Technical document

Modelling forest carbon dynamics for REDD+ using the Generic Carbon Budget Model (GCBM)

Pilot Project
Los Rios Region - Chile

Progress to date

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The views expressed in this report do not necessarily reflect the positions of the Government of Chile or the Government of Canada.

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Executive Summary

REDD+ (Reducing emissions from deforestation and forest degradation, conservation of forest carbon stocks, sustainable management of forests and enhancement of carbon stocks) is one of the main mechanisms of the United Nations Framework Convention on Climate Change (UNFCCC) for driving emission reductions and enhanced removals of greenhouse gases (GHG) in the land sector (UNFCCC, 2016). The REDD+ approach incentivizes countries to voluntarily report annual estimates of GHG emissions and removals from forests. For this purpose, countries typically establish national MRV (measurement, reporting, and verification) systems (Birdsey et al., 2013; GOFC-GOLD (2014)).

One of the challenges in developing MRV systems is the integration of national and global data to obtain GHG fluxes to fulfill the principles of transparency, accuracy, comparability, consistency and completeness (TACCC) (IPCC 2003). To face these challenges, the moja global project, of the Linux Foundation, is developing the Full Lands Integration Tool (FLINT) which is an open-source modelling framework that integrates different data types and modules to calculate GHG fluxes more efficiently for the land sector, while adhering to the TACCC principles (moja global, 2017). One of the implementations of the FLINT is the Generic Carbon Budget Model (GCBM), developed by the Canadian Forest Service, and based on the same science modules used in the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al., 2009) for UNFCCC GHG inventory reporting and mitigation scenarios analysis.

Chile is one of the countries that already consigned their Forest Reference Emissions Levels (FREL) (2001-2013), along with a Technical Annex on REDD+ results (2014-2016), to the UNFCCC. This makes the country potentially eligible for results-based payments through funds such as those established by the Green Climate Fund (GCF) and the Forest Carbon Partnership Facility (FCPF). Although Chile has a relatively mature MRV system in place, the calculations are being made using tabular data, so new tools are being tested to analyze and report spatially-explicit results in an integrated framework, allowing the country to gradually implement more complex forest carbon models. The GCBM is one of the tools evaluated.

The purpose of this report is threefold:

1) Provide an overview of the steps conducted in a GCBM proof of concept in a pilot area, considering a subset of the REDD+ activities and carbon pools included in Chile’s FREL;

2) Reflect on the next steps required for the full implementation of the GCBM model to account for all of the activities and regions eligible for REDD+, along with the required steps to improve GHG emissions estimation, reporting and analysis capabilities in Chile using open-source modelling tools, and

3) Reflect on the potential role a non-profit consortium, such as moja global, may have in supporting countries to achieve multiple objectives for sustainable land-use planning and policy development.
Chile’s MRV professionals, located in the National Forestry Corporation (CONAF), designed and conducted the proof of concept implementation and simulation runs in collaboration with the Canadian Forest Service, moja global and the Mullion Group. The pilot project was undertaken in the Los Rios Region in southern Chile, and included estimations of GHG emissions and removals from changes in the total biomass component resulting from the following activities: deforestation (conversion of forest to non-forest land use), substitution (conversion of native forest to exotic trees plantations), and afforestation (conversion of non-forest to forest land use).

National data included in the land-use cadastre maps and the national forest inventory were preprocessed and used as input to the model, while specific parameters were left as default when not available from the national data. The process to customize the GCBM included the adjustment of the volume to biomass parameters, the root parameters, the inclusion of a local spatial data layer of temperature and the creation of custom disturbance matrices, among others. To obtain annual disturbance layers for the area from discrete land-use maps covering multi-year periods, the year of the disturbance was assigned at random within the periods between the land use maps.

Although this exercise was only a rapid proof of concept and a demonstration of how the available spatially-explicit data can be integrated in a transparent and consistent way, it is also possible to examine the numerical results as long as it is understood that these will be revised with improved implementation of data that reflect the Chilean forest conditions. The estimates of GHG emissions from total biomass in the deforestation and substitution activities were very similar to the ones presented in Chile’s FREL, with differences of less than 4% between both approaches (the GCBM producing slightly higher emissions). The afforestation activity estimates from the GCBM showed a difference of +25.4% relative to the FREL, which was attributed to model assumptions before the start of the FREL period (e.g., annual GHG removals from afforestation activities include the year 1997 and onwards; the GCBM pilot assumes zero GHG emissions from afforestation activities, while Chile’s FREL accounts for biomass losses due to the conversion of non-forest land to forest land use). These assumptions can be revised to be consistent with the assumptions previously used by Chile.

This initial phase showed that the GCBM was able to produce similar estimates for the main source of GHG emissions reported in the FREL, which corresponds to forest biomass losses due to substitution and deforestation (62.2% of the net emissions reported in the FREL of Los Rios Region). Furthermore, the GCBM implementation on the Chilean case is capable of producing spatially-explicit results of forest carbon dynamics that can potentially inform national policy making and be used to monitor actions to address the risks of reversals and to reduce displacement of emissions as referred in the Cancun safeguards (UNFCCC, 2010).

This exercise proved that the use of complex models such as the GCBM can be easier when performed by the national professionals that work with the data on a day-to-day basis, together with the support of a global community of users of and contributors to open-source tools such as moja global. This can enable the country and the domestic professionals to implement sophisticated platforms, that have the potential of improving analytical power and reducing
dependencies on rotating consultant on short term contracts, showing the importance of national staff consolidation and training.

This implementation of the GCBM is one of the first attempts to adapt a spatially-explicit model for forest carbon accounting with the Chilean data at a regional level. Examples of the next steps include continuing to improve model calibration and assumptions of biomass, dead organic matter and soil organic carbon components, the inclusion of the REDD+ activities occurring in forest land remaining as forest land, expanding the project to all the Chilean accountability zone for REDD+ activities, and supporting the development of open-source tools that can enhance MRV-AFOLU systems globally.


