (sources), and existing reservoirs or storage of carbon within soil and vegetation.

When determining the baseline, a project developer should use a baseline reference period of 3 to 10 years, to estimate the GHG balance of what would happen over the project period in the absence of the project. This is in line with the GHG Protocol Agricultural Guidance[6] that recommend to use a base period of at least three years. In this way crop rotation cycles will be included and average GHG fluxes are more accurate.

Three distinct scenarios characterize baseline carbon stocks based on the land's prior usage:

a) Empty land//fallow land

c) Pasture land/Grassland

b) Crop land (conventional farming)

[6] https://ghgprotocol.org/sites/default/files/2022-12/GHG%20Protocol%20Agricultural%20Guidance%20%28April%2026%29_0.pdf

Table 1 provides an overview of sources and sinks of both baseline scenarios. Both scenarios are further explained.

Table 1: GHG sources and sinks of baseline scenarios to be considered in the project's scope

		Baseline scenarios		
GHG sources	GHG type	Empty/Fallow land	Pasture land/Grassland	Crop land (conventional farming)
Plowing activities	CO_2	NO	NO	YES
Mowing	CO_2	NO	YES	NO
Livestock	CH_4	NO	YES	NO
Drainage/tillage	CO_2, CH_4, N_2O	NO	NO	YES
Planting crops/trees machinery	CO_2	NO	NO	YES
Irrigation installation machinery	CO_2	NO	Optional	YES
Transport of employees	CO_2	NO	Optional	YES
Water pump electricity	CO_2	NO	Optional	YES
Fertilizer use	CO_2, CH_4, N_2O	NO	Optional	YES

Carbon sinks/pools	GHG type	Empty/Fallow land	Pasture land/Grassland	Crop land (conventional farming)
Soil organic carbon (SOC)	CO_2	NO	YES	YES
Non-tree biomass (Grass, Herbs, etc)	CO_2	NO	YES	YES
Litter (Small branches, Leaves, Lying dead wood, etc)	CO_2	NO	NO	YES
Above Ground Biomass (AGB)		NO	NO	Optional
Stem	CO_2			
Branches	CO_2			
Bark	CO_2			
Leaves	CO_2			
Below Ground BIomass (BGB)		NO	NO	Optional
Stump roots	CO_2			
Lateral roots	CO_2			
Fine roots	CO_2			

Note: The categories listed in the baseline scenarios table represent a broad framework; however, they may require adjustment to align with the specific characteristics and requirements of each project. It is the responsibility of the project developer to provide evidence and justify the inclusion or exclusion of particular categories.

2.1.1. Scenario 1: Empty/Fallow land

Description: for this scenario, research has shown that the land:

- Has not not been used for the past 10 year for human activities that have an impact on the land
- Has no clear plan for future use and is not part of a development project (agriculture, housing, industrial etc.)

Sources: In the absence of recent or intensive land-use practices like agriculture, deforestation, or degradation, GHG emissions are expected to be notably low. Minimal human activities and insignificant microbial decomposition of organic matter characterize this scenario.

Sinks: Limited natural sinks due to the relatively undeveloped state of the land. Soil organic carbon and existing vegetation are anticipated to exhibit minimal or negligible carbon sequestration potential. It is assumed, in agreement with *IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (2003)*[7] that the net GHG removals by sinks in the baseline equals zero.

Reservoirs: Both soil organic carbon and existing vegetation reservoirs are likely to be minimal, aligning with the land's prolonged fallow period and reduced anthropogenic influence.

For each GHG project using this methodology and having this baseline scenario, this results in the following assumption:

Sources=0, Sinks=0, Reservoirs=0, GHG baseline=0

Note: These assumptions are fitted to the scenarios where there are no trees or small shrubs. If there is evidence indicating the presence of mature trees on the empty/fallow land, the carbon sinks and reservoirs should be evaluated properly.

[7] https://www.ipcc.ch/site/assets/uploads/2018/03/GPG_LULUCF_FULLEN.pdf

2.1.2. Scenario 2: Pasture land/Grassland

Description: In this scenario, the land designated for Paulownia tree plantation previously served as Pasture land/Grassland, primarily utilized for grazing livestock. This land typically features a mix of grasses and other ground cover, managed to support animals such as cattle, sheep, or goats.

Sources: On pasture land, the main sources of emissions include methane (CH_4) from livestock digestion and manure, as well as CO_2 emissions from soil disturbance due to grazing.

Sinks: The grasses and soil in pasture lands act as carbon sinks, capturing CO_2 from the atmosphere through photosynthesis and soil organic matter accumulation.

Reservoirs: The primary carbon reservoirs in pasture lands are the soil organic carbon (SOC) and the biomass of grasses and other vegetation.

2.1.3. Scenario 3: Previously Cropland, conventional farming

Description: In this scenario, the land where Paulownia trees are planted was formerly used for agricultural annual crops (cereals, crop rotation system).

Sources: The historical use of the land for crop cultivation implies potential greenhouse gas (CO_2, NO_2) sources, including emissions from synthetic fertilizers, plowing, machinery, and various soil management practices. Assessments typically follow a Scope 1, 2, 3 approach.

Note: Historical data of similar cultivation can be used, or emission factors specific to the region can be used for the calculations.

Sinks: Despite prior cultivation, some carbon sinks might persist in residual vegetation or soil organic carbon. In case specific data for residual vegetation and soil organic carbon assessment is not readily available, refer to Appendix 1.2 for further guidance.

Reservoirs: While reservoirs in the form of SOC and existing vegetation might exist, their quantity and capacity may have been impacted by previous agricultural practices. These reservoirs might exhibit reduced capacity due to the land's historical use.

Regarding the calculations of the Baseline emissions, refer to Appendix 1, where relevant emission factors databases, methodologies, and calculation tools are presented.

2.2. Calculation of Leakage

Following the establishment of baseline scenarios, it's imperative to address potential leakage to ensure a comprehensive understanding of a project's net carbon impact. Leakage occurs when project-induced carbon sequestration efforts inevitably lead to increased greenhouse gas emissions or diminished sequestration outside the project area. This phenomenon may occur when converting cropland into a Paulownia plantation. This leads to the relocation of agricultural activities. Such displacement might result in those activities being reestablished in new locations, consequently generating emissions. Mitigating such leakage involves careful project design and management strategies to minimize external impacts, ensuring a project's net carbon impact accurately reflects its environmental contribution.

Baseline Scenario 1

As the project area is set on formerly unused land, there is no risk of leakage, as no activity was performed on the planted land prior to the project.

Baseline Scenarios 2, 3

If the land was used for crops or pasture, the Project analyzes the consequences of the discontinuation of the production within the relevant geographical scope. For example, if the land was used for potatoes, will the farming of potatoes be moved to another location within the economic zone? In which proportion?

Using historical data on land use and trends in the economic region and running interviews with market stakeholders can help make an assumption for the leakage. If the leakage risk is high, then the net carbon yield calculation should be corrected accordingly to avoid overestimating the potential yield.

