Activities report

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

Pilot Project
Los Ríos Region - Chile

Progresses in the implementation of the model:

December 2020 – March 2021

31 March 2021

This Activities report was prepared as part of the deliverables of the “Expanding Market Opportunities” contribution agreement between Her Majesty the Queen in Right of Canada, represented by the Minister of Natural Resources and the non-for-profit organization “Climate Advisers Trust” (Project: "moja global - International collaboration on sustainable forest management tools”).

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1 Introduction

As part of Chile's stepwise approach to improve their Measurement, Reporting, and Verification (MRV) system for REDD+[1] accounting, new tools are being tested to integrate the internal processes for estimation and reporting. As Chile already consigned their Forest Reference Emission Levels (FREL) to the United Nations Framework Convention on Climate Change (UNFCCC), which was consequently reviewed and approved, it is necessary that spatially-explicit tools such as the Generic Carbon Budget Model (GCBM) are, in the first place, able to replicate the procedures that are already in place at national and subnational levels.

During the period between June 2019 and March 2020, the first phase of a pilot project to implement the GCBM in Los Rios Region, Chile, was developed. The GCBM is one of the existing implementations of 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. The GCBM is based on the same science modules used in the Carbon Budget Model of the Canadian Forest Sector and uses disturbance matrices to ensure carbon mass balance (CBM-CFS3; Kurz et al., 2009).

In this first stage of the project, the GCBM was used to reproduce the results of Chile's national FREL for REDD+ activities that imply land use changes, such as deforestation, substitution of native forest by forest plantations and afforestation. The results of this work showed that using existing data and assumptions provided by CONAF, the GCBM can be adapted to meet Chile's requirements for estimating and reporting, producing emission estimates that showed to be very similar to the ones reported by Chile in its FREL. For example, the GCBM yielded deforestation emissions from biomass results that were less than 4% larger than in the FREL, and emissions from substitution 0.5% smaller (Cabezas *et al*., 2020).

In order to complete the pilot project in Los Rios Region, a second phase workplan was designed and which is described in this activity report. This second phase has the objective of improving the estimates of the GCBM implementation in Los Rios Region, by enhancing model calibration and the inclusion of REDD+ activities in permanent forest (forest remaining forest).

With this objective in mind, a series of activities were executed between December 2020 and March 2021. These activities, along with others planned for the period between April and June 2021, will result in the implementation and emission estimates of all the REDD+ activities and carbon pools reported in Chile's FREL (Table 1), with the exception of the non-CO_2 emissions from forest fires, for which there is no spatially explicit information available.

[1] REDD+: It stands for reducing emissions from deforestation and forest degradation, conservation of existing forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks. It is an international framework in which actions in the forest sector of developing countries can contribute to mitigating climate change.

Table 1. REDD+ activities included in Chile's FREL

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

* Non-CO_2 emissions are not included in this pilot project

2 Coordination with Chile MRV professionals

To develop the second phase of the GCBM pilot project in Chile three meetings were conducted on 21 October, 15 December and 22 December 2020, with Chilean professionals Georgina Trujillo and Daniel Montaner from the MRV unit of the National Forestry Corporation (CONAF), along with the expert in charge of the implementation Julian Cabezas, and the Mullion Group consultant Marcela Olguín.

In these meetings, a prioritization of the different possible activities was performed, where the MRV professionals stated that one of the top priorities in the short term would be to include new disturbance types in GCBM, that can help them further understand the dynamics of the degradation and enhancement of forest carbon stocks in permanent forest (forest remaining forest) in a spatially explicit manner.

As part of the participation of the MRV team of the project, a letter to the professionals in CONAF was drafted, including a request for information that could help further calibrate the model to Chilean conditions, including parameters for aboveground biomass such as turnover rates and proportions of the different parts of the tree (bark, foliage, stem and branches) in Chilean forests. This letter was distributed to CONAF's forestry professionals through its internal network, to identify and compile reports or databases containing parameters of interest, that will be used in further developments of the model. The letter can be found in Appendix 1 (in Spanish).

3 Model setup

As the pilot project implementation started in June 2019, the codebase of the project used an old version of the GCBM. In order to fix possible bugs and increase the functionality of the model, the configuration of the GCBM implementation was updated to use the September-2020 build of the model. This update included the upgrade of the Python version from 2.7 to 3.7, implying changes in the preprocessing codes written in this language. Additionally, as the input database structure presented slight changes, the SQL queries used to include Chile specific parameters had to be updated.