1 Introduction

The Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) sets ambitious goals for reducing greenhouse gas (GHG) emissions to limit global warming to less than 2°C above pre-industrial levels before the end of this century (UNFCCC, 2015; IPCC, 2018). According to the Intergovernmental Panel on Climate Change (IPCC), the Agriculture, Forest and Other Land Use (AFOLU) sector generates about 23% of the total net anthropogenic emissions of GHG (IPCC, 2019). However, with enough economic investment and capacity building support, particularly in developing countries, the AFOLU sector can help achieve net zero GHG emissions, while providing other important social and natural co-benefits (e.g., increased adaptation, biodiversity conservation, improved water and soil health; IPBES, 2019; FABLE, 2019).

REDD+ is one mechanism for driving reductions and enhanced removals from the land sector, through results-based payments. REDD+ stands for reducing emissions from deforestation and forest degradation plus conservation, sustainable management of forests and enhancement of forest carbon stocks (UNFCCC, 2016). Under the UNFCCC’s Cancun Agreements, REDD+ is divided into three phases (UNFCCC, 2010, 2011): Readiness, Demonstration Activities, and Activities for Results-based Payments. The REDD+ mechanism requires that countries undertaking REDD+ activities for results-based payments provide annual estimates of changes in forest carbon stocks, and their corresponding GHG emissions and removals, by establishing a system for national measurement, reporting and verification (MRV). In order to be credible, these systems must be able to generate results that adhere to the TACCC principles: transparency, accuracy, comparability, consistency and completeness, as described in the IPCC’s 2003 Guidance for National Greenhouse Gas Inventories (IPCC 2003).

In general, to design and implement MRV systems for REDD+, countries rely on a combination of remote-sensing imagery and data collected through ground-level forest inventories to help monitor carbon stock and stock changes (Birdsey et al., 2013; GOFC-GOLD, 2014). These approaches include monitoring changes from the past, improving the level of understanding of the drivers of these changes, and estimating emissions in the future (e.g., for both reference emissions levels and mitigation pathways). Although substantial progress has been made on the quality of the available information, particularly in the remote-sensing arena (Hansen et al., 2013; Wulder et al., 2019; Dubayah et al., 2020), there is still a need to enhance the data integration processes to reflect realities on the ground in a scalable, operational context. For example, integrating multiple sources of data (both spatial and aspatial) under the same analytical framework creates consistency, and can help countries to fulfill their UNFCCC reporting requirements while informing operational decision-making. In addition, many developing countries face the challenge that REDD+ activities and other land sector data are occurring at a variety of scales (national, sub-national, and project level), and therefore require a system that can estimate emissions at all scales.
In 2017, the Linux Foundation launched the *moja global* project, an open-source initiative to support sustainable land management efforts through the continuous development of software for the land sector (moja global, 2017). The first major project for *moja global* software is the Full Lands Integration Tool (FLINT) which is a modelling framework that integrates different data types (spatial and aspatial) and modules to calculate GHG emissions and removals for the AFOLU sector. FLINT builds on 20 years of experience with integration frameworks developed and operated in the land sector by countries like Australia and Canada. Because modules, data, and output processes can be attached to the FLINT framework in a unique configuration (known as an “implementation”), the system can be tailored to meet country-specific needs and capacity in a progressive and efficient manner. To date, there are three examples of implementations of FLINT and available modules: the System for Land Based Emissions Estimation in Kenya (SLEEK), a software-as-a-service version of FLINT called FLINTpro, and the Generic Carbon Budget Model (GCBM) developed by the Canadian Forest Service. The latter is based on the same science modules used in the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al., 2009), which is a modelling framework focused on forest carbon dynamics, with several applications outside of Canada (Kim et al., 2015; Pilli et al., 2016; Dugan et al., 2018), including examples for the analysis of REDD+ scenarios (Olguin et al., 2011, 2018).

Currently, Chile is one of a growing number of countries that have published a Forest Reference Emissions Level / Forest Reference Level (FREL) and a Technical Annex of REDD+ Results (UNFCCC 2020), making it eligible to apply for results-based payments under the Green Climate Fund of the UNFCCC (i.e., US$ 63.3m in 2019). However, many of the estimates of GHG emissions and removals are conducted mainly using Excel spreadsheets, limiting the country’s ability to obtain spatially-explicit results. The possibility to model forest carbon dynamics and report forest carbon results in a spatially-explicit manner is one of the key aspects of the planned steps Chile identified to improve their MRV system. This would also allow the country to enhance the information that is available to policy makers and to monitor Cancun safeguards such as emissions reversals and to reduce emissions displacements (decision 1/CP.16; UNFCCC, 2010).

The purpose of this report is to document progress to date on the use of the GCBM tool by Chilean government experts in Chile, located in the National Forestry Corporation (CONAF), the national focal point for REDD+. This report is part of Chile’s stepwise approach to compare results between the methods used in the compilation of the FREL, against those of a forest carbon dynamics model with a spatially-explicit approach (GCBM). Specifically, the study provides an overview of the steps conducted in a proof of concept in the Los Ríos Region, considering a subset of the REDD+ activities and pools included in Chile’s FREL. These results will help define the next steps for the full implementation of the GCBM model in the complete accountability zone for REDD+, along with the required steps to improve GHG emissions estimation, reporting and analysis capabilities in Chile using open-source carbon modelling tools. The hope is that this kind of tools will improve the capacity of the country to obtain accurate, spatially-explicit, and streamlined estimates of GHG fluxes associated with REDD+ activities. Finally, the report also

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1 Documents available at [https://redd.unfccc.int/submissions.html?country=chl](https://redd.unfccc.int/submissions.html?country=chl)
reflects on the potential role a non-profit consortium, such as moja global, may have in supporting countries to achieve multiple objectives for sustainable land-use planning and policy development.
2 Methods and input data

As part of its REDD+ Program, Chile submitted its subnational FREL to the UNFCCC, which comprised four REDD+ activity types: reducing emissions from deforestation, reducing emissions from forest degradation, conservation of forest carbon stocks, and enhancement of forest carbon stocks. The reference level was constructed at a subnational scale, covering five regions from central-south Chile: Maule, Biobío (including the Ñuble region), La Araucanía, Los Ríos and Los Lagos, comprising 11 out of 12 Chilean forest types and 41% of the forest area of the country. After the successful publication of the FREL on March 3, 2017, Chile started developing the Technical Annex of REDD+ Results, which was submitted on 3 December 2018. Measured against the FREL, the results reported a reduction of emissions of 6,454,090 tCO₂e per year for the years 2014-2016. One of the purposes of this proof of concept is to test if the assumptions and calculations made by Chile can be replicated using the alternative, model-based approach of the GCBM.

