Discussion paper: Estimation of carbon stock changes in woody biomass & soil

Purpose of this document

- This document outlines key concepts proposed for inclusion in the measurement and modelling Schedules of the IFLM method, advancing concepts put forward at the IFLM expert workshop held in Canberra in June 2024.

Background and Summary

- In the CMI ILFM Taskforce discussion paper put forward before the June 2024 Expert Workshop in Canberra, it was proposed there would be total of five Abatement Schedules for estimation of soil and woody carbon stocks. These included:
    - National model – woody biomass:
    - Spatially referenced models – Soil
    - Spatially referenced models – Woody biomass
    - Spatially explicit models – Soil
    - Spatially explicit models – Woody biomass
- This discussion paper provides an explanation in simple terms on how all five estimation schedules could work.

Problem statement

- The IFLM Method Framework represents a step change from existing single-activity carbon farming methods, involving a modular framework that allows for multiple carbon farming activities and multiple carbon pools to be implemented as one carbon farming project.
- The modular framework necessitates and appropriate set of measurement and estimation approaches to ensure conservative and high accuracy calculation of net carbon abatement. This flexible and technology neutral framework has been adopted in other methods such as the 2021 Soil Carbon Method (which contained two measurement schedules), and the 2022 Plantation Forestry Method (which contained four measurement schedules).
- This paper proposes very similar measurement options to those already applied in the 2021 soil carbon method, and also included in the last technical consultation draft of the IFLM method released by DCCEEW in September 2023. That is, the IFLM method would allow for:
    - a measured-only approach (which is described in this paper as a 'spatially referenced model);
    - a measure-model approach (which is described in this paper as a 'spatially explicit approach'); and
    - a national model, i.e. FullCAM or equivalent, which would be applicable for estimation of woody biomass for a limited set of activities and areas.

Simple method guide to estimation of carbon stocks in woody biomass and soil

Step 1: Establish the project area

Identify the area in which your project activity will occur using a combination of remotely sensed imagery, a land cover assessment, and the Carbon Farming Initiative Mapping Guidelines.

Using this information, you must then divide, or stratify, the project area into different areas called strata. Each stratum must be classified as one of the following:

- a carbon estimation area (CEA)
- an exclusion area

A project must contain at least one CEA, but exclusion zones are optional.

CEAs are the core areas of your project in which carbon will be stored and for which ACCUs may be issued. If your project area becomes disturbed, for example, by fire or pests, then you may need to re-stratify the CEAs before submitting a project report.

Exclusion zones are parts of your project area where project activities are not conducted, such as a road, building or dam.

Step 2: Calculate initial carbon stock

The initial carbon stock represents the starting point against which any changes in the amount of carbon stored by a project in a reporting period are measured. This is calculated at the first estimation event.

To undertake the first estimation event, you need to work through a sequence of equations as follows. All steps apply to both woody biomass and soil CEAs unless noted otherwise.

2.1 Choose an estimation schedule for your CEAs

2.2 For woody biomass CEAs: Choose allometric equations

2.3 Choose a high accuracy measurement approach

2.4 Select a model for carbon stock estimation

2.5 Undertake baseline measurement surveys

2.6: Calculate eligible carbon stock ratio

2.7 Validate your carbon stock model

2.8 For soil & woody biomass CEAs: Calculate initial carbon stocks

Each of these is explained briefly in this guide. Refer to the relevant sections of the method and explanatory statement for detailed information.

Step 2.1: Choose an estimation schedule for your CEAs

Before conducting your first estimation event, you must decide on your approach to estimate carbon stocks in the CEA. The following options are available:

- Approved national model (i.e. FullCAM or equivalent) – for woody biomass CEAs only;
- Spatially referenced model, or
- Spatially explicit model.

Each option is described in separate schedules. The choice will determine how you collect and analyse your carbon stock data throughout the project.

The national model schedule can only be used for specific woody biomass activities that meet the assumptions of the Australian Government's Full Carbon Accounting Model (FullCAM). To use the national model schedule, CEAs must have the potential to achieve forest cover (meaning a canopy area of >20% above 2m tall), and in addition, for CEAs undertaking spontaneous regeneration activities, they must also conduct the gap analysis to demonstrate there is sequestration potential due to anthropogenic barriers that have constrained carbon stock. No measurements of carbon stock are required but CEAs must meet project progress gateways defined in terms of canopy cover. Projects using the national model schedule must also follow the IFLM Guidelines for FullCAM Modelling.

The spatially referenced and spatially explicit schedules use measurements and models to estimate carbon stock changes through time. These options are available for both soil and woody biomass CEA. If using these schedules for woody biomass CEAs, you can choose from a broader range of eligible abatement activities the activities than apply under the national model approach, as activities not constrained by the calibration settings that apply to the national model. In both the spatially explicit and spatially referenced Schedules, measurements are used to validate models of carbon stocks across CEAs or the broader project area. Different types of models may be used that best suit the characteristics of a given project, as long as they meet the model validation criteria at project gateways.

Box 1. What are the differences between spatially referenced and spatially explicit schedules?

Spatially referenced estimation schedules

- Calculate total carbon stocks by multiplying the mean carbon density by the CEA area
- Require measurements to be taken inside each CEA;
- Involve stratification into CEAs or strata are that are groupings of land that is assumed to have the same carbon stock;
- Provide summary statistics (mean and variance) for each CEA.