For further information on quantifying and measuring leakage please refer to Appendix 1.2.

2.3. Plantation design

This chapter provides guidance for project developers on designing a Paulownia plantation project optimized for carbon sequestration. A crucial aspect of this design is the strategic layout and structure of the plantation. This foundational planning plays an important role in determining the effectiveness of ongoing monitoring activities. Precision in data gathering is important for a thorough assessment of the project's carbon sequestration performance. The actions that the project developer should follow are described below:

1. Site Preparation:
    a. Conduct soil quality assessments, considering Paulownia's specific soil preferences. This includes recent soil samples, topography evaluation, and existing vegetation assessment.
    b. Review land history, particularly previous agricultural use, as Paulownia species can benefit from or be hindered by certain soil conditions.
    c. Pinpoint the exact geographical coordinates or identify the specific location, taking into account Paulownia's climatic requirements.
2. Selection of Paulownia species or varieties:
    a. Choose between different Paulownia species/varieties, considering local climate and soil conditions. Tree density per hectare may vary based on the tree species and environmental factors of the plantation site.
    b. Consider the crown size of different Paulownia species/varieties, ensuring sufficient sunlight and growth potential for effective carbon sequestration.

3. Planting Density and Layout:
    a. Determine optimal planting density to balance growth rate, tree shape, and biomass production based on the chosen Paulownia species/varieties.
    b. Layout should facilitate efficient maintenance and harvesting, considering factors like access routes and machinery operation.
    c. Table 2 illustrates a template example for the necessary data that need to be submitted related to the Paulownia plantation's attributes (input data).

Table 2: Paulownia plantation's input data

Paulownia species	Amount of hectares (ha)	Amount of plots/ha	Density/Number of trees (trees/ha)	Distribution between rows (m)	Distribution between trees (m)
...	...	...	...	...	...

Note: The amount of trees per plot and the amount of plots per hectare can vary depending on the project's spatial scale.

4. Incorporating a mortality ratio:
    a. This ratio reflects the expected percentage of tree losses based on specific characteristics of the project location, including climatic conditions, pest prevalence, and management practices.
    b. Apply the mortality ratio annually to reflect expected losses, adjusting the count of surviving trees in the plantation.
5. Biodiversity Considerations:
    a. Monitor the impact of Paulownia plantation on local biodiversity and ecosystems.
    b. Regulatory Compliance: Ensure that the plantation meets all local and national environmental regulations, especially those related to forest/plantation management and biodiversity conservation.
6. Socio-economic Factors:
    a. Engage with local communities to ensure the project supports local needs and sustainable development.
    b. Consider job creation, community benefits, and potential impacts on local land use and resources

2.4. Determine project emissions

It is important to clearly define the project boundary and include all relevant emission sources to accurately assess the total carbon benefit potential (Net carbon yield, Phase 6). Additionally, regular updates of the SSRs occurring during the implementation phase will ensure that any changes in emission sources are accounted for and properly addressed. In Table 3 emission sources included in or excluded from the project boundary can be seen.

Table 3: Project emissions to be considered

One-time	Irrigation installation machinery	CO2	Yes	This equipment consumes fossil fuels during operations
	Plowing machinery	CO2	Yes	This equipment consumes fossil fuels during operations

	Herbicide application machinery	CO_2	Yes	This equipment consumes fossil fuels during operations
	Transport of young trees	CO_2	Yes	Vehicle use for young trees transportation generates CO_2 emissions through fossil fuel combustion
	Planting trees machinery	CO_2	Yes	This equipment consumes fossil fuels during operations
	Transport of employees	CO_2	Yes	Vehicle use for employee transportation generates CO_2 emissions through fossil fuel combustion
Recurring	Maintenance machinery	CO_2	Yes	Machinery used for maintenance operations utilizes fossil fuels, contributing to GHG emissions
	Harvesting machinery	CO_2	Yes	Similar to planting and maintenance machinery, harvesting equipment consumes fossil fuels
	Water pump electricity	CO_2	Yes	Electricity consumption for water pumping often relies on fossil fuel-powered sources, leading to CO_2 emissions. If it can be proven that electricity from renewables is used, this source becomes zero.
	Transport of employees	CO_2	Yes	Vehicle use for employee transportation generates CO_2 emissions through fossil fuel combustion
	Transport of timber	CO_2	Yes	Vehicle use for timber transportation generates CO_2 emissions through fossil fuel combustion

2.4.1. Total Greenhouse Gasses (GHG) sources

Throughout the growth stages of the Paulownia trees, a range of emissions that occur only once and others that are generated from ongoing activities need to be calculated separately. These emissions collectively account for the total greenhouse gas (GHG) sources (equation 1) of the Paulownia forestry project.

$$GHGtotal = GHGonetime + GHGreccuring$$ **(eq. 1)**

Where:

GHGtotal (eq. 1)	Total amount of GHG sources during implementation phase
GHGone-time (eq. 2)	Total amount of GHG emissions prior to and during the planting period
GHGreccuring(eq. 3)	Total amount of GHG emissions during the monitoring visits (growth period) and harvesting period

To accurately calculate total greenhouse gas (GHG) sources in this period, it is critical to include both one-time emissions that occur during the implementation phase (such as land preparation and planting) and recurring emissions that arise from ongoing activities like monitoring visits and harvesting.

2.4.2. One-time project emissions (equation 2)

These equations encompass emissions from activities carried out prior to and during the planting period. Given that these activities, such as preparing the soil, installing irrigation systems, and transporting saplings and employees, occur only once in the project's lifetime, their associated emissions represent a unique subset of the project's total GHG footprint.

The project developer has two options for accounting for these emissions:

Immediate Deduction After First Harvest: This approach involves deducting the total emissions calculated from these equations once, immediately following the first harvest. This method acknowledges the upfront nature of these emissions, attributing them entirely to the project's initial phase.