2.1 Pilot area

In order to test the capability of the model to work with Chilean data, a representative pilot region was chosen from the regions described in the subnational FREL. Los Ríos Region was selected as it contains activity records for the four REDD+ activities that Chile reports, and it contains 10 of the 11 forest types of the reporting area. Additionally, the data were well-organized and available to use for the integration framework.

Located in southern Chile (Figure 1), Los Ríos Region is 18,429.5 km² (2.4% of the national territory) in size, and comprises 11.1% of the area reported in the FREL. It is characterized by the presence of temperate rainforest, a high amount of rainfall, that ranges from 1,487 mm per annum in San Jose de la Mariquina (Central Valley) to 3,903 mm per annum in the Valdivian Coastal Reserve. The mean annual temperature is 11 °C (Pichoy Meteorological Station) (Center for Climate and Resilience Research, 2019a).

The Capital of Los Ríos Region is Valdivia and according to the 2017 census, the total population of the region is 384,837 inhabitants meaning a density of 20.88 inhabitants per square kilometer. A large part of the regional economy is based on the forestry industry (Biblioteca del Congreso Nacional, 2019), with a high presence of exotic planted forest, mainly *Pinus radiata* and *Eucalyptus globulus* species.
2.2 General approach

As part of Chile’s stepwise procedures to improve their MRV processes, new tools are being tested to integrate the internal processes for estimation and reporting. As Chile already consigned their FREL to the UNFCCC, which was consequently reviewed and approved, it is necessary that tools such as the GCBM are, in the first place, able to replicate the procedures that are already in place. Thus, this proof of concept focused on the replication of the assumptions and methodologies presented in the Chilean FREL using the GCBM. At the same time, tools such as the GCBM can allow for continuous improvements in methods also required by mechanisms such as the GCF and FCPF.

In this pilot, a subset of REDD+ activities was selected as part of this first test run, with the eventual aim of implementing all the REDD+ activities in Chile. The pilot project had the objective of quantifying the CO₂ emissions and removals derived from REDD+ activities or sub-activities that involve a land-use change, meaning deforestation, substitution (land-use change from native forest to forest plantation) and afforestation (planting of new native forests) (Table 1). It is important to point out that for REDD+ accounting purposes, the forest plantations with exotic species (hereafter forest plantations) are not considered in the context of the national definition.

Figure 1- Location of Los Rios Region
Table 1. REDD+ activities included in Chile’s FREL

<table>
<thead>
<tr>
<th>REDD+ activity</th>
<th>Land Use Change</th>
<th>Permanent forest (Forest remaining forest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reducing emissions from Deforestation</td>
<td>Conversion of native forest to other non forest land uses*</td>
<td></td>
</tr>
<tr>
<td>Reducing Emissions from Forest degradation</td>
<td>Conversion of native forest to forest plantations (substitution)*</td>
<td>Permanent forest degradation Forest fires</td>
</tr>
<tr>
<td>Enhancement of forest carbon stocks</td>
<td>Transformation of other land uses to native forests*</td>
<td>Recovery of degraded forests</td>
</tr>
<tr>
<td>Conservation of forest carbon stocks</td>
<td></td>
<td>Net flux of emissions in permanent forest by degradation of permanent forest and recovery of degraded forest in conservation areas</td>
</tr>
</tbody>
</table>

* Included in this Pilot project.

2.3 Modelling approach

The Generic Carbon Budget Model (GCBM) is an open-source modelling framework focused on forest carbon dynamics, consistent with the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National GHG Inventories reporting (IPCC, 2006) and the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003), that combines empirical data on biomass dynamics with a process modelling approach for the simulation of dead organic matter (DOM) and soil organic carbon (SOC) pools. The GCBM is built on the platform of the Full Lands Integration Tool (FLINT) using Tier 3 modules, that are based on the well documented science of the CBM-CFS3 (Kurz et al., 2009). The GCBM allows the integration of inputs using a spatially-explicit approach (Approach 3 of IPCC 2003). In general, the GCBM integrates information from forest inventories, growth and yield curves, and natural and/or anthropogenic disturbance events, to simulate carbon stocks for the IPCC’s five forest carbon pools (above and belowground biomass, dead wood, litter and soil), and the fluxes associated with changes in these pools, both at the stand (e.g. pixel) and landscape levels.

The GCBM implements the IPCC gain-loss method to estimate stocks and stock changes. The GCBM models the overall ecosystem carbon balance from all sources and sinks at each annual time step, considering carbon gains from gross forest growth minus carbon losses due to decomposition of DOM at the pixel level, plus carbon stock changes due to the effect of disturbances over larger regions and time spans. The model tracks carbon mass transfers through known pathways in and out of the forest ecosystem to ensure carbon mass balance.

In order to be able to obtain similar results between the FREL report and the GCBM runs, several of the model parameters were customized using local data, while others were left as defaults for this proof of concept. In future applications of the integration framework, some of the parameters
that were left as defaults, such as decomposition or litterfall rates, can be changed to national variables taken from the literature or other research programs.

In this first pilot project, the calibration of the parameters was performed focusing on the GHG emissions and removals associated with carbon stock changes in the forest biomass (both below and aboveground), while the DOM and SOC values were left “as is” and would have to be improved in future applications of the model to better reflect Chile’s national ecosystem conditions.

2.4 Sources of data

To feed the model with the necessary information, two main sources of data were used: The Forest Cadastre maps, and the National Forest Inventory.

The Forest Cadastre maps are the product of an ongoing project called “Cadastre and Evaluation of Vegetation Resources in Chile”, developed by the Government of Chile from 1993 to the present time. The main objective of this government project is to create a national cadastre of land use and vegetation classification, with a focus on the native and planted forest. This information is periodically updated via regional projects that monitor the changes in land use and vegetation, providing public data that are used for decision making and land management.