Spatially referenced estimation schedules are well suited to smaller or more homogeneous project areas. They may also be applied where it is not possible to spatially estimate the carbon stock for each pixel or area of land using characteristics that are observable in remotely sensed imagery (as might be the case with soil CEAs). This approach can be efficient where there is limited spatial variation in carbon stocks as only a few measurements are required to provide high certainty in the estimated mean. The modelled carbon stock must represent the whole CEA.

An example of a spatially referenced approach is application of Schedule 1 under the 2021 soil carbon method (where soil carbon stocks are averaged per CEA), and for estimation of woody biomass under the avoided deforestation method.

Spatially explicit estimation approaches have become possible with advances in remote sensing technologies. The approaches:

- Involve interpretation of remotely sensed imagery and high-accuracy measurements, to translate woody biomass size metrics into estimates of aboveground woody biomass;
- Describe carbon distribution within a CEA at a resolution smaller than the CEA itself;
- Calculate total carbon stocks by summing the carbon stocks of individual mapping units (e.g. pixels) within the CEA
- Can be validated by measurements taken inside and/or outside the CEA

Spatially explicit schedules provide more detailed information about carbon distribution across the landscape. This makes it particularly suitable for larger or more heterogeneous project areas and can help identify specific areas of carbon change within a CEA. Normally, variable CEAs require a high degree of measurement effort, however the efficiency can be increased by targeting measurements to areas that reduce uncertainty the most. There are a growing number of spatially explicit biomass maps that may be suitable for carbon stock estimation, after they have been validated for your project to a sufficient accuracy requirement. Your choice between these approaches will depend on factors such as the size and heterogeneity of your project area, available resources for data collection and processing, and the level of detail required for your carbon accounting.

Step 2.2: Choose allometric equations for woody biomass

Note: this step is not required for soil carbon CEAs or projects using the national model schedule for woody biomass.

IFLM projects use mathematical equations called allometric equations to estimate the amount of biomass (and therefore carbon) in a project tree or forest based on a readily measurable proxy variable, such as diameter, height or canopy size. These equations make forest biomass estimation efficient. Instead of weighing every tree, allometric equations allow you to estimate tree biomass by measuring simple characteristics of trees or forests. Allometric equations are necessary for undertaking measurements of biomass at sufficient scales to validate spatially referenced or spatially explicit carbon stock estimates.

There are two options for allometric equations:

1. Use existing, pre-qualified allometric equations if they are fit for purpose for your project area and tree species. National allometric equations are available that relate stem diameter to biomass for major plant functional types.
2. Develop new allometric equations suitable for your project. Size variables may be measured on a per-tree or per-area basis.

For both pre-qualified and newly developed allometric equations, you must provide comprehensive metadata for independent review by an auditor and/or the Clean Energy Regulator. This includes the equation's mathematical form and parameters, the size variables used, the number of trees used to develop the equation, measures of equation fit and a description of the allometric domain (tree species, size ranges, and geographic applicability). Details about measurement methods and validation procedures must be provided. By providing this metadata, you demonstrate the suitability of the equations for your project area and contribute to the transparency and scientific soundness of your carbon stock estimates.

Box 2. Using allometric equations to estimate biomass

Allometric equations capture the statistical relationship between the proportions of readily measurable tree or forest characteristics (like trunk diameter, height or canopy area), and more difficult-to-measure characteristics like volume and weight.

Allometric equations are used to estimate biomass, which is the total weight of plant material in all the living parts of a tree. This is an efficient way of estimating the biomass of a forest, because only a relatively small number of sample trees need to be measured to identify the allometric relationship.

Once the relationship is identified and a valid allometric equation is developed, the allometric equation can be applied to all trees growing within the allometric domain. The allometric domain reflects the conditions under which an allometric equation is likely to apply, because the conditions in that domain, for example tree species and sizes, are the same as those used when developing the allometric equation.

New allometric equations could be developed using either destructive techniques (i.e. where the tree is cut down and samples are weighed); or using technologies like Terrestrial Laser Scanning (TLS). TLS can create detailed 3D models of trees, allowing for precise volume estimates without cutting down trees. The process to develop an allometric equation using destructive techniques has already been applied in the avoided deforestation method, and this approach remains fit for purpose under the IFLM. However, the IFLM method will need to articulate a new process for developing allometric equations using TLS.

New allometries can potentially allow you to measure a wider range of tree characteristics more efficiently. This could include detailed crown structure, stem taper, and even internal architecture for some tree species. However, it's important to note that while lidar provides excellent structural data, you still need to convert volume estimates to biomass using wood density values.

In IFLM projects, allometric equations are developed for the aboveground parts of a tree. The belowground biomass is determined using root:shoot ratios, which vary depending on the vegetation type. The amount of biomass is then converted to an amount of carbon for the purposes of calculating the forest's carbon stocks.

Step 2.3: Choose a high-accuracy measurement approach

The IFLM method is not prescriptive about which technology is applied to undertake high accuracy measurements to be used for model validation. Given the rapid innovation in modelling and measurement technologies, the IFLM method includes a pre-approved library of measurement tools that are deemed eligible for validation of models. For soil, these include soil cores. For woody biomass, approved measurement technologies include measurement tapes and/or height sticks, and LIDAR technologies.