Spreading Across 40 Years: Alternatively, the total emissions can be evenly distributed over a 40-year period, reflecting a long-term view of the project's impact. In this scenario, each year accounts for 1/40th of these initial emissions. This method considers the emissions impact over the project's lifespan, aligning it with the long-term nature of tree growth and carbon sequestration.

$$GHGonetime = GHGprior,plant + GHGdur,plant$$ **(eq. 2)**

Where:

$GHG_{one\text{-}time}$ (eq. 2)	Total amount of GHG emissions prior to and during the planting period
$GHG_{prior,plant}$ (eq. 3)	Total amount of GHG emissions before planting
$GHG_{dur,plant}$ (eq. 4)	Total amount of GHG emissions during the planting period

Prior to the planting period (equation 3), quantifying emissions requires a thorough evaluation of various management practices. This assessment encompasses emissions resulting from the use of machinery during the installation of irrigation systems, plowing, and potential herbicide and pesticide applications. Prior to planting, these treatments are used to prepare the soil and control weeds, ensuring a favorable environment for tree growth. Additionally, it extends to accounting for emissions related to employee transportation to the site.

$$GHGprior,plant = GHGma,ir + GHGma,plo + GHGma,herb + GHGempA,trans$$ **(eq. 3)**

Where:

$GHG_{prior,plant}$ (eq. 3)	Total amount of GHG emissions before planting
$GHG_{ma,ir}$	GHG emissions due the usage of irrigation machinery
$GHG_{ma,plo}$	GHG emissions due to the plowing machinery
$GHG_{ma,herb}$	GHG emissions due to the herbicide application machinery
$GHG_{empA,trans}$	GHG emissions due to the transportation of the employees"A"

During the planting period (equation 4), the quantification of emissions is based on assessing the various aspects of tree planting activities. This involves evaluating emissions generated from machinery operations, the transportation of saplings (young trees), and employee transportation during the initial phase of tree planting.

$$GHGdur, plant = GHGma, pla + GHGsapl, trans + GHGempB, trans + \ldots \quad \textbf{(eq. 4)}$$

Where:

$GHG_{dur,plant}$	Total amount of GHG emissions during the planting period
$GHG_{ma,pla}$	GHG emissions due the usage of planting machinery
$GHG_{trans,sapl}$	GHG emissions due to the transportation of the young trees
$GHG_{empB,trans}$	GHG emissions due to the transportation of the employees"B"

2.4.3. Recurring emissions (equation 5)

These equations encompass emissions from activities conducted during the growth (monitoring visits), such as the use of maintenance machinery, electricity for irrigation, transportation of the employees and the application of fertilizers. Additionally, during the harvesting stage, which occurs every 7-10 years based on Paulownia species/variety attributes, emissions originate from harvesting machinery operation, employee transportation, and timber transport.

These recurring emissions form a continuous component of the project's GHG footprint, requiring regular assessment and management.

$$GHGreccuring = GHGdur, grow, year + GHGdur, harv, period \textbf{ (eq. 5)}$$

Where:

$GHG_{reccuring}$	Total amount of GHG emissions during the monitoring visits (growth period) and harvesting period
$GHG_{dur,grow,year}$	Total amount of GHG emissions during monitoring visits the (growing period) the year “y”
$GHG_{dur,harv,period}$	Total amount of GHG emissions during the Harvesting period “p”

During the growth period (equation 6) of the trees, quantifying emissions involves assessing the impact of maintenance machinery, the electricity consumption from water pumps used for irrigation, and fertilizer application if any. This encompasses monitoring emissions generated during the various phases of tree development.

$$GHGdur, grow, year = GHGma, main + GHGel, ir + \ldots \textbf{ (eq. 6)}$$

Where:

$GHG_{dur,grow,year}$	Total amount of GHG emissions during monitoring visits the (growing period) the year “y”
$GHG_{ma,main}$	GHG emissions due to the machinery used for maintenance
$GHG_{el,ir}$	GHG emissions due to the electricity that was consumed by the water pump (irrigation system)

During the Harvesting period (equation 7) which will be scheduled at regular intervals every few years based on the growth rate and maturity of the tree species, calculating emissions is crucial. This involves assessing emissions from harvesting machinery, employees, and timber transportation. These factors contribute significantly to the project's environmental footprint throughout the harvest cycle.

$$GHGdur, harv = GHGempC, trans + GHGma, harv + GHGtimb, trans + \ldots$$

(eq. 7)

Where:

$GHG_{dur,harv}$	Total amount of GHG emissions during the Harvesting period
$GHG_{empC,trans}$	GHG emissions due to the transportation of the employees"C"
$GHG_{ma, harv}$	GHG emissions due to the machinery used for harvesting
$GHG_{timb,trans}$	GHG emissions due to timber transportation

In Appendix 1, crucial databases containing essential information on emission factors can be found, offering valuable insights into emissions associated with various activities.

2.5. Estimation of Carbon Sequestration

The Project developer is responsible for estimating and adequately presenting the carbon sequestration potential of their Paulownia plantation. Therefore, the carbon sequestration potential should be precisely calculated and presented using the **tool** that was developed for this purpose. Project developers should input their data and generate accurate estimates. Example templates that closely resemble the actual sheets in the tool are included in each of the following sections.

Note: The tool allows for customization, allowing project developers to tailor the calculations to their specific plantation conditions and management practices.

2.5.1. Standard Values and Allometric Equation:

The use of standardized values and allometric equations is essential for the estimation procedure of the plantation's carbon sequestration potential. These values and equations have been researched and validated to provide reliable estimates of plantation growth and carbon sequestration potential. Table 4 provides a detailed presentation of the data set that are applied and used as inputs in the tool.

Table 4: Standardized Values and Allometric Equation for Paulownia species

Parameter	Value	Source
Wood Density (ρ)	270 kg/m³	Multiple references (see Appendix 1)
Carbon Content	47%	IPCC 2006[8]
Biomass Expansion Factor (branches, twigs, etc)	1.4	IPCC, Good Practice Guidance for Land Use, Land-Use Change and Forestry[9]
Allometric Equation (eq. 8)	$\ln(VOL) = f(\ln(DBH^2 * SHT))$	Berg et al., 2020[10]
Below Ground Biomass (BGB) "root-shoot ratio"	15% of AGB	ICIMOD (2015)[11], MacDicken (1997)[12]

[8] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pdf

[9] https://www.ipcc.ch/site/assets/uploads/2018/03/GPG_LULUCF_FULLEN.pdf

[10] https://doi.org/10.1007/s11676-019-01021-9

[11] https://lib.icimod.org/record/31838

[12] https://www.researchgate.net/publication/237434580_A_Guide_to_Monitoring_Carbon_Storage_in_Forestry_and_Agroforestry_Projects#fullTextFileContent

Parameter	Value	Source
Wood Density (ρ)	270 kg/m³	Multiple references (see Appendix 1)
Carbon Content	47%	IPCC 2006[8]
C to CO2	3.67	Pearson et al. (2007)

Note: Refer to Appendix 2.1 for more information on these standard values and the allometric equation.

These data are tailored for the Paulownia species, and based on scientific literature/research. Moreover, the application of an allometric equation (derived from scientific literature and relevant to the Paulownia species), adheres to the guidelines set by the Carbon Development Mechanism CDM[13].

2.5.2. Applying Information from the "Plantation Design" Phase

The data gathered in the Plantation Design Phase will be inputted into the tool designed for calculating the plantation's overall carbon sequestration potential. Essential details such as the total area in hectares and the density of trees per hectare are necessary for estimating the total amount of carbon that is sequestered across the entire plantation.

2.5.3. Growth Rate Assumptions:

Assumptions about averages of DBH and SHT will be utilized for preliminary estimations. These will be based on data from similar Paulownia projects (climatic conditions, soil composition) and scientific sources. They will inform initial estimations of biomass (based on volume and wood density) across the plantation related to the information submitted during the previous phases (Plantation design).