The methodology used to build the Forest Cadastre was developed by Etienne & Prado (1982) and consists of the manual interpretation of land use data that is supported by fieldwork and interpretation of high-resolution satellite and aerial photos. This allows Chile to have a rich set of information that includes the forest type (as classified by Donoso, 1981), forest structure and detailed land use, among others.

In the case of Los Rios Region, the baseline of the Cadastre was developed in 1997, with updates in 2006 and 2013. These land use maps were developed using manual interpretation along with a mixture of high- and medium-resolution satellite data, supported by extensive fieldwork. In 2017, another update of the land use maps was developed using semi-automated remote sensing techniques, allowing the country to have data in shorter periods of time.

The four above mentioned land-use maps are merged together into an integrated file called “Trazabilidad”, that consists of polygons of land use and an associated attribute table containing the historical variations of the polygons in the four periods of time, allowing the user to quickly derive the land-use changes, and accordingly, the REDD+ activities which are reported to have occurred in the different periods of time.

The second set of input data used in this project is the National Forest Inventory. This project, called “Continuous Inventory of Forest Ecosystems”, is managed by the National Forest Institute (INFOR) since 2000. The purpose of the inventory is to generate detailed information about the native forests of Chile, supporting the decision-making process. The Forest Inventory uses a two-stage statistical sampling design, distributing three circular plots in an area of 500 m², and using a 7x5 km systematic grid. The first cycle of measurements was developed between 2001 and 2010. A portion of the sample is re-measured each year in order to obtain information about the
growth and functionality of the forests. The Forest Inventory is used to obtain the Annual Periodical Increment (growth) of each forest type, the regional emission factors for deforestation, and the factors used for volume to biomass conversions.

2.5 Simulation runs

To conduct simulation runs, the GCBM uses a stepwise iterative approach which allows users to change data sources, if and when new or improved data become available. Using this stepwise approach, the different aspects of the GCBM were filled in order to transition from using the GCBM with default parameters to running the simulations with customized Chilean parameters. To accomplish this, the different components of the GCBM were customized using Python (Version 2.7) and R (Version 2.6.3) codes, allowing the user to input the data of the “Trazabilidad” layer and the factors derived from the National Forest Inventory into the GCBM. A general workflow of the input data used and the processing steps involved in the GCBM implementation, that will be explained in detail in the next sections, can be found in Figure 2.
The resolution used for the conversion of the polygon data provided by the cadastre into the raster data used by the GCBM was set to 0.0005 degrees, being approximately equivalent to a pixel size of 55 m by 55 m. This resolution was chosen because the more detailed maps of the “Trazabilidad” file (2017) were produced with a minimum mapping unit of 0.36 ha.

2.5.1 Inventory data at the start of the simulation (Classifiers)

The GCBM, as in the CBM-CFS3, requires an initial dataset called “inventory”, comprising the forest stands that are present at the beginning of the simulation. This dataset, that in the GCBM
has to be spatially explicit, contains the age of the stand and a set of characteristics of the stand called “classifiers,” which are defined by the user and can be related to site productivity, leading species and ownership, among others. Each set of unique classifiers is related to a specific yield curve (Kurz et al., 2009).

In order to start the modelling, the “inventory” dataset to run the GCBM was derived from the first year of the Forest Cadaster (1997). To create the inventory layer, three classifiers were used to associate the stands with the different land uses and growth curves that were included in the FREL (Table 2). The first classifier corresponds to the forest type classification of Donoso (1981), that is determined by the dominant species of the ecosystem and has a strong influence on the growth rate of the forests. The second classifier is the “Structure” of the forest, as it also influences the growth rates. The latter classifier is measured in the forest cadaster and reflects the vertical and horizontal layer distribution and is comprised by four categories: (a) Renoval: Secondary grown forest, generally presenting a high number of trees per hectare. (b) Adulto: Adult forest, primary grown, with a high presence of old trees with high DBH. (c) Adulto-Renoval. A stand containing a mixture of secondary and primary grown forests (d) Achaparrado: Low height forest growing in climate and soil restrictive conditions, as in the high altitudes of the Andes Ranges. Additional to these categories, two more classes were created: Bosque Mixto, to reflect native forest with a high presence of exotic invasive species, and non-forests, for land uses different to native forest. Apart from these two classifiers that are used in the FREL to determine the annual growth of the forest, a new classifier was created (Origin) to track the emission reductions derived from non-forest to forest land use changes (afforestation or reforestation).

The initial age of the forest stands in the inventory layer was set to 100 years old, to reflect a forest reaching the regional average of merchantable volume. Thus, the native forest coming from the initial inventory have 375.29 m³/ha of merchantable volume (average in Los Rios Region). This assumption is used in the FREL, as the assumed maximum carbon stock for intact forests, and thus a complete reduction of that stock would be classified as deforestation.
### Table 2. Classifiers used in Chile’s GCBM implementation

<table>
<thead>
<tr>
<th>Classifier</th>
<th>Forest type</th>
<th>Structure</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alerce</td>
<td></td>
<td>Renoval (secondary grown)</td>
<td>Initial (Native Forest coming from the 1997 Forest Cadaster)</td>
</tr>
<tr>
<td>Bosque Mixto</td>
<td></td>
<td>Adulto Renoval (Mixture of primary and secondary grown forests)</td>
<td></td>
</tr>
<tr>
<td>Cipres de la Cordillera</td>
<td></td>
<td>Achaparrado (low-height Forest growing in climate and soil restrictive conditions)</td>
<td></td>
</tr>
<tr>
<td>Ciprés de las Guaiéacas</td>
<td></td>
<td>Non-forest (includes forest plantations)</td>
<td></td>
</tr>
<tr>
<td>Coihue - Rauí - Tepa</td>
<td></td>
<td>Bosque Mixto (Native forest with high presence of exotic species)</td>
<td></td>
</tr>
<tr>
<td>Coihue de Magallanes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esclerofilo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lenga</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roble - Rauí - Coihue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siempreverde</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-forest (includes forest plantations)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.5.2 Biomass dynamics

#### 2.5.2.1 Growth curves

In order to model forest biomass accumulation through time, the GCBM requires yield or growth curves that are linked to different sets of classifiers. These curves are represented as merchantable volume of stem wood per year, for each set of classifiers. The GCBM growth curve library can accommodate a wide range of growth curve types defined by the user. These could be simple “constant growth” rates similar to those used in Tier 1 or Tier 2 emission factors (growth per hectare and year by forest type). More sophisticated sigmoidal growth curves (e.g. Chapman-Richards growth equations) or derived from growth and yield models can also be used, where these are available.