For measurement approaches that are not in the pre-approved library, the IFLM method includes a qualification process, whereby a new technology could be deemed eligible for measurement and validation of a model if it is:

- published in peer reviewed literature [3+ articles], with a stated accuracy above a certain threshold; or
- the new technology must demonstrate a high correlation with an existing approved high-accuracy measurement technology via a one-off upfront validation program, comparing the 'new' and the 'existing' technology.

The measurement or modelling validation processes would be subject to audit.

Recommended reading: Section 2.2.4 of the CEOS Land Product Validation Subgroup Aboveground Woody Biomass Product Validation Good Practices Protocol (ver 1.0; 2021)

Step 2.4: Select a model for carbon stock estimation

Regardless of which estimation schedule is applied, IFLM projects use models to estimate carbon stocks across the project area. Some of these models are quite simple (i.e. in the case of spatially referenced approaches, the model is an average of measurements in each CEA); while others might be more complex.

The models help create carbon stock maps, which are essential for calculating the amount of carbon stored in your project and tracking changes over time. You may choose an existing model or develop a new model, appropriate to your project. The model is used to produce an accurate carbon stock map for your project area.

Projects using the national model schedule for woody biomass must use the Australian Government's FullCAM and follow the IFLM Guidelines for FullCAM Modelling. Alternatively, proponents may choose to use another model to estimate carbon stock changes. The IFLM method is not prescriptive about which model is used, but the model must comply with the ERAC 'Principles for assessing models used for Emissions Reduction Fund methods'[1], and must meet strict validation criteria as described in the Schedules for spatially referenced or spatially explicit approaches to carbon stock estimation. This ensures that any chosen model is producing accurate carbon stock estimates.

The type of model applied is based on one of three approaches, depending on your project's circumstances and available resources:

1. **Use a pre-calibrated model**: You may have access to an existing model that estimates carbon stocks based on remotely sensed data or other auxiliary variables. These models will have already been developed and tested in similar environments. Alternatively, you might use a process-based model that simulates carbon stocks over time based on environmental conditions and management practices. This includes FullCAM, but there are also a growing number of commercially available models for woody biomass and soil carbon.
2. **Develop a new model calibration**: If a suitable pre-calibrated model isn't available, you'll need to develop your own. If you're developing a new model calibration, you'll usually need to collect biomass or soil carbon data to develop your initial carbon stock map. The IFLM method doesn't specify how to calibrate your model, but the model must be compliant with the ERAC principles for assessing models, and model fit will be tested via a validation process. Calibration data could be collected from outside the project area, and it could be collected prior to project commencement. Data used to validate the model must be independent from the calibration dataset to ensure an unbiased assessment of your model's performance. Calibration and validation data may be collected separately, or together, so long as they are treated as two separate datasets.
3. **Using a simple empirical model**: For spatially referenced estimation schedules, you might choose to use a simple model based on the mean and variance of your measurement data

[1] Available at: https://www.dcceew.gov.au/sites/default/files/documents/erac-principles-assessing-models-used-in-erf-methods.pdf

(i.e. empirical data). This approach doesn't require complex modelling but assumes that your measurements adequately represent the carbon stocks across your entire Carbon Estimation Area (CEA). Simple statistical models are straightforward to implement but are limited in their application. They can only provide a carbon stock estimate for a single CEA, at a single timepoint, and require additional measurements for updates over time.

Spatially referenced or spatially explicit carbon stock maps must be accompanied by their estimated uncertainty. For spatially referenced models, this is the carbon stock variance for the CEA (including spatial variance and uncertainty). For spatially explicit models, this is an uncertainty map with standard deviations for each mapping unit in your carbon stock map.

Once you have selected a model, you can generate your initial carbon stock estimate. Soil carbon CEAs may require two or more carbon stock maps – representing carbon stocks in the top 30cm of soil and a second to the nominated sampling depth of the CEA. Whichever approach you choose, your model must meet the validation requirements outlined in the next section.

Step 2.5: Undertake baseline measurement surveys

Note: This step not required for woody biomass CEAs using the national model schedule.

As part of calculating your project's initial carbon stock, you will need to conduct measurements surveys. These surveys will provide the reference biomass or baseline soil carbon data needed to validate your carbon stock maps. The baseline measurement survey should be conducted at the time the CEA is first created.

For soil CEAs, the process to conduct baseline soil carbon measurements is outlined in the Supplement to the soil carbon method. The main difference in IFLM is the proposal to introduce a qualification process to allow for new high-accuracy measurement approaches to be introduced.

For woody biomass, you will need to measure the characteristics of the trees that form the basis of your allometric equations (e.g., stem diameter, height) within a pre-selected sampling area - usually a plot or a transect. This can be done on the ground or from the air, depending on the size variables used in your allometric equations, so long as all trees in the sampling area are accounted for. For soil carbon, you must take soil cores at pre-selected sampling points to a depth of at least 30 cm.

How you design your survey depends on whether you're using a spatially referenced or spatially explicit estimation schedule:

1. For spatially referenced estimation schedules, surveys must be undertaken within CEAs at multiple sampling locations. Sampling locations are chosen randomly within groups (strata) in your CEA. This approach aims to give each part of your CEA an equal chance of being sampled. There are a range of examples of spatially referenced sampling protocols that are already applied in ACCU methods, including the sampling protocols described in the Supplement to the soil carbon method, in the Avoided Deforestation method and the Reforestation and Afforestation method

2. For spatially explicit estimation schedules the objective is to validate how well a carbon stock map describes the distribution of carbon across a landscape, meaning that surveys should sample areas with low carbon stock, medium carbon stock, and high carbon stock. This means sampling may be conducted both inside and outside the CEA (although the validation data should always be collected from within the Project Area). This approach aims to minimize uncertainty in your overall carbon stock estimate.