[13] https://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-17-v1.pdf

Table 5: Assumptions Table: Average Trees Measurements (Inputs) and Total Biomass in the plantation (output)

Assumptions									
Year	**Number of trees (N)**	**AVG DBH (cm)**	**AVG THT (with crown) (m)**	**AVG SHT (m)**	**AVG stem volume/tree (kg/m3) based on *Berg et. al., 2020***	**Total stem Volume (kg/m3)**	**Total AGB (kg)**	**Total BGB (kg)**	**Total Biomass (branches, crown etc)**
2023	2000	5	1.2	1	...	...	...	...	...
2024	...	8	2	1.5	...	...	...	...	...
2025	....	10	2.6	2	...	...	...	...	...
....	...	....	....	....	...	...	...	...	...
2031	...	40	7	...	...	...	...	...	...

Note: The data presented in this table are hypothetical examples from a Paulownia plantation that launched operations in 2023. The measurements here reflect the plantation's status eight years post-establishment. These examples are provided for illustrative purposes to demonstrate how the data should be recorded and interpreted.

2.5.4. On-Field Data Collection:

A year after the project's initiation, the project developer has to collect the annual data of each of the sample trees in a spreadsheet (THT, SHT, and DBH). Every sample tree should have a unique “Tree ID”, so it can be identified and measured again in later stages. From these measurements averages will be extracted and will be used as inputs for the Table 6 “On field measurements” which assists in the annual calculations of the carbon sequestration.

To ensure thorough data collection, a balanced sampling approach should be adopted, targeting 20–30 trees characterized by a certain diversity regarding their size (DBH, THT, and SHT). This diverse sampling is crucial for capturing a comprehensive dataset that accurately represents the plantation's tree size variability.

Regarding the volume measurements, project developers can utilize scientifically derived formulas. These formulas are integral to forestry and carbon stock assessment due to their ability to provide accurate volume estimates based on measurable tree attributes (DBH, THT, SHT). In the context of short rotation forestry projects, particularly involving species like Paulownia, pruning plays a crucial role in shaping the growth pattern of the trees. Regular pruning from the second year onwards encourages the trees to grow taller and straighter, with fewer side branches, thereby enhancing their wood quality. This pruning technique aligns the tree growth more closely with a cylindrical form, making it ideal for volume estimation using:

Huber's formula[14]*:* Primarily used for trees with relatively uniform stem diameters along their length. It calculates the volume of a tree by multiplying the cross-sectional area at breast height (DBH) by the tree's total height. This formula is particularly effective for columnar-shaped trees.

Using the volume measurements obtained and their correlation with SHT and DBH, a refined regression analysis will be conducted on Berg's formula. This analysis will result in updated coefficients, offering a more precise representation of the relationship between these tree dimensions and their volume.

Detailed guidelines on the sampling process and data collection tables that the project developer should utilize can be found in *Appendix 3.2.*

Table 6: Average Tree Measurements and Total Biomass in the Paulownia plantation based on field measurements.

On field measurements									
Year	**Number of trees (N)**	**AVG DBH (cm)**	**AVG THT (m)**	**AVG SHT (m)**	**AVG stem volume/tree (m3) based on *Berg et. al., 2020***	**Total stem Volume (m3)**	**Total AGB (kg) of the stem**	**Total BGB (kg)**	**Total Biomass (branches, crown etc)**
2023	...	...	...	...	...	...	...	...	...
2024	...	...	...	...	...	...	...	...	...

[14] https://ojs.upsi.edu.my/index.php/EJSMT/article/view/2458/2248

2025	...	...	...	...	...	...	...	...	...
....	...	....	....	....	...	...	...	...	...
2031	...	...	...	...	...	...	...	...	...

2.5.5. Monitoring and Reporting

Regularly monitoring and reporting on the plantation's growth and tree health are crucial for a comprehensive understanding of the project's progress. This entails selecting a diverse range of trees with different growth characteristics within the plantation, ensuring that the sampled trees proportionally represent the range of growth observed across the plantation. Measurements should be scheduled within a designated annual time frame to ensure consistency and accuracy in data collection. Any changes due to losses from pests, diseases, extreme weather conditions, or other environmental challenges should be recorded. For that reason, the number of trees per hectare should be reassessed each year based on the mortality ratio that the project developer established in Phase 3.

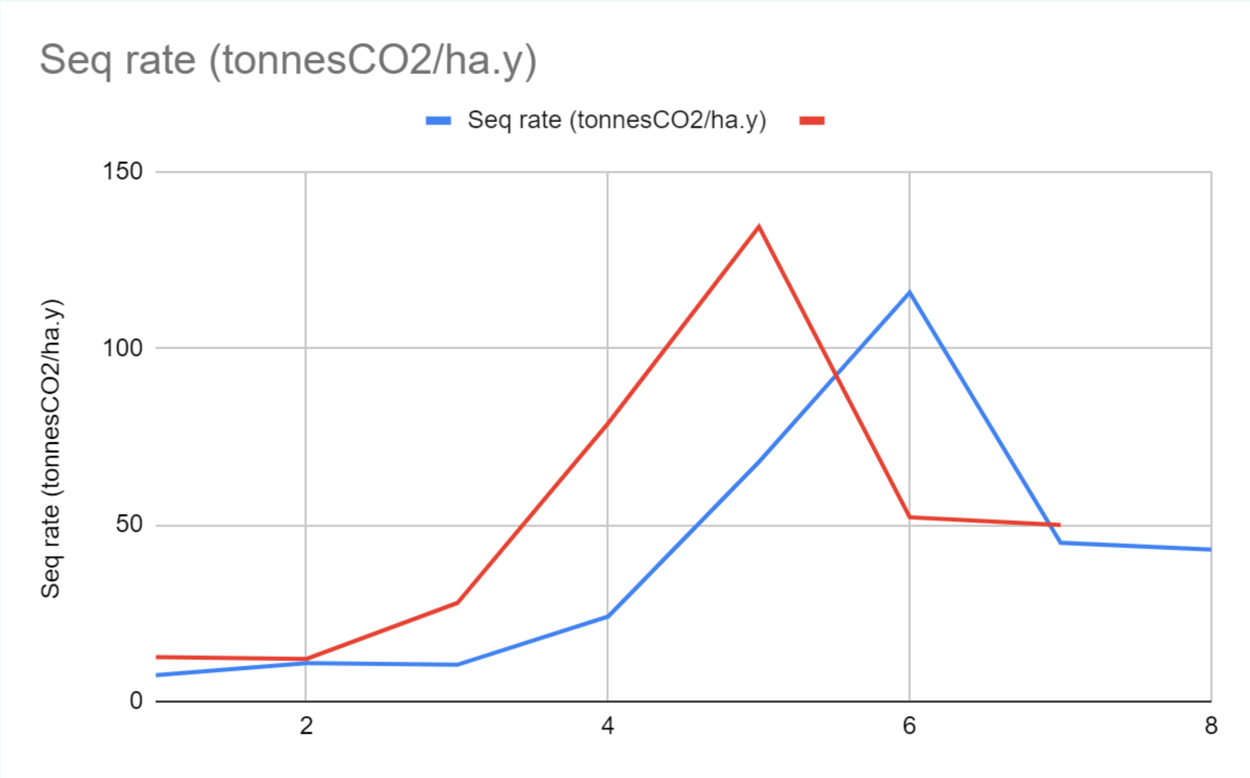
2.5.6. Evaluating assumptions against on field data

In this step, the project developer will compare the initial assumptions to the actual on field measurements, by using the tool to conduct a comparative analysis. This table will compare the total biomass, Carbon Content, CO2 Equivalent, and Carbon Storage per Year as calculated from both the annual averages of the initial assumptions and the actual field data.