In the Chilean case, to reflect the dynamics of the native forest of Los Rios Region, customized growth curves were constructed and used as input data for the model. To incorporate the different assumptions that were used in the FREL, two groups of growth curves were developed, using the “Origin” classifier to differentiate them.

**Origin: Initial Forest**

In order to estimate the CO₂ emissions from deforestation, Chile’s FREL uses regionally-specific emission factors (Tier 2), derived from the National Forest Inventory. These emission factors do not change with time, and thus, a single growth curve was used (Figure 3) to reflect this “static,” homogeneous condition. This growth curve reaches its maximum at the age of 100 years, a number that was used as an approximation of the age in which the native forest reaches dynamic equilibrium, representing 375.29 m³/ha of merchantable volume (average in Los Rios Region).
For the afforestation activities, Chile’s FREL uses Annual Periodic Increment values to calculate the growth of each new forest, according to forest type and structure. To reflect this decision, linear growth curves were constructed for each combination of forest type and structure (see Table 2 for structure classes). To be consistent with the initial forest condition, the growth curves stop their increments at the age of 100 years (Figure 4), when they reach the maximum volume value (Annual Periodic Increment * 100). The Bosque Mixto structure, that is not included in Figure 4, presents an average annual periodic increment weighted by area of the different forest types in the region (the same assumption as in the FREL).
Figure 4. Simplified growth curves by forest type and structure (new forests) used in the pilot.
With additional data and time, the growth curves can be improved.

2.5.2.2 Volume to biomass expansion

The GCBM model growth curves use values of merchantable stem wood volume per hectare (m$^3$/ha), that are converted to aboveground merchantable stem biomass per hectare in the model using parameters derived from sample plot measurements. After that, this variable is used to get the biomass values of the different biomass components of the forest, including sapling trees, branches and foliage of merchantable and non-merchantable wood. In order to do that, the equations of Boudewyn et al. (2007) were fitted for a set of Canadian forests in the original CBM-CFS3 model.

The approach of Boudewyn et al. (2007), includes several equations to derive the biomass of the different tree components from the volumes of merchantable total biomass. However, Chile’s approach in the FREL is to use a single expansion factor (1.75) to derive the total volume of the forest and then to use the basic wood density (0.5) to get the oven-dry biomass and a factor of 0.5 to estimate the carbon content in that biomass. In order to reconcile these two different approaches, only the merchantable total biomass was calculated for the forests in this GCBM pilot. Equation 1 of Boudewyn et al. (2007) was used to calculate the total merchantable stem biomass:

$$b_m = a \times \text{volume}^b$$
where,

\[ \text{volume} = \frac{\text{gross merchantable volume/ha of all live trees (volume does not include stumps, tops, or trees< merchantable DBH)}, \text{ in m3/ha.}}{\text{b_m}} = \text{total stem wood biomass of merchantable-sized live trees (biomass includes stumps and tops), in metric tonnes per ha.} \]

\[ a,b = \text{non-linear model parameters fit separately by Canadian jurisdictions, ecozones, and lead tree species} \]

In the case of Los Rios Region, “a” was set to 0.875 (expansion factor = 1.75 multiplied by the basic wood density = 0.5) and “b” was set to 1.

The other equations included in Boudewyn et al. (2007) were parameterized to give a value of zero for non-merchantable-sized trees, saplings, and a proportion of zero for bark, branches and foliage, making the stem wood the only component of the tree that was considered in this simulation.

The root parameter in this case was set to 0.2829 for hardwood and softwood values (same value as in the FREL). The proportions for the coarse and fine root components were left as default.

### 2.5.2.3 Dead Organic Matter and Soil Carbon

In accordance with the mass balance concept in the 2006 IPCC guidelines, the GCBM explicitly links dead organic matter (DOM) and soil organic carbon (SOC) dynamics with the dynamics in the live biomass carbon pools. Similar to the CBM-CFS3 model (Kurz et al. 2009), the initialization of the DOM and SOC pools in GCBM uses a spin-up procedure to track carbon transfers from live to dead biomass, as a function of tree productivity, decay rates, climate (mean annual temperature), historic disturbances, as well as the type of, and time since, the last stand-replacing disturbance.

In this study, all the ecological parameters required to calibrate DOM dynamics (e.g., biomass turnover rates, litterfall transfer rates, decomposition rates) were obtained from default data available within the GCBM. Only the information on climate was specific to Chile. These data were derived from the raster products from the Center for Climate and Resilience Research (CR2). To obtain the mean annual temperature for the period, the CR2MET monthly observations (Center for Climate and Resilience Research, 2019b) were averaged for the period of 1997 and 2016. These were used to create a raster layer with 5 km spatial resolution, that was used as input for the GCBM. In the future finer resolution climate data can also be used, where available.

### 2.5.3 Disturbances

To simulate the effect of natural and human disturbances (e.g. land-use changes, selective harvesting, wildfire, hurricanes, pests, etc.) on ecosystem carbon dynamics, the GCBM uses
disturbance matrices. These matrices contain information about 22 carbon pools that can be easily grouped into the five IPCC carbon pools, to represent carbon transfers among carbon pools in the forest ecosystem and among these pools and the atmosphere due to land cover change events (Kurz et al., 2009). Where harvesting occurs, the disturbance matrix also defined the amount of carbon transferred to the wood product sector. To recreate deforestation activities as in the FREL, a customized disturbance matrix was created in which 100 per cent of the biomass in the aboveground and belowground components of the trees are immediately converted to CO$_2$ (instant oxidation). This assumption matches the assumption used in the FREL. In the future, biomass can be transferred to dead organic matter pools and then either be burned or decompose over time to generate a more realistic representation of the impacts of land-use changes.