The measurements gathered from the surveys are then used in Equations A, B, and C to determine the total carbon stock at each sample location.

Step 2.6: Calculate the eligible carbon stock ratio

Note: This step is not applicable for woody biomass CEAs using the national model

The eligible carbon stock ratio ensures that only carbon stock changes that are due to your project activities are issued as ACCUs. The eligible carbon stock ratio is applied to your baseline estimate and is re-applied at each reporting event. It works differently for trees and soil.

The case of both soil and woody biomass, the eligible carbon stock ratio would be held in reserve until a project gateway. Some of the reserved carbon stock change may be eligible for release if it is shown to be conservative.

For woody biomass CEAs:

To account for eligible sequestration in CEAs where some trees are impacted by the management change, and others are not, an eligible carbon stock ratio can be applied. In this way, CEAs don't need to be homogenous and not all areas of existing vegetation must be excluded from the CEA, so long as estimates of carbon stock change are adjusted to account for ineligible trees.

The eligible carbon stock ratio uses tree size to determine eligible and ineligible trees. For example, grazing may not be a barrier for trees that are already above grazing height. In the case of mechanical or chemical suppression, if trees above a certain size were not eligible to be cleared (say 20cm DBH), then eligible carbon stock ratio would be used to exclude sequestration in trees above this size.

The eligible carbon stock ratio looks at how many trees in a CEA are smaller than a certain size threshold:

$$\theta_{CEA} = \frac{\text{Number of eligible trees}}{\text{Total number of trees}}$$

If preferred, the eligible carbon stock ratio could be applied based on the area of eligible vs ineligible trees (rather than based on stem counts as shown in the equation above). The equation is broadly the same for both approaches.

As an example, if your CEA has 100 trees, and 75 of them are smaller than the eligible size limit, your eligible ratio would be 75/100 = 0.75. Rather than measuring every tree in your CEA this is estimated in several plots and the average is then applied within the CEA.

As an example based on area-based size metrics, if you take an aerial lidar scan over 10 hectares, and 7.5 hectares have tree canopies below the eligible size limit, then your eligible carbon stock ratio is 7.5 / 10 = 0.75.

Because eligible carbon stock ratios are reconciled at project gateways, they can be re-used for multiple estimation events without re-measuring.

Step 2.7: Validate your carbon stock model

Once you've completed your measurement surveys, you need to compare the results with your carbon stock maps at the same location to see how accurate your estimates are. This step involves comparison of your measured vs modelled carbon stock estimates at a single point in time (eg: at project commencement). It does not involve validation of a forecast or future time series of estimates.

This comparison uses three main metrics:

1. **Systematic deviation (or bias)**: This is the average difference between your carbon stock model values and the measured data. It is calculated by subtracting each measured value from the corresponding model value and taking the average of these differences. A positive Systematic Deviation (SD) indicates that your model tends to overestimate carbon stocks, while a negative SD suggests underestimation. The method requires the bias to be within a certain range.

$$SD = \frac{1}{N}\sum_{i=1}^{N}(\hat{c}_i - c_i)$$

Where {c_hat} is the model estimate and {c} is the measured value, at validation point {i} and {N} is the number of validation points.

2. **Relative Root Mean Square Deviation (relRMSD)**: This quantifies the typical magnitude of differences between your model values and measured data, expressed as a percentage of the mean measured value. It is calculated by taking the square root of the average squared differences between modelled and measured values, then dividing by the mean of the measured values and multiplying by 100. Lower values indicate a better match between your model (expressed in map form) and measurements. relRMSD is useful because it allows for consistent comparison of errors across different carbon stock levels, unlike absolute RMSD which can vary in magnitude between areas of low and high carbon stocks.

$$relRMSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\hat{c}_i - c_i}{c_i}\right)^2} \times 100$$

3. **Precision**: This indicates how consistently your model estimates align with the measured values. It is calculated as the inverse of relRMSD and is expressed as a percentage. This statistic shows how consistent your map estimates are compared to the measurements. Higher precision indicates that your carbon stock map more consistently estimates close to the measured values. The IFLM method requires the precision to be greater than a certain threshold (e.g. 85%).

$$Precision = 100 - relRMSD$$

Soil carbon CEAs may need to calculate validation metrics for multiple soil depths.

These thresholds validation metrics are an important control for the integrity of your carbon stock project. If your model doesn't meet the required thresholds, you may need to improve it using additional data or different modelling techniques before proceeding with your project. One approach may be to add measurements data to your model calibration set, including from this round of measurement surveys. While this is a viable option, you'll need to undertake a new round of surveys to maintain the independence of your calibration and validation datasets.

Recommended reading: Section 3.2.5.2 of the CEOS Land Product Validation Subgroup Aboveground Woody Biomass Product Validation Good Practices Protocol (ver 1.0; 2021)

Step 2.8 Calculate initial carbon stocks

Having validated your initial carbon stock model (which is displayed in map form), you can now calculate the initial carbon stocks for your CEAs. The method for this calculation depends on whether you're using the national model schedule, or a spatially referenced or spatially explicit approach.