Table 7: Comparative Analysis Data

Year	Total Biomass in Plantation (kg)		Carbon Content (%)		CO2 Equivalent (tonnes)		Carbon Storage per year (tonnes)	
2023	Assumptions	On Field	Assumptions	On Field	Assumptions	On Field	Assumptions	On Field
...	...	...	...	...	...	...	...	...
2031	...	...	...	...	...	...	...	...

Alongside the table, a graph will be provided to visually depict the differences between the assumed and actual measurements. Example of the "Graphical Visualization":



This process of collecting and analyzing data annually is used for:

- Assessing the project's current progress against its initial assumptions
- Verifying and modifying the prior estimations to ensure they remain accurate over time
- Maintaining transparency regarding its impact on carbon sequestration

The initial steps outlined above, integral to estimating carbon sequestration for the Paulownia plantation, have been incorporated into the tool and are accessible via the following link to the Google Sheet: Google Sheet for Carbon Sequestration Estimation.

In *Appendix 2.2*, an explanation of the equations used in these calculations can be found, while providing insights into their application.

2.6. Post-harvest measurements of Paulownia trees

During the initial harvest, which typically occurs between the 7th and 10th year (based on the Paulownia species/variety), project developers are enabled to validate their carbon sequestration estimates through direct measurements. Since these trees are destined for timber, employing destructive sampling methods allows for the actual volume of the trees to be accurately measured.

2.6.1. Utilization of “Destructive Sampling”

The goal of collecting annual data and the post-harvest measurement of stem volume is to improve the accuracy (refine coefficients and R^2 of the allometric equation 8) of the method to calculate the actual biomass and carbon Yield.

The harvested sample trees, intended for use as timber in construction, will undergo destructive sampling. This process involves felling the trees and measuring their DBH, stem height. A subset of these harvested trees will be also measured for their stem volume, utilizing:

- Water Displacement[15]: Based on Archimedes' principle, this method measures volume by submerging the tree section in water and measuring the amount of water displaced. This method is highly accurate for irregularly shaped sections that do not conform to simple geometric shapes

Further information regarding these volume estimation methods is provided in *Appendix 3.*

2.6.2. Data collection

The measurements that will be obtained from the same sample trees, regarding the stem volume, will be systematically recorded in a structured format (tool). This organized data collection enables efficient data management and analysis. Example template for Data Collection is provided in *Appendix 3.3*

2.7. Annual Net Carbon Yield after harvesting periods

The next step is determining the Annual Net Carbon Yield (NCYannual) and the Total Net Carbon Yield (NCY total) of each harvest cycle. This key phase builds upon the using essential formulas based on scientific standards. In order for these biomass estimates to be translated into carbon storage, the carbon fraction of biomass and the conversion of this carbon into CO2 equivalent will be applied.

[15] J. B. DARGAVEL & NELL DITCHBURNE (1971) A Comparison of the Volumes of Tree Stems Obtained by Direct Measurement and by Water Displacement, Australian Forestry, 35:3, 191-198, DOI: 10.1080/00049158.1971.10675553

In calculating Net Carbon Yield (NCY), the baseline emissions from Phase 1 are incorporated as a reference for what emissions would have been without the project. Project emissions identified in Phase 3, including both one-time and recurring emissions, are also included into the NCY. One-time emissions are subtracted after the first harvest cycle, while recurring emissions are deducted annually.

BGB's carbon storage will be considered only once during this first harvest cycle (7-10 years) and its estimation will be based on root to shoot ratio. The reason for this is that after 8 years, the root system only continues to grow in a marginal and difficult-to-measure way. Only counting the BGB carbon pool once is aligned with the conservativeness principle and ensures a responsible assessment of the project's carbon sequestration.

To further enhance conservativeness and reliability in the calculations, a buffer is also applied. This buffer, a predetermined percentage of the NCY, accounts for uncertainties such as potential risk of loss due to natural disturbances, pest diseases and other unforeseen factors that could impact carbon sequestration effectiveness. Incorporating this buffer ensures that the reported NCY reflects a proper, conservative estimate, safeguarding against overestimation and aligning with best practices for realistic and responsible carbon accounting.

$$NCY = CStotal - (GHGtotal - Baseline\ emissions - Leakage) * (1 - Buffer\%)$$

(eq.9)

Where:

Parameter	Unit	Description
NCYannual	*tCO2e*	Net Carbon Yield from the whole project (tonnes of CO2e) per year
CSannual	*tCO2e*	Annual carbon storage in trees' biomass of the project (tonnes of CO2e) *include BGB only at the 1st harvest cycle
GHGreccuring	*tCO2e*	Direct and indirect greenhouse gas emissions due to the project activities (tonnes of CO2e) per year

		*include the one-time emissions only at the 1st harvest cycle
Baseline emissions	*tCO2e*	Estimated emissions that would have occurred under standard scenarios if the project had not been implemented (tonnes of CO2e) per year
Leakage	*tCO2e*	Leakage emission due to the displacement of agricultural activities per year
Buffer % (Uncertainties, Risk, etc)	%	Buffer percentage can vary based on the project characteristics

For the NCY calculations, the same tool that was used during the whole process may be employed again. This ensures an efficient and consistent approach for calculating the Annual Net Carbon Yield.

Appendix 1: Calculation of Baseline, Leakage, and Project emissions

1.1. Baseline and project emissions measurement

If specific data for vegetation (prior to the project implementation) and soil organic carbon assessment are not readily available, the project developer can follow these guidelines.

Existing vegetation:

- Procedure: Identify representative plots within the area previously used for crop cultivation. The number and size of the plots should be determined based on the heterogeneity of the land.
- Data collection: Measure or estimate the biomass of the existing vegetation within each plot. This includes stems, leaves, and branches, while considering both woody and herbaceous vegetation.
- Biomass conversion: Convert biomass measurements to carbon stocks using appropriate conversion factors. Different vegetation types may require specific conversion factors based on carbon content.