The abovementioned disturbance matrix was also used for the substitution activity, as the conversion of native forest to forest plantations is calculated as a deforestation event for Chile's REDD+ purposes (consistent with the policy assumptions made by Chile, the growth of the forest plantations are not considered in the emission/removal estimations). In the future, the contribution of forest plantations to the GHG balance can also be evaluated for other reporting purposes.

The third disturbance type that was considered is afforestation. This disturbance occurs when a non-forest polygon (including forest plantations) is converted to native forest. In each of the new forest polygons, the forest type and structure were specified, and the origin classifier was set to “New forest” to link it with the corresponding growth curve.

As mentioned above, the land use maps that are being used to derive the disturbances were produced in the years 1997, 2006, 2013 and 2017. Thus, in order to create a more realistic scenario, a randomization of the disturbance year was implemented. As an example, if a disturbance in a polygon was detected in the 2006 land use map, a random year between 1997 and 2006 was assigned to the disturbance event. In the future, auxiliary data on land cover changes could be used to detect and assign the year of disturbance.
3 Results and Discussion

3.1 Areas of Disturbance

The results of the randomization of the disturbance year are shown in Figure 5. The results show a large proportion of the substitution events were detected between 1997 and 2006, with a large decrease in the 2014-2016 period, while the deforestation regime tends to have a more homogeneous behavior over time. On the other hand, the afforestation events had a much larger contribution in the results-based payment period (2014-2016) than in the reference level period (2001-2013). Note that the sum of the disturbances in any of the periods is based on data, while the allocation of the sum to individual years in the period is based on random allocation. With more time, Monte-Carlo simulation with alternative allocations could be conducted to quantify the contribution to the uncertainties resulting from annual allocation of disturbance events within each of the periods.

![Figure 5. Annual areas affected by afforestation, deforestation and substitution disturbances](image)

To determine the annualized area of disturbance in the FREL, a linear interpolation was used. To compare the approach of the FREL with the one used in this pilot project, the mean disturbance rates were calculated and compared with the ones reported by Chile (Table 3). It is possible to see that the interpolation and randomization approaches produced relatively small differences.
Table 3. Comparison between the disturbance areas in the FREL and this pilot project.

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Area (ha/year) GCBM Pilot Project</th>
<th>Area (ha/year) FREL</th>
<th>Difference between FREL - Pilot Project</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deforestation</td>
<td>756.19</td>
<td>750.77</td>
<td>5.43</td>
<td>0.72%</td>
</tr>
<tr>
<td>Substitution</td>
<td>908.43</td>
<td>919.21</td>
<td>-10.77</td>
<td>-1.17%</td>
</tr>
<tr>
<td>Afforestation</td>
<td>912.84</td>
<td>911.93</td>
<td>0.91</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

3.2 Results for the deforestation emissions

The deforestation activity was modeled in the GCBM, and calculations of the CO₂ emissions from losses of live biomass (both above and belowground biomass) and DOM were extracted (although the latter was not calibrated for this pilot and should therefore only be interpreted as examples). As seen in Figure 6, the emissions from biomass are far larger than the ones coming from the transfer of DOM to CO₂ (atmosphere).
When comparing these results with the ones presented in the FREL for the period between 2001 and 2013, it is clear that the emissions from biomass were relatively similar, with the emissions calculated by the GCBM only 3.92% larger than the ones calculated in the FREL. This difference can be attributed to the fact that, in the FREL, the biomass of the post-disturbance land use classes is subtracted from the CO₂ emissions from deforestation. In the case of the GCBM, all the non-forest land use classes have default biomass of zero, which contributes to these small differences.

In the case of the emissions from DOM, the estimations of the GCBM are significantly less than the ones reported in the FREL (-75.02%). This difference is due to the fact that the volume to biomass factors that were used in the model were set to only consider the stem biomass, omitting the inclusion of foliage, branches and other elements that contribute to the accumulation of DOM. This caused the spin-up procedure of the GCBM to accumulate low quantities of carbon in the DOM reservoir, and thus making the emissions significantly less. This behavior of the figures demonstrates that the model was designed with an integrated approach as the main focus, respecting mass balance at all times, and showing that it is important to take into account the interaction between carbon pools to obtain consistent estimates.
Although not the focus of this pilot the large difference in the emissions from the DOM pool makes the total emissions from deforestation lower than reported in the FREL (-15.86%), as indicated in Table 4.

Table 4. Comparison of CO$_2$ emissions from deforestation between the FREL and the GCBM. Note that DOM emission estimates are based on a preliminary and incomplete implementation of the model.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>GCBM estimated emissions (tCO$_2$/year)</th>
<th>FREL estimated emissions (tCO$_2$/year)</th>
<th>Differences between FREL and GCBM estimations (tCO$_2$/year)</th>
<th>Differences between FREL and GCBM estimations (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ emissions from DOM</td>
<td>40,368</td>
<td>161,591</td>
<td>-121,223</td>
<td>-75.02%</td>
</tr>
<tr>
<td>CO$_2$ emissions from Biomass</td>
<td>502,065</td>
<td>483,105</td>
<td>18,961</td>
<td>3.92%</td>
</tr>
<tr>
<td>Total CO$_2$ emissions</td>
<td>542,434</td>
<td>644,696</td>
<td>-102,262</td>
<td>-15.86%</td>
</tr>
</tbody>
</table>