1. **National model** – the initial carbon stock is the carbon stock in trees and coarse woody debris for the CEA taken the day before the project commencement.

$$C_{CEA,t_0} = (C_{T,t_0} + C_{WD,t_0}) \times A_{CEA}$$

Where {C_CEA} is the carbon stock of the CEA, {t0} is the date prior to project commencement, {C_T} is the carbon stock of trees, {C_WD} is the carbon stock of woody debris and {A_CEA} is the area of the CEA.

2. **Spatially referenced** – the initial carbon stock for a CEA is simply the mean carbon stock value from your validated map, for woody biomass or soil carbon, multiplied by the area of the CEA.

$$C_{CEA,t_0} = \bar{C}_{t_0} \times A_{CEA}$$

Where {C_bar} is the spatially referenced mean carbon stock and {t_0} refers to the day the carbon stock map was validated.

3. **Spatially explicit** – the initial carbon stock for a CEA is the integral over carbon stocks of the CEA.

$$C_{CEA,t_0} = \iint_{A_{CEA}} C_{t_0}(x, y)\,da$$

Where {C(x, y)} are the values of the carbon stock map at coordinates (x, y) and {t_0} refers to the day the carbon stock map was validated.

Box 3. What is integration?

Integration is useful to summarise the spatial distribution of variable quantities, like woody or soil carbon, and is especially suited for complex shapes like CEA boundaries, where in the case of spatially explicit calculation approaches, each mapping unit contained within the CEA boundaries has its own woody carbon stock value.

Instead of representing the woody carbon stock of the CEA as an average, we add up the individual mapping units, weighted accordingly, to get a more precise result of the overall CEA. If you're more familiar with sums, it can be approximated as:

$$C_{CEA,t_0} \approx \sum_{i=1}^{n} C_{t_0,i} A_i$$

Where {i} is an individual mapping unit, {A_i} is the area of that unit, and there are {n} mapping units contained with the CEA boundaries.

The advantage of using integration over summation is that it naturally accounts for differences in map unit size which can be important when dealing with complex shapes like CEA boundaries.

This process is repeated for all CEAs in your project using the same carbon stock model. These initial carbon stock values serve as the starting point for your project. They will be used as the baseline against which future changes in carbon stocks are measured.

Step 3: Calculate net abatement at end of reporting period

Net abatement represents the total carbon stock change for your project, and is calculated at the end of each reporting period. Prior to reporting, the carbon stock map is updated at a subsequent estimation event and then the carbon stock change for each CEA is calculated, with adjustments to account for differences in eligibility and uncertainty in the carbon stock estimates. Then, net abatement for the project area is calculated. Emissions from project activities or natural disturbances are deducted, and then the creditable ACCUs are calculated.

Subsequent estimation events have several steps:

3.1 Collect measurement data from a sample of CEAs

3.2 Validate the carbon stock model

3.3 Calculate subsequent carbon stocks and carbon stock change

3.4 Apply the eligible carbon stock ratio

3.5 Adjust for probability of exceedance

3.6 Deduct emissions

3.7 Calculate net abatement and creditable ACCUs

Each of these is explained briefly but the relevant sections of the method and explanatory statement should be reviewed for more detailed information.

Step 3.1 Collect measurement data from a sample of CEAs

Models can be validated using data collected from within the CEA, or from another carbon farming project registered under the IFLM method that is using the same model (this is known as a 'portfolio validation' approach). Similar to the approach in the 2021 soil method, data from each CEA needs to be collected and used to validate the model at least once every ten years.

Step 3.2 Validate the carbon stock model

Note: This step is not required for woody biomass CEAs using the national model approach

Your carbon stock model must be validated prior to each subsequent estimation event to demonstrate its suitability for carbon stock estimation. Validation ensures that your model is accurately predicting carbon stocks across different areas and conditions.

The portfolio validation approach is applicable where there are multiple projects using the same model. In this case, you may choose to create a 'validation group' to leverage the measurement surveys undertaken for validation on other projects. This approach can substantially increase the efficiency of measurement surveys and allow you to report more frequently than if you were using a simple statistical model that requires measurement data at each subsequent estimation event.

The method does not prescribe criteria around the set of projects eligible to be included in a validation group. However, the validation group should include projects that cover a variety of conditions over which the model is applied, such as different soil types, vegetation, or management practices. Defining validation groups that cover these differences helps ensure your model works well in all the areas where you'll use it. For example, if your validation group includes soil CEAs in both grasslands and woodlands, you should take measurements in both types of areas.

Alternatively, you may choose to create separate models and separate validation groups to cater for these different conditions. In other words, if your validation group does not represent the broader modelled cohort, then the model will not successfully validate.

Box 4. Why stratify?

Stratification helps capture the variability within and between projects where a model is applied. Stratification means grouping areas that represent different conditions into strata. By stratifying, you can:

- Improve the accuracy of your carbon stock estimates
- Reduce the number of measurements needed for validation
- Ensure your model works well across all types of land in your project
- Increase ACCU issuance by reducing uncertainty of estimates.

Stratification helps to identify similar areas across your validation group. Rather than sampling all areas at each estimation event, it's enough to show that your model works for a set of similar areas to make new carbon stock estimates.

Subgroups of each stratum are randomly selected for sampling, excluding projects that had an estimation event less than a year ago. Because the validation group is stratified, subgroups should consist of similar areas and a minimum of two subgroups must be used for each stratum. There is no maximum number of subgroups.