Soil organic carbon:

- Methodologies for estimating carbon sequestration in agricultural soils
- Soil sampling: Collect soil samples from various plots within the cropland, ensuring representations of different soil types and land-use histories. Sampling depths should include 0–30 cm and 30–60 cm.
- Laboratory analysis: send the soil samples to the laboratory for analysis. Methods like dry combustion or wet oxidation can be used to determine the organic carbon content.
- Conversion to Carbon Stocks: Multiply the organic carbon content by a factor (usually 1.72) to convert it into carbon stocks per unit area (e.g., tons of carbon per hectare).

Developers are encouraged to leverage these resources to accurately measure and report emissions, ensuring their projects align with best practices. Table 9 includes applicable methodologies and tools related to SOC.

1.2. Quantifying and Managing Leakage

Estimating displaced activities: The initial phase involves estimating the volume of agricultural production (grains and cereals) or the amount of livestock that will be displaced by the Paulownia plantation project. Understanding the land's current agricultural yield or livestock and the market demand for these two is crucial. This step lays the foundation for assessing the broader impacts of the project on local and potentially international markets.

Assessing market dynamics: Following the estimation of displaced activities, the project developer examines how the reduction in local crop production influences market dynamics. This includes potential increases in imports or a shift in production to other domestic or international regions, factoring in the project's broader economic ripple effects.

Evaluating Land-Use changes: Should agricultural production relocate, the project developer assesses the consequent land-use changes in the new area. This entails evaluating whether the transition leads to the creation of new agricultural lands, possibly at the expense of natural habitats, and the associated GHG emissions from such conversions.

Utilizing methodologies, tools and emission factors: Using methodologies and tools, along with emission factors detailed in Table 9 and 10, the developer can accurately estimate GHG emissions from land-use changes. These resources provide a solid foundation for the analysis, drawing from established guidelines such as those from the IPCC and CDM.

Calculating Leakage: The project developer then quantifies the total GHG impact of leakage, expressing this as a percentage of the emission reductions expected from the forestry project. This calculation offers insight into the scale of leakage compared to the project's anticipated environmental benefits.

Considering indirect effects: Indirect effects, such as alterations in market prices due to reduced crop and livestock availability and their influence on production decisions elsewhere, are also considered. These effects necessitate a broader view of the project's impact on agricultural markets and production patterns.

Monitoring and updating estimates: Acknowledging the dynamic nature of leakage, the project developer commits to regular monitoring and updating of estimates based on actual observed changes in agricultural and land-use patterns over time.

Documentation and verification: Finally, thorough documentation of all methodologies, data sources, and assumptions used in the leakage analysis is maintained. This documentation is crucial for the verification process, especially pertinent if the project aims to generate carbon credits.

1.3. Applicable methodologies and tools

Table 8: Applicable methodologies and retrieved by CDM

To be measured	Methodologies/Tools
SOC	• Tool for estimation of change in soil organic carbon stocks due to the implementation of A/R CDM proj • CDM_ARWG30_SOC_Tool_Multiz... • https://data.apps.fao.org/glosis/?lang=en
Leakage	• A/R Methodological tool Estimation of the increase in GHG emissions attributable to displacement of pre-project agricultural activities in A/R CDM project activity • Methodological tool Project and leakage emissions from biomass • Methodological tool Project and leakage emissions from transportation of freight

Note: Soil organic carbon is likely to change at a slow rate and is also likely to be an expensive pool to measure. However it should at least be considered, as sequestration of carbon into the soil, or prevention of emissions of carbon from soils, can be important – especially in grazing land and cropland systems – and omission of soil carbon is an omission of a source of reductions in atmospheric greenhouse gasses. Potentially, where forest is planted on land that was previously grassland, a loss in soil carbon can occur (because of the very high soil carbon stocks in perennial grassland[16]

1.4. Emission Factors Databases

GHG protocol[17] proposes the agricultural emissions to be divided based on mechanical and non mechanical emissions. The project developer can follow the guidelines of the GHG protocol and include these types of emissions both in the baseline scenario “previously crop land” and during the project emissions of the Paulownia plantation project.

[16] SOURCEBOOK FOR LAND USE, LAND-USE CHANGE AND FORESTRY PROJECTS

[17] https://ghgprotocol.org/sites/default/files/2022-12/GHG%20Protocol%20Agricultural%20Guidance%20%28April%2026%29_0.pdf

Table 9: Agricultural emissions to be considered based on GHG protocol

Mechanical	Non-mechanical
Purchased electricity: CO2, CH4 and N2O	Drainage and tillage of soils: CO2, CH4 and N2O
Mobile Machinery (e.g. tilling, sowing, harvesting and transport)	Addition of synthetic fertilizers, livestock waste, and crop residues to soils: CO2, CH4 and N2O
Stationary Machinery (e.g., milling and irrigation equipment)	Addition to urea and lime to soils: CO2
Mobile Machinery for fertilizer application (e.g. tractor)	Enteric fermentation: CH4
etc.	Manure management: CH4 and N2O
	Land use change
	etc.

Project developer need to assess the GHG emissions by sources (per each source) based on site/activity specific data, scientific literature, or the most recent default emission factors provided by IPCC (e.g.,IPCC 2003, 2006, 2019) and other databases. Many of these calculations and emission factors are available in Table 11.

Table 10: Available Emission Factors Online Databases

Databases	Links
FAOSTAT	FAOSTAT
European Environment Agency	EEA Member Countries
IPCC	EFDB - Main Page
UNFCCC	Greenhouse Gas Inventory Data National Inventory Submissions 2023
Our World in Data	Our World in Data
CO_2 Emissiefactoren (Netherlands)	Lijst Emissiefactoren

1.5. Online tools to be used for calculations

Project developers in order to measure the baseline, project emissions, and leakage for the carbon farming projects , can leverage several online websites/tools. In Table 12 a brief overview of what each tool offers is presented.

Table 11: Available online tools to be used for further calculations

Website	Link	Features
CoolFarmTool.org	[Cool Farm Tool]()	Greenhouse gas emissions calculation based on the cultivation's characteristics
Erfemissiescan.nl	[Erfemissiescan]()	Designed to help farmers assess the risk of emission of crop protection agents from their farms and plots to the environment
Boerenbunder.nl	[boerenbunder]()	Historical crop data going back up to several years. GPS coordinates. Insight into crop rotations for planning and land suitability. Access to satellite images for monitoring crop growth and land conditions
Global Soil Information System/FAOSTAT	https://data.apps.fao.org/glosis/?lang=en	GSP's open-access Global Soil Information System is a spatial data infrastructure that brings together soil information collected by national institutions and other data holding entities

However, access to the full range of features and data these platforms offer may vary. Some, like Erfemissiescan.nl, offer free access for basic use but might require an account registration. Others might have country-specific data or require subscriptions for full access, particularly when detailed, localized data or advanced analytical tools are needed. Project developers should consider these factors when planning to integrate such tools into their reporting frameworks.