3.3 Results for the substitution emissions

Regarding the emissions from the conversion of native forest to forest plantations (substitution), the results of the model show, as in the previous section, that the emissions from biomass are significantly larger than those from the DOM (Figure 7).
When comparing the GCBM estimated emissions with the ones reported in the FREL, as expected, the behavior is similar to that observed in the deforestation emissions, presenting a much lower amount of emissions from DOM (-77.43%) due to the assumptions described above (e.g., volume to biomass conversion). In the case of the GCBM estimates from biomass, the emissions are almost equal to the ones reported in the FREL (-0.5%). This can be attributed to the differences between the randomization of the disturbance year and the interpolation of the disturbed area used in the FREL, as in the FREL the forest plantations are considered to have zero biomass, hence not affecting the emission estimations. The total CO$_2$ in this case shows a difference of 156,102 tCO$_2$, being much lower (-20.15%) in this GCBM pilot project (Table 5).
Table 5. Comparison of CO₂ emissions from substitution between the FREL and the GCBM. Note that DOM emission estimates are based on a preliminary implementation of the model.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>GCBM estimated emissions (tCO₂/year)</th>
<th>FREL estimated emissions (tCO₂/year)</th>
<th>Differences between FREL and GCBM estimations (tCO₂/year)</th>
<th>Differences between FREL and GCBM estimations (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from DOM</td>
<td>44,6519</td>
<td>197,845</td>
<td>-153,194</td>
<td>-77.43%</td>
</tr>
<tr>
<td>CO₂ emissions from Biomass</td>
<td>573,869</td>
<td>576,777</td>
<td>-2,908</td>
<td>-0.50%</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>618,520</td>
<td>774,621.5</td>
<td>-156,102</td>
<td>-20.15%</td>
</tr>
</tbody>
</table>

3.4 Afforestation removals

The results for the afforestation activities were measured with the “Delta total biomass” indicator (Figure 8), with the knowledge that in the FREL, the removals due to DOM accumulation were not considered. This indicator shows a steady increment with the inclusion of new forest areas, as new forests are planted, increasing the removals in time.
The comparison of the estimations of the GCBM and the FREL gives greater results for the former of +24.41% (Table 6). This result can be explained by two main differences between the approaches. In the first place, in this pilot all the new native forest areas planted from 1997 to 2016 were considered to calculate the mean yearly removal in 2001-2013, while in the FREL a mean annual afforestation rate was calculated and applied in 2001 onwards, producing much lower removal rates in the first years of the reference level period. In the second place, the GCBM model does not consider a biomass value for the pre-afforestation land uses, while the FREL considers the emissions caused by the land use change, subtracting them from the afforestation removals.

**Table 6. Comparison of CO₂ removals from afforestation between the FREL and the GCBM**

<table>
<thead>
<tr>
<th>Indicator</th>
<th>GCBM estimated removals (tCO₂/year)</th>
<th>FREL estimated removals (tCO₂/year)</th>
<th>Differences between FREL and GCBM estimations (tCO₂/year)</th>
<th>Differences between FREL and GCBM estimations (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CO₂ removals</td>
<td>66,383</td>
<td>53,356</td>
<td>13,027</td>
<td>24.41%</td>
</tr>
</tbody>
</table>

**Figure 8. Delta total biomass indicator in new forests (afforestation)**
3.5 Spatially-Explicit Results

One of the key aspects of the GCBM model is its capability to generate spatially-explicit results. As an example, in Figure 9, the annual change in total biomass carbon density (tCO₂/ha/year) indicator results are shown in a zone south of Valdivia, where several deforestation and substitution events occurred between 2002 and 2005 (considering the year of disturbance randomization approach), while on the other hand new forests are planted, accumulating removals year by year.

Moreover, results like the ones shown in Figure 9 could be compared against other remote sensing analyses that can demonstrate that areas protected are indeed still present. Also, these results can be used to monitor safeguards such as removals reversal or emissions leakage, when implemented across a broader area.

Figure 9. Example of the spatially-explicit outputs produced by the GCBM
4 Lessons learned

The implementation of this first step in Chile’s pilot project on the use of the GCBM integration framework has generated several lessons. These lessons can be valuable for the next steps in the implementation of this kind of model or for other similar initiatives in the region.

Firstly, this model was implemented in a short amount of time, because a great portion of the spatially explicit data in Chile was already preprocessed and integrated into consolidated land use change files. The professionals that programmed the preprocessing steps were already familiar with the characteristics of the Chilean data and the assumptions made in the calculation of the FREL, making the comparative nature of this pilot process much more cost-effective.

When comparing the GHG emission from biomass values, both results (GCBM and FREL) were quite similar, showing that the GCBM can potentially provide almost the same results as in the FREL. Despite the understandable differences in the DOM emissions, this initial phase showed that the GCBM was able to produce similar estimates for the main source of GHG emissions reported in the FREL, which corresponds to forest biomass losses due to substitution and deforestation (62.2% of the net emissions reported in the FREL of Los Rios Region). Moreover, as in this pilot project the focus was centered on the calibration of biomass values, the national team was able to assess the effects of the biomass parameters in the DOM estimations in the GCBM model, demonstrating the effects of certain assumptions on the accumulation rates and transfer of carbon between the different forest carbon pools, showing the importance of considering an integrated approach for forest carbon modelling.

The GCBM has the big advantage of providing spatially-explicit results that could significantly improve the way the MRV system of Chile operates. The GCBM also provides an opportunity for continuous improvement beyond the limitations of spreadsheet-based approaches (e.g., difficult to integrate large quantities of data, more time consuming and prone to human errors), enhancing the quality of the estimates (e.g., ensuring carbon mass balance) and progressively transitioning to more complex analysis of forest carbon dynamics, that includes transfers and interaction between the different carbon pools. In addition, it enhances the operational capabilities that MRV systems need to have to comply with a range of reporting and scenario analysis commitments (e.g., FCTF, UNFCCC, Nationally Determined Contributions, etc.), without compromising any of the TACCC principles. GCBM data processing can all be scripted (e.g. using Python) and because of that the scripts can be re-used and audited by other team members or outside experts, This increases both the transparency and the reproducibility of the results – important criteria when requesting results-based payments.

The internal capacity of Chile’s team was complemented by the help of the professionals from the Canadian Forest Service Carbon Accounting Team (CFS-CAT), professionals from the moja global project, and the Mullion Group, which collaborated with their experience of the model functioning and implementation. This synergy between local knowledge and the broader experience in forest carbon modelling was crucial to the success of an early stage implementation of the model in Chile, that started with a training workshop on the use of the CBM-CFS3 organized
in Santiago, Chile, with participation of professionals from seven countries of Latin America (moja global, 2019). The following communication between the local community and the global experts was performed via e-mail or by verbal communication and as such should be codified, via the inclusion of user manuals, public forums and technical documents like this one.