To keep your model accurate over time without measuring every area every year, you'll set up a rotation schedule for your surveys. Each project in your validation group must be measured at least once every ten years. For example, if you have a stratum spread across five projects, you might measure one project every two years. For strata with larger subgroups, you may need to sample from multiple projects each year to meet the required ten-year sampling interval. This way, you're regularly checking and updating your model, but you're spreading the work (and cost) of measurements over time.

In the areas selected for measurement surveys, you'll compare your model's predictions to actual carbon stock measurements and calculate the validation metrics described previously to make sure your model still meets the necessary thresholds for accurate carbon stock estimation. If the model successfully validates based on the sample, then it is deemed applicable across all projects within scope of the model.

Precedents – Schedule 2 of the 2021 Soil Carbon Method.

Recommended reading: Appendix 2 of the 2021 Soil Carbon Simple Method Guide.

Step 3.3: Calculate subsequent carbon stocks and carbon stock change

Having produced carbon stock estimates with a validated map, calculate the subsequent carbon stocks and carbon stock change for your CEAs. The method for this calculation depends on whether you're using a national model, spatially referenced or spatially explicit approach.

1. **National model only** – the carbon stock is the carbon stock in trees and coarse woody debris for the CEA taken the day of the subsequent estimation event.

$$C_{CEA,t_x} = (C_{T,t_x} + C_{WD,t_x}) \times A_{CEA}$$

Where {C_CEA} is the carbon stock of the CEA, {t_x} is the date of the end of reporting period {x}, {C_T} is the carbon stock of trees, {C_WD} is the carbon stock of woody debris and {A_CEA} is the area of the CEA.

2. **Spatially referenced** – the carbon stock for a CEA is the mean carbon stock value from your validated map, for woody biomass or soil carbon, multiplied by the area of the CEA.

$$C_{CEA,t_x} = \bar{C}_{t_x} \times A_{CEA}$$

Where {C_bar} is the spatially referenced mean carbon stock and {t_x} refers to the date of the subsequent estimation event {x}.

3. **Spatially explicit** – the carbon stock for a CEA is the integral over carbon stocks of the CEA.

$$C_{CEA,t_x} = \iint_{A_{CEA}} C_{t_x}(x, y)\, da$$

Where {C(x, y)} are the values of the carbon stock map at coordinates (x, y) and {t_x} refers to the date of the subsequent estimation event {x}.

Carbon stock change is calculated as the difference between the current CEA carbon stock and the carbon stock at the preceding estimation event

$$\Delta C_{CEA,t_x} = (C_{CEA,t_x} - C_{CEA,t_{x-1}}) \times \theta_{CEA,t_x}$$

Where {Delta C_CEA} is the change in carbon stock for the CEA, {t_x} is the current estimation event, {t_x – 1} is the previous estimation event and {theta_CEA} is the eligible carbon stock ratio for the CEA for the current estimation event.

Step 3.4: Apply the eligible carbon stock ratio

For both woody biomass and soil CEAs, the eligible carbon stock ratios are used as a conservative adjustment of total carbon stock change. The carbon stock of ineligible trees is allocated to a buffer, and this is held in reserve until the CEA reaches a project gateway (i.e. CEA measurement event – Refer Step 4.3). At this time, the buffer may be partially released if the initial eligible carbon stock ratio is overly conservative. It is expected that most CEAs, the initial eligible carbon stock ratio would be conservative, as the biomass stored in trees that have the most sequestration potential would generally be small at first measurement, but is expected to grow over time.

Step 3.5: Adjust for the probability of exceedance

Note: This step is not applicable for CEAs using a national model schedule

After calculating the eligible change in carbon stocks, you need to account for the uncertainty in your measurements and model estimates by applying a probability of exceedance adjustment.

The probability of exceedance adjustment adjusts your carbon stock change estimate downward to be confident that the carbon benefits of your project are not being overestimated. This means you can be more certain that the actual carbon change is at least as much as what you're claiming.

The probability of exceedance adjustment is applied as follows:

$$\Delta C_{\mathrm{PoE},CEA,t_x} = \Delta C_{CEA,t_x} + \mathrm{SE}_{\Delta C_{CEA,t_x}} \times t_\alpha(df_{\Delta C_{CEA,t_x}})$$

Where {Delta CEA_POE} is the adjusted carbon stock change at estimation event {x}, {SE_DeltaC} is the standard error of the carbon stock change, {t_alpha} is the t-value for your chosen probability level and {df_DeltaC} are the degrees of freedom for carbon stock change from two successive estimation events.

Box 5. What is a t-value?
The t-value is calculated mathematically using the quantile function of the t-distribution. The adjustment is designed with the critical value {alpha} set to 0.4 and will return a value less than zero. This means that there's a high probability (60%) that the actual change is equal to or greater than your adjusted estimate. By reporting the lower bound, we acknowledge that the project might be generating more carbon benefits than are being credited.

Because the t-value is negative, it's in our interest to increase our sampling effort. By minimising the standard error and the t-value, we are more confident in our estimates of carbon stock change and the corresponding adjustment is smaller.