Appendix 2: Standard values & equations

2.1. Standard Values Description

These values are derived from scientific literature, reports, and guidelines from Climate Change and Carbon Management Frameworks (IPCC, CDM, GHG Protocol, etc).

Parameter	Value	Source
Paulownia wood density (ρ)	270 kg/m^3	Various Sources (see Table 9)
Carbon Content	47%	IPCC 2006[18]
Biomass Expansion Factor (branches, twigs, roots, etc)	1.4	IPCC, Good Practice Guidance for Land Use, Land-Use Change and Forestry[19]
Allometric Equation for estimation Phase	$\ln(VOL) = f(\ln(DBH^2 * THT))$	Berg et al., 2020[20]
Below Ground Biomass (BGB) "root-shoot ratio"	10% of AGB	ICIMOD (2015)[21]
C to CO2	3.67	Pearson et al. (2007)

Paulownia species wood density (ρ): This refers to the mass of wood per unit volume, typically measured in kg/m^3. In forestry, wood density is a vital parameter as it influences biomass

[18] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pdf

[19] https://www.ipcc.ch/site/assets/uploads/2018/03/GPG_LULUCF_FULLEN.pdf

[20] https://doi.org/10.1007/s11676-019-01021-9

[21] https://lib.icimod.org/record/31838

calculations and subsequently, the carbon storage potential of trees. An example of how this value was derived can be seen in Table 9.

Table 12: Procedure of adopting an average value based on scientific sources

In the context of estimating biomass for short rotation forestry projects with Paulownia species, a critical parameter is the specific wood density of the trees. Given the lack of readily available data specific to our Paulownia species, a methodical approach to determine a standardized wood density value has been adopted. This approach leverages existing scientific literature to derive an average density that is representative of the species. According to a comprehensive study published by Jakubowski (2022), the density of Paulownia wood, at a moisture content of 12%, varies between 220 and 350 kg/m³. The same study presents an average density of approximately 270 kg/m³ for Paulownia wood. Another scientific investigation found the oven-dried wood density of Paulownia to be 268 kg/m³. This value aligns closely with the average presented in the first study. Complementing this, based on ICRAF's tree functional attributes and ecological databases the mean wood density is at 267 kg/m³. Given these findings, it has been decided to adopt an average wood density of 275 kg/m³ as a standardized value for this project. This average is derived from a range of values reported in the scientific literature and reflects the typical wood density for Paulownia species under similar conditions. This standardized density will be utilized in our calculations to estimate the biomass based on the volume and density of the trees in our plantation. This approach ensures a scientifically grounded and transparent method for biomass estimation, essential for the accuracy and reliability of our project's carbon sequestration calculations. It also underscores our commitment to using the best available data and practices in the absence of species-specific measurements.

Note: If the project developer possesses data on wood density that has been derived through scientific methods, this specific value can be utilized in place of the standard wood density provided in this document.

Biomass Expansion Factor: This factor is used to estimate the total biomass of a tree, including parts not directly measured, like branches and twigs. It helps in scaling up from known biomass measurements to a whole-tree biomass estimation.

Below Ground Biomass (BGB) "root-shoot ratio": This ratio compares the biomass of a tree's roots to its above-ground parts. It's essential for estimating the total biomass, including the often-unseen root system, which is significant for total carbon storage calculations.

Allometric Equation (Berg et al., 2020): An allometric equation is used to estimate the volume of a tree from easily measurable parameters like diameter at breast height (DBH) and total height

(THT). These equations are critical in forestry for estimating tree biomass and, by extension, the carbon storage without directly measuring the entire volume of the tree.

$ln(vol) = f(ln(DBH^2 * SHT)$ **(eq. 10)**

Carbon Content: This is the percentage of a tree's biomass that is carbon. It's a critical factor in calculating how much carbon is stored in a tree.

C to CO2 Conversion: This factor converts the mass of carbon stored in trees to its equivalent in carbon dioxide (CO2). It's based on the molecular relationship between carbon and CO2 and is crucial for translating carbon sequestration into terms used in greenhouse gas accounting.

2.2. Estimation of Carbon Sequestration (Phase 4) and relevant equations

The equations are fundamental to calculating total biomass, both from initial estimations and actual field measurements. This approach allows for a comparative analysis, as outlined in Phase 4, where the estimated biomass from both methods is translated into carbon sequestration and ultimately into CO2 equivalent. These equations are also applied as inputs in the example tables that are illustrated in Phase 4.

1) Calculate Average Stem Volume:

$ln(Vavg, stem) = f(ln(DBHavg^2 * SHTavg))$ **(eq. 8)**

Where:

$Vavg, stem$	Average Stem Volume per tree (kg/m3)

$DBHavg$	Average Diameter at Breast Height (cm)
$THTavg$	Average Stem Height (SHT) of the tree (m)
f	Represents the function defined in the allometric equation, which relates the natural logarithm of the product of the squared average DBH and the average height to the natural logarithm of the average volume

2) Total Volume of trees:

$$Vtotal = Vavg * Ntrees \text{ (eq. 10)}$$

Where:

$Vtotal$	Total Stem Volume for the entire plantation (m3)
$Vavg$	Average Stem Volume per tree (m3)
$Ntrees$	Total number of trees in the plantation

3) Above Ground "stem" Biomass:

$$AGBstem, total = Vtotal * \rho \textbf{ (eq. 11)}$$

Where:

$AGBstem, total$	Total Above Ground "stem" Biomass for the entire plantation (kg)
$Vtotal$	Total Stem Volume of the plantation (m3)
ρ	Wood density, a standard value for the Paulownia species (kg/m3)

4) Total Above Ground Biomass:

$AGBtotal = AGBstem, total * BEF$ **(eq. 12)**

Where:

$AGBtotal$	Total Above Ground "stem" Biomass for the entire plantation (kg)
$AGBstem, total$	Total Above Ground "stem" Biomass for the entire plantation (kg)
BEF	Biomass Expansion Factor

5) Total Biomass (including BGB):

$Total\ Biomass\ (AGB, BGB) = AGBtotal + (AGBtotal * RSR)$ **(eq. 13)**

Where:

$Total\ Biomass\ (AGB, BGB)$	Total biomass of the plantation, including both Above Ground Biomass (AGB) and Below Ground Biomass (BGB) (kg)
$AGBtotal$	Total Above Ground "stem" Biomass for the entire plantation (kg)
RSR	Root-Shoot Ratio

6) Total Carbon Stored in Tree:

$Ctrees = Total\ Biomass\ (AGB, BGB) * Carbon\ Content$ **(eq. 14)**

Where:

$Ctrees$	Total Carbon storage in trees
$Total\ Biomass\ (AGB, BGB)$	Total biomass of the plantation, including both Above Ground Biomass (AGB) and Below Ground Biomass (BGB) (kg)
$Carbon\ Content$	Proportion of biomass that is carbon (set at 47%)

7) C to CO2 conversion (CO2 equivalent):

$$CO2\ Equivalent, total\ =\ Ctrees\ *\ 44/12$$ **(eq. 15)**

Where:

$CO2\ Equivalent, total$	Carbon storage in trees
$Ctrees$	Carbon storage in trees
$44/12$	Molecular weight ratio of CO2 to carbon.