For the implementation and customization of the GCBM for this pilot project, intermediate skills in the SQL and Python programming languages were necessary, making the inclusion of a professional with intermediate knowledge of computer programming necessary in the first phase. However, in future iterations, because the GCBM is already customized, changing simple variables or the inclusion of updated data is straightforward and can be done with the computer skills of a professional from the environmental sciences. This fact makes the GCBM suitable for countries that want to have a semi-automated framework to obtain spatially-explicit results and to test their estimations, producing different scenarios for REDD+ or other forest carbon accounting applications. The establishment of these models can also provide a cost-effective tool to help the country test different scenarios of public policy, such as reforestation initiatives helping the country to make policy decisions based on national data.

To implement MRV systems on these more sophisticated platforms has the potential to greatly improve the analytical power, reduce dependencies on rotating consultants on short-term contracts, and ultimately will lead to increased national capacity to support both reporting and projections of GHG emissions and removals in the land sector. To be successful, however, countries need to invest into staff training, and commit to sustaining the teams that are the basis for national reporting and projection capacities. Recurring tasks such as GHG reporting, Biannual Reporting, submission of Nationally Determined Contributions and collection of results-based payments, all require that capacity in domestic MRV systems is developed and maintained. Moja global was created to facilitate such capacity building through the use of open-source software such as the models tested in this pilot project.
5 Next Steps

The potential next steps in the development of the implementation of the GCBM in the Chilean case study include:

A. **Include the results period (2014-2016) in the analysis:** So far, the analysis was done using the reference period (2001-2013) for the comparison of results. The results period, 2014-2016, was not considered in the pilot project.

B. **Improve the estimates of emissions from Biomass and DOM components:** As seen in the methods section, the calibration of the model took into account the biomass, but not the DOM, causing the emissions from DOM to be considerably underestimated. In order to improve the DOM estimations, the way the volume to biomass factors are designed has to be changed to be able to input variables in a more generic and simple approach, improving both the biomass and DOM estimations. These changes should be complemented by an intensive, specific literature review and expert opinions, that takes into account the most recent scientific findings on rates of litterfall, decomposition rates, dead organic matter to soil organic carbon transfer rates, and many other parameters that are not included in the FREL. In the case of the biomass components, new more detailed growth curves can be included, together with the inclusion of snags, branches and foliage data in the volume to biomass conversions. For example, depending on time and resources available, future simulations could include testing and selecting those species from the GCBM database with the most similar allometry to the Chilean species, or, developing a database of volume to biomass parameters within the GCBM structure that is specific to Chile.

C. **Inclusion of the activities that occur in forest remaining forest:** The activities that were included in this pilot project have one characteristic that makes them easy to implement: all of them follow a gain-loss approach in the Chilean FREL. On the other hand, the estimations for the activities that occur in permanent forest (forest remaining forest) were made using a stock-difference approach based on mosaics of Landsat images, that were used to interpolate ground data and calculate the difference in forest stocks in two different years.

The implementation of the permanent forest related REDD+ activities will take longer than the implementation of the land-use change based activities, due to the fact that the input data would have to be adapted in order to meet the requirements of the GCBM gain-loss based approach.
Overcoming this barrier, it will be possible to evaluate the use of this type of tool in new managed forest areas as a result of the implementation of results-based-payments (e.g., the green climate fund between the years 2020-2025 or others as FCPF CF).

D. **Expand the pilot program to the rest of the regions of the FREL:** This pilot project considered only one out of the five regions included in Chile’s sub-national REDD+ accounting area. As the format and characteristics of the information in Los Rios region is relatively similar to the other regions, the implementation of the GCBM in all the regions between Maule and Los Lagos should be straightforward.

E. **Continuing to support global initiatives that enhances the operational capabilities of MRV-AFOLU systems:** The *moja global* project of the Linux Foundation builds on an international community of users and contributors that supports open-source tools for MRV-AFOLU systems. Applying the best available science, technical skills and software, *moja global* promotes the creation of operational systems that can be tailored to meet country-specific needs and capacity in a progressive and efficient manner.

This report describes progress to date in replicable steps of the use of the GCBM-FLINT tool in MRV-Chile for FREL/REDD+ analysis. At the same time, it exemplifies how this type of global initiative can support countries to speed up the analytical and reporting capabilities of their MRV systems, paving the way for new collaboration opportunities with other countries, that will then strengthen regional capacity-building processes (e.g. South-South collaboration) and the consistency of international reporting of GHG emissions in the AFOLU sector.
6 Conclusions

The implementation of the GCBM in the Chilean case allowed Chile to test, compare, and learn about the most recent practices in forest carbon modelling, allowing the country to have more options and approaches to update their FREL and REDD+ Technical Annex in the future. It also allowed them to obtain spatially-explicit results, improving the capabilities of the National Forest Measurement and Monitoring System. Thus, the GCBM could be one possible solution to integrate and automate the estimation and reporting workflows for the UNFCCC and other reporting requirements, allowing the country to have one core, vertically-integrated, accurate, and spatially-explicit system for forest carbon accounting.

The implementation of the model was developed in a short time due to the availability of global networks, that allowed Chile’s MRV professionals to test and receive feedback about the different problems they faced when implementing it. This has demonstrated that developing the internal capacity of individual countries, complemented by horizontal international collaboration is a more effective way to improve countries' MRV processes.

This project corresponds to one of the first attempts of the country to obtain spatially-explicit and integrated results on the REDD+ activities, generating coherent results when comparing them with the established FREL, providing an effective proof of concept of what can be done in the future in terms of the development of integrated carbon models for Chile’s MRV system. Furthermore, with the use of these technologies, in the near future Chile could undertake accounting with an integrated and semi-automatic platform to test scenarios, build reports for different initiatives and manage REDD+ policies, among others, in a cost-effective manner.
Acknowledgments

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