This upgrade will allow the model to include more than one set of root parameters, and to include user inputted initial values for the non-biomass components: dead organic matter (DOM) and soil organic carbon (SOC). Additionally, this upgrade will prevent future bugs in the model, as Python 2.7 and its related libraries will lose support in the near future.

The new project template, including the codes to set up the specific configuration for Chile's forest parameters, was uploaded to the GitHub repository of the pilot project[2]. The implementation of this second phase uses a higher spatial resolution, using pixels of 0.0003 degrees of size (approximately 30 m size pixels). This resolution was selected as a tradeoff between processing time (approximately 12 hours in a four core Intel i5-7300HQ CPU with 16 Gb RAM laptop) and the representation of small elements in the landscape, that were not accurately represented using the lower resolution of 0.0005 in the last iteration of the model.

[2] https://github.com/moja-global/GCBM.Chile.Implementation

4 Implementation of REDD+ activities in permanent forest

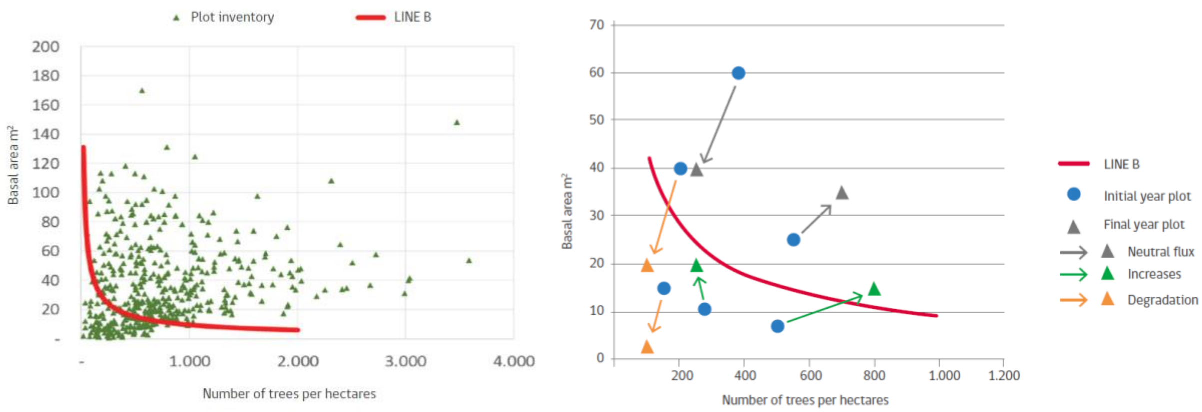
4.1 National FREL methodology

In order to estimate the carbon emissions from forest remaining forest (permanent forest), Chile employs a stock-difference approach, that uses the National Forest Inventory data and a density diagram (also called stocking chart) for specific Chilean forest types, developing a methodology based in Bahamondez *et al* (2009). Firstly, the location in the stocking chart for each forest plot in the inventory was determined (Figure 1, left) using the number of trees and basal area variables. Then, the B line, which can be interpreted as the limit at which trees can fully occupy the capacity of the site without excessive competition, was used as the threshold of the natural resilience of the forest and to determine forest degradation or enhancement (Montaner *et al*, 2019).

As shown in Figure 1 (right), the movement of the plots in the stocking chart determine if an enhancement (increase) or degradation in forest carbon stocks is estimated. In Chile's FREL, only the *Roble-Rauli-Coihue* forest type stocking chart was used for all forest types, as it was the only one available at the time.

In order to extrapolate the plot information to the entire Los Rios Region, Landsat mosaics were constructed for the years 2001 and 2010, and the number of trees per hectare and basal area variables in the inventory plots were extrapolated using a k-means methodology. The result was a 100x100 m resolution raster containing the aboveground CO_2 forest carbon stock in two years (2001 and 2010) and a code describing the movement of the pixel in the stocking chart. The emission or removal was calculated with the CO_2 difference between 2010 and 2001.

The conservation REDD+ activity was estimated using the private and public conservation areas, and estimating the net flux of forest carbon (removals minus emissions).



Source: Montaner *et al*. (2019)

Figure 1- *Roble-Rauli-Coihue* stocking chart B-line construction generated with measurements from the National Forest Inventory (left). Examples of carbon fluxes that represent enhancements (Increases) or degradations (right)

4.2 Adaptation of the FREL methodology to the GCBM

The GCBM implements the IPCC´s gain-loss approach to estimate stocks and stock changes, modelling 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 biomass turnover rates and 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.