The standard error of the carbon stock change can be calculated from the variance of the model estimates at the current and preceding estimation events:

$$\mathrm{SE}_{\Delta C_{CEA,t_x}} = \sqrt{\mathrm{Var}(C_{CEA,t_x}) + \mathrm{Var}(C_{CEA,t_{x-1}})}$$

Where {Var} means variance of the model estimate. The calculation of variance and degrees of freedom are slightly different for CEAs using the spatially-referenced or spatially-explicit estimation schedules:

The degrees of freedom for carbon stock change are also calculated using the variance and the degrees of freedom at each estimation event:

$$df_{\Delta C_{CEA,t_x}} = \frac{(\mathrm{Var}(C_{CEA,t_x}) + \mathrm{Var}(C_{CEA,t_{x-1}}))^2}{\frac{\mathrm{Var}(C_{CEA,t_x})^2}{df_{t_x}} + \frac{\mathrm{Var}(C_{CEA,t_{x-1}})^2}{df_{t_{x-1}}}}$$

These equations represent the amount of uncertainty in carbon stock change, given the sampling intensity at two estimation events. These equations require variances and degrees of freedom from the carbon stock estimates at time points {x} and {x – 1}.

Calculating the variance and the degrees of freedom for a specific estimation event differs slightly between estimation schedules:

1. **Spatially referenced** - The variance can be calculated from the validation samples in our validation group, where there is data on both measured and modelled carbon stocks. For each sample, compare the model's estimate to what we measured:

$$\mathrm{Var}(C_{\mathrm{CEA},t_x}) = A_{\mathrm{CEA}}^2 \times \frac{1}{n}\sum_{i=1}^{n}(\bar{C}_i - C_i)^2$$

Where {A_CEA} is the area of the CEA, {n} is the number of measured areas in the relevant stratum of the validation group, {C_hat} is the model estimate of the mean carbon stock and {C} is the measured estimate of the mean carbon stock for area {i}.

Sometimes, like at the first estimation event, these will be calculated using measurement surveys taken on your project. Other times, these will come from the measurement surveys taken from the validation group of your model. Since unmeasured CEAs in the same stratum share similar characteristics with the measured ones, the uncertainty in carbon stock estimates measured in the validation subgroup can be applied to all CEAs in a stratum, even those that haven't directly measured. This approach includes it includes both the uncertainty in the model and the natural variability within the validation group.

The degrees of freedom for a validation stratum can be calculated as:

$$df_{t_x} = n - 1$$

This reflects the number of independent pieces of information available to estimate the variance.

2. **Spatially explicit estimation schedules.** Most spatially explicit models will also provide spatially explicit uncertainty maps in the form of standard deviations per pixel

$$Var(C_{CEA,t_x}) = \iint_{A_{CEA}} \sigma^2(x, y)\, da$$

Where {sigma(x,y)} is the standard deviation at coordinates {x} and {y}. This differs for the spatially referenced analysis in that uncertainties are provided per mapping unit, meaning that once the map has been validate the variance can be calculated for an individual CEA.

The degrees of freedom for a spatially explicit carbon stock map can be calculated as:

$$df_{t_x} = N^*_{\text{ef}} - 1$$

Where {N*_ef} is the effective sample size calculated through variogram analysis.

Box 6. Potential option: Variogram analysis to account for spatially correlation

In spatially explicit models, it's common that carbon stocks are correlated. That means that measuring two neighbouring mapping units might provide some information, but less than two very distant mapping units. We account for this effect with variogram analysis. It's a way of reducing the effective sample size proportionally to how 'clumpy' carbon stocks are in space. It's a bit technical, but in effect it tests for the distance at which mapping units stop being related to each other.

The calculation of a variogram is as follows:

$$\hat{\gamma}(h) = \frac{1}{2|N(h)|} \sum_{(i,j)\in N(h)} [C(x_i, y_i) - C(x_j, y_j)]^2$$

Where {gamma_h} is the proportion of variance at distance {h} which is measured in meters, {N(h)} is the number of pairs of validation samples at distance {h}, {C(x, y)} are the estimated carbon stocks at coordinates {x} and {y}, which are compared for pairs of mapping units {i} and {j}.

In plain English, this tells us on average how similar two points are in carbon stocks at a given distance. As {h} increases, we expect to see the number of pairs increase, and the average similarity to decrease. As similarity decreases, the variance is expected to increase.

We want to find out the distance {h} where the variance is nearly that of the average variance in carbon stock map. In geostatistics is the average variance is called the sill and the target of our search is the distance that approaches the sill, which is called the range:

$$\text{sill} = \frac{1}{A_{\text{total}}} \iint_{A_{\text{total}}} \sigma^2(x, y)\, da$$

$$\text{Range} = \min\{h : \hat{\gamma}(h) \geq 0.95 \cdot \text{sill}\}$$

where {A_total} is the area of the map, and {sigma} is the standard deviation at coordinates {x} and {y}.

It might take a few attempts to find the range that exceeds 95% of the sill. While it's not important to get the range exactly right, it's in your interest to minimise the range as it can have an impact on your effective sample size. The effective sample size treats samples of spatially explicit biomass maps as circles with radii the length of the range:

$$N^*_{\text{ef}} = \frac{A_{\text{total}}}{\pi \cdot \text{Range}^2}$$

Where {N*_ef} is the effective sample size of the spatially explicit biomass map.

This approach is necessary because the spatial distribution of carbon stocks can be mapped in fine resolution, providing a very large sample size, which might make the probability of exceedance adjustment appear overconfident. By accounting for spatially correlated carbon stocks, variogram analysis ensures that we adjust our estimates of carbon stock change in a way that reflects our confidence in models and measurements.