8) Annual Carbon storage:

$$Annual\ CO2\ equivalent\ =\ CO2\ Equivalent, total/Nyears$$ (eq. 16)

Where:

$Annual\ CO2\ equivalent$	Total Carbon storage in CO2e per year
$CO2\ Equivalent, total$	Carbon storage in trees
$Nyears$	Number of years until harvest

Appendix 3: Empirical Data collection methods

In this section, the recommended equipment for data collection in Paulownia projects is presented. They are specifically tailored for accuracy and simplicity of use in the field. Additionally, recommended data collection templates are designed to facilitate the systematic recording of data.

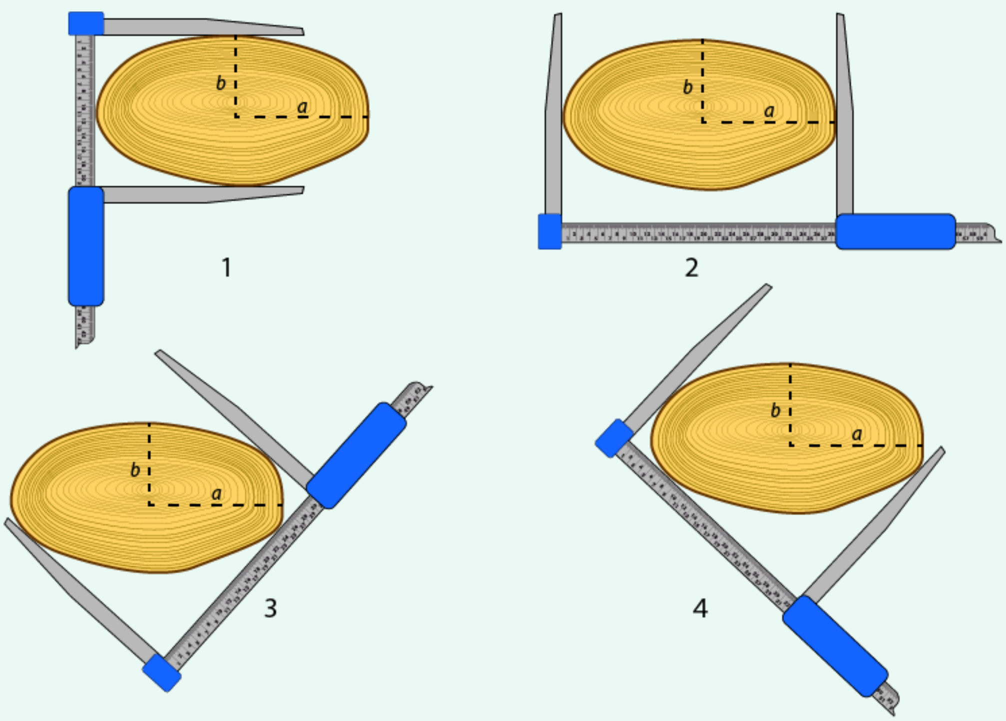
3.1. Recommended equipment:

3.1.1. Measuring the Diameter at Breast Height (DBH) of the Paulownia Tree samples

Measuring the Diameter at Breast Height (DBH) of trees is a key task in forestry, requiring precise tools like diameter tapes, calipers, and Biltmore sticks. Accuracy is crucial, as DBH measurements contribute to understanding tree health and forest dynamics. Proper use and regular maintenance of these tools are essential for reliable data.

Example: MANUAL DIAMETER: "Calibrated Tree Trunk Thickness Gauge"

It is designed for forestry use to accurately measure tree diameters. It has a measuring range of up to 60 cm and weighs 900 grams.



3.1.2. Measuring the Height of a Paulownia Tree

Measuring the height of a tree is essential in forestry and ecological studies, typically done using tools like clinometers or hypsometers for accuracy. Proper technique in using these instruments is crucial for reliable height measurements.

Example: The "BOSCH MEASURING BAR" - GR 500

It is a specialized tool designed for measuring the height of trees, such as the Paulownia.
It features an extension capability of up to 5 meters, making it suitable for use in a variety of conditions

3.2. Measurement techniques of tree volume

Huber's formula[22]:

It is a widely accepted method in forestry that calculates the volume of a tree by treating it as a geometric shape—either a cone or a cylinder. The formula takes into account the diameter at breast height (DBH) and total tree height (THT). In the case of pruned trees, the cylindrical assumption becomes more accurate, as pruning minimizes irregularities in the tree's shape. The formula is expressed as:

$$V = \pi * SHT * (DBH^2/4) \text{ (eq. 17)}$$

Water displacement: Based on Archimedes' principle, this method measures volume by submerging the tree section in water and measuring the amount of water displaced. This method is highly accurate for irregularly shaped sections that do not conform to simple geometric shapes.

3.3. Example on-field measurements



[22] https://medcraveonline.com/BBIJ/BBIJ-09-00308.pdf

The project developer is tasked with effectively recording detailed annual measurements for each sample tree, encompassing DBH, THT, SHT, and selected volume samples, utilizing Excel or Google Sheets for systematic record-keeping. This procedure guarantees that the information is systematically organized and readily available for validation, review, or any subsequent verification processes. To further ensure the data's integrity and validity, it is crucial to maintain comprehensive records of all measurements in Portable Document Format (PDF). The inherent characteristics of the PDF format prevent unauthorized modification, thereby safeguarding the data. This approach to meticulous documentation enhances transparency, accountability and upholds the project's reporting and analysis phase to the highest standards of data management and accountability, facilitating straightforward future verification or validation efforts.

Table 13: Annually data collection and measurements

Data Collection/Measurements (annually and harvesting stage)							
Employee in charge (Data Collector):							
Tree ID	**Location**	**Date**	**THT(m)**	**DBH(cm)**	**SHT(m)**	**Volume(m3) based on Huber's formula**	**Notes**
1	...	15/11/2024	...	...	...		...
2	...	15/11/2024	...	...	...		...
3	...	15/11/2024	...	...	...		...
...	...	...	...	...	...		...
25	...	15/11/2024	...	...	...		...

Instructions:

- Date: Enter the date of data collection.
- Data Collector's Name: Record the name of the individual collecting the data.
- Tree ID: The specific trees that the numbers are derived from

- DBH (Diameter at Breast Height): Measure and record the DBH in centimeters.
- THT (Total Height): Record the total height of the tree in meters.
- SHT (Stem Height): Record the stem height of the tree in meters.
- Volume: If calculated based on Huber's formula, enter the volume of the tree in cubic meters.
- Notes: Any additional observations or relevant information.

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