As the GCBM is based on a gain-loss approach, Chile's stock-difference approach for estimating emissions and removals in forest remaining forest had to be adapted to reflect the carbon transfers in each year. For this purpose, the forest degradation and enhancement activities were developed following different approaches.

4.2.1 Forest Degradation Emissions approach

In the previous phase of the GCBM pilot project, the volume of the forest present in the inventory layer was fixed at 375.29 m^3/ha, the regional average of the merchantable volume for Los Rios Region (Montaner *et al*., 2019). Using this figure, the percentage of volume loss for each pixel was calculated using the CO2 difference between 2001 and 2010 (converted to merchantable volume), as the disturbances in the GCBM use proportions of a carbon reservoir being transfer to another to calculate emissions (in this case, the transfer from forest biomass to CO2).

The degradation activity in Los Rios Region can present a wide variety of intensity levels (loss of CO2 from 2001 to 2010), that go from 1 ton CO2/ha to 757 ton CO2/ha, that correspond to 0.16% and 125.74% of the regional average of CO2 contained in aboveground forest biomass (602.02 ton CO2/ha). To represent this high variance, 20 disturbances with different intensities were built for the degradation activity, evenly distributing groups of pixels following percentiles. For example, the first group (intensity level 1) contained the first 5% of pixels and the last group (intensity level 20) contained the pixels above the 95% percentile value. As the pixels have the same area (1 ha), each disturbance intensity contains roughly the same area.

The disturbance matrices (transfers from a source pool to a sink pool), for the different degradation intensities were constructed considering the mean of the percentage of the regional average volume loss in the transition for the pixels contained in the disturbance intensity level. For example, the disturbance “Forest degradation intensity 5” comprises 2169 pixels (roughly 2169 hectares) that present values biomass loss between 5.32% and 6.15% (Table 2). By taking the mean percentage of biomass loss (5.85%), the disturbance matrix is constructed transferring 5.85% of the total carbon in each of the aboveground biomass pools to the CO2 pool.

Table 2. Forest Degradation disturbance intensities in Los Rios Region

Degradation Intensity level	Interval (% of biomass loss)	Mean biomass loss in degradation (%)	Number of pixels
1	[0.166,1.33]	0.64	2324
2	(1.33,2.82]	2.18	2150
3	(2.82,4.09]	3.49	1962
4	(4.09,5.32]	4.75	2221
5	(5.32,6.15]	5.85	2169
6	(6.15,7.31]	6.73	2158
7	(7.31,9.14]	8.32	2209
8	(9.14,10.5]	9.87	2057
9	(10.5,12.6]	11.63	2116
10	(12.6,14.9]	13.84	2137
11	(14.9,18.1]	16.61	2186
12	(18.1,21.3]	19.75	2054
13	(21.3,25.4]	23.27	2202
14	(25.4,29.7]	27.64	2130
15	(29.7,34.2]	32.09	2110
16	(34.2,37.9]	36.18	2197
17	(37.9,41.5]	39.71	2118
18	(41.5,45.8]	43.74	2139
19	(45.8,51.8]	48.67	2145
20	(51.8,125]	59.27	2121

As shown in Figure 2, a great portion of the degradation disturbances present low percentages of biomass loss, while some outliers, that can be attributed to artifacts in the Landsat mosaics, can be found in the bigger intensity level.