Step 3.6: Deduct emissions

There are three types of emissions that need to be deducted – direct emissions due to project activities, emissions due to leakage, and emissions due natural disturbances.

Emissions due to project activities can be calculated using emissions factors. For natural disturbances, it's necessary to work out how much carbon has been lost from a CEA. Emissions due to leakage are calculated in accordance with the Guidelines for reporting and monitoring leakage.

Regardless of the source of emissions, you'll need to convert emission from gasses like NO2 and CH4 into carbon dioxide equivalents (CO2-e) using their global warming potential.

Step 3.7: Calculate net abatement and creditable ACCUs.

Your project's net abatement is calculated by carefully adjusting the estimated carbon stock changes to account for several factors.

First, the eligible carbon stock ratio ensures you're only crediting changes that result from your project activities. Then, adjusting for uncertainty using the probability of exceedance method provides a conservative estimate of carbon changes. Finally, deducting any emissions that occurred in your project area, including those from natural disturbances and project activities, ensures that the carbon credits issued for your project accurately represent the real, additional, and verifiable carbon benefits resulting from your land management practices.

The final equation is:

$$\text{Net Abatement} = \left(\sum_{i=1}^{N} \Delta C_{\text{PoE},i} \times \frac{44}{12} - E_i \right) - E_{project}$$

Where {N} is the number of CEAs, {Delta_C_PoE} is the eligible change in carbon stocks after the probability of exceedance adjustment, and {E} are the emissions from your CEA.

Step 4: Project gateways

Note: This step applies to woody biomass CEAs only

Your projects will encounter regular project gateways to assess whether the ecosystem is sequestering carbon and advancing toward its maximum sustainable carbon stock. The gateway represents a time point when the CEA stratification is adjusted based on observations of growth. For projects using spatially referenced or spatially explicit models to estimate biomass, gateways occur at each CEA measurement event (i.e. at least once every ten years). For projects using the national model approach, the gateways occur every five years.

Step 4.1 Assess progress towards forest cover

Note: This step is only required for woody biomass CEAs using the national model approach.

Every five years, your project is required to demonstrate progress towards achieving forest cover, measured as a % canopy cover over a given spatial scale. The canopy cover and spatial scale to be applied at each gateway is determined by the 'Forest Cover Assessment Date' for your project, which is based on the model commencement date and the number of growth pauses that have been applied. Areas of CEA that are not meeting the required canopy cover thresholds must either be removed from the CEA if they do not have forest potential or they can be paused in the FullCAM model.

Step 4.2 Repeat gap analysis based on carbon stocks

Note: This step is only required for woody biomass CEAs using the spatially referenced or spatially explicit approach.

Every time your CEA is measured (i.e. at least once every ten years), you must conduct a check that carbon stocks in your CEAs (and other relevant biophysical variables if desired) are advancing towards your nominated ecosystem benchmarks. This is done via a repeated gap analysis. If your CEAs are not advancing towards the ecosystem benchmark, you will be required to provide additional evidence on why no progress had been made (such as experiencing drought or other conditions), or else the CEA should be removed if it does not have sequestration potential.

Step 4.3 Adjust the eligible carbon stock ratio

Note: This step is only required for woody biomass CEAs using the spatially referenced or spatially explicit approach.

Every time your CEA is measured (i.e. at least once every ten years), you will adjust the eligible carbon stock ratio, based on actual growth of the eligible and ineligible size cohorts.

At the subsequent measurement event, you will measure the number of ineligible and eligible trees, based on the number of eligible and ineligible determined at the first measurement event. You will biomass of trees in each category. The eligible carbon stock ratio is adjusted based on the proportion of eligible vs ineligible biomass in the sample. The re-measurement could be conducted using permanent sample plots, but this is not mandatory due to the difficulties in relocating permanent sample plots.

For example, at the first estimation event, if 25 trees per hectare or plot were too large to be eligible then biomass change attributed to the largest 25 trees per hectare or plot is assumed to be ineligible. The new eligible carbon stock ratio compared to the initial estimated eligible carbon stock ratio, and carbon may be released from the eligible carbon buffer if it is found to be conservative.

If using area-based metrics and the eligibility criteria is based on tree height, if 2.5 ha had canopies above the height limit at the first estimation event, the biomass change attributed to the tallest 2.5 ha is compared to the reserve carbon stock change.

It is important to use absolute terms and not percentages for calculation of the eligible carbon stock ratio, as new trees may recruit between project gateways, generating eligible abatement. This is conservative because it assumes that ineligible trees are 'permanent' and do not die during the course of the project period.

Box 7: Potential alternative approach – lookup eligible carbon stock ratio

One potential weakness of the eligible carbon stock ratio approach described above, is the potential for the eligible carbon stock ratio to vary significantly from the initial measurement, if the plots at the subsequent sampling event have a substantially different size class structure to the plots used at the initial measurement event. One way around this issue is to use permanent sample plots (i.e. re-visit the same plots each time). However, revisiting the same plot locations can be difficult at large scales.

An alternative to the re-measurement approach, is the have a simple lookup table, estimating the eligible carbon stock ratio over time for a given starting position. This would require an expert group to develop modelled forecasts of eligible and ineligible carbon stock over time, based on given starting size class structures. This would likely need to be conducted for each Major Vegetation Group in Australia.

Another alternative could be to monitor growth of different size cohorts in control sites. This is likely a parallel R&D initiative that could be used to validate or complement the other suggested approaches.