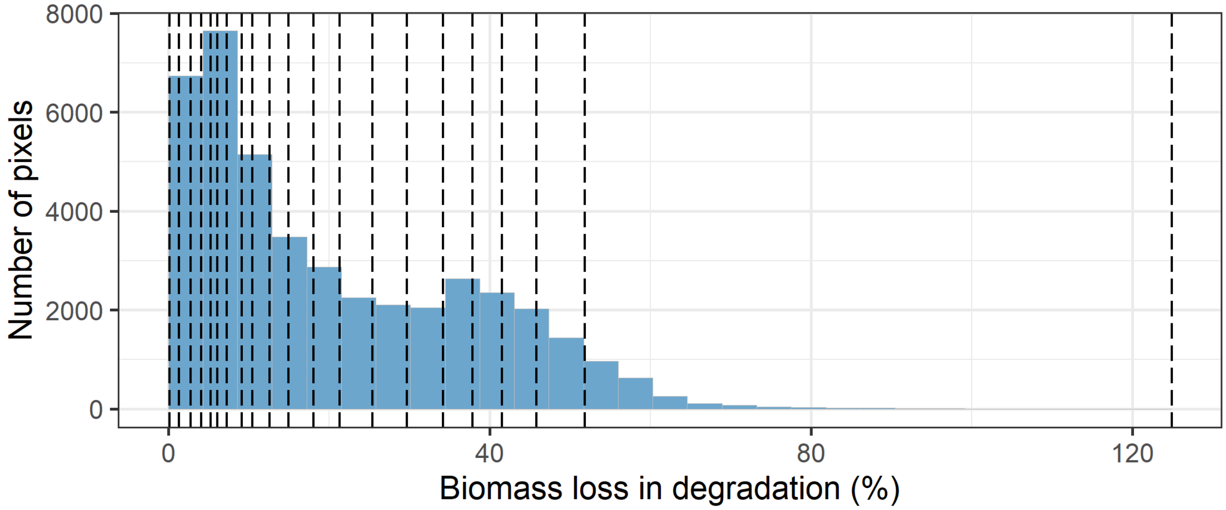


Figure 2. Distribution of the biomass loss in degradation. Dashed back lines represent the breakpoints between the intensity levels

Each disturbance associated pixel was assigned an intensity level and a year of disturbance, that corresponds to a random year between 2002 and 2010, following the same approach as in the degradation and substitution activities (Cabezas *et al*., 2020).

4.2.2 Forest Enhancement removals approach

The forest enhancement related removals methodology followed a similar approach to the forest degradation. In this case, as the forest enhancement activity corresponds to human related actions to increase the natural growth of the forest, the total growth in volume associated with each pixel was calculated, to then obtain the yearly volume growth to account for the volume difference between 2010 and 2001. These yearly grow values were separated into 20 intensities using the quantile values, as seen in Table 3.

Table 3. Forest enhancement disturbance intensities in Los Rios Region

Intensity level (Quantile)	Interval (m3/ha year)	Mean volume growth (m3/ha year)	Number of pixels
1	[0.111,1.67]	0.81	4144
2	(1.67,3.22]	2.56	4177
3	(3.22,4.33]	3.89	4204
4	(4.33,5.44]	4.93	3846
5	(5.44,6.78]	6.19	4111
6	(6.78,8]	7.45	4000
7	(8,9.33]	8.72	4133
8	(9.33,11]	10.17	3802
9	(11,12.8]	11.91	4005
10	(12.8,14.9]	13.91	4198
11	(14.9,17.2]	16.03	3885
12	(17.2,20.8]	18.90	4006
13	(20.8,24.8]	22.94	4075
14	(24.8,28.3]	26.59	4109
15	(28.3,31.9]	30.14	4050

16	(31.9,35.4]	33.68	4033
17	(35.4,39.9]	37.64	3987
18	(39.9,52.8]	44.55	3991
19	(52.8,88]	73.09	4051
20	(88,184]	114.30	4030

In order to represent these new growth rates, 20 growth curves were developed (one for each intensity level). When the pixel is affected by a forest enhancement activity, the Origin classifier is changed to the respective forest enhancement intensity (e.g. Forest enhancement lvl 5) and a new growth curve is assigned, keeping the Forest type and Structure classifiers (see Cabezas *et al*., 2020). This change in the growth curve was applied in year 2002, to then reverse it to the original classifier set in 2010., producing 9 years of increased growth.

In order to estimate the CO2 removals product of the enhancement activities following the same principles as in the FREL, a new indicator had to be created and was included to the GCBM template for Chile. This new indicator, the "Delta aboveground biomass", similarly to the "Delta total biomass" indicator (already included in the GCBM), accounts for the delta between the aboveground biomass gross growth minus the emissions from the aboveground biomass.

4.2.3 Conservation approach

Following the guidelines of the national FREL, the conservation activity was calculated using the net flux of the degradation and enhancement activities in conservation areas. For these two activities, the same approach as outside the conservation areas was used; thus, for the degradation activity, 20 intensities were determined, looking at the quantiles of the percentage of biomass loss in degradation pixels located in conservation areas, while the enhancement intensities were also determined by the quantiles of the yearly growth in volume in the same areas. The removals of the conservation activity were calculated by subtracting the annual forest degradation emissions from the annual removals from forest enhancement.

4.3 Results of permanent forest activities

4.3.1 Forest degradation emissions

In the case of the forest degradation emissions, the randomization of the year of disturbance led to relatively similar emission figures for all the years between 2002 and 2010, as seen in Figure 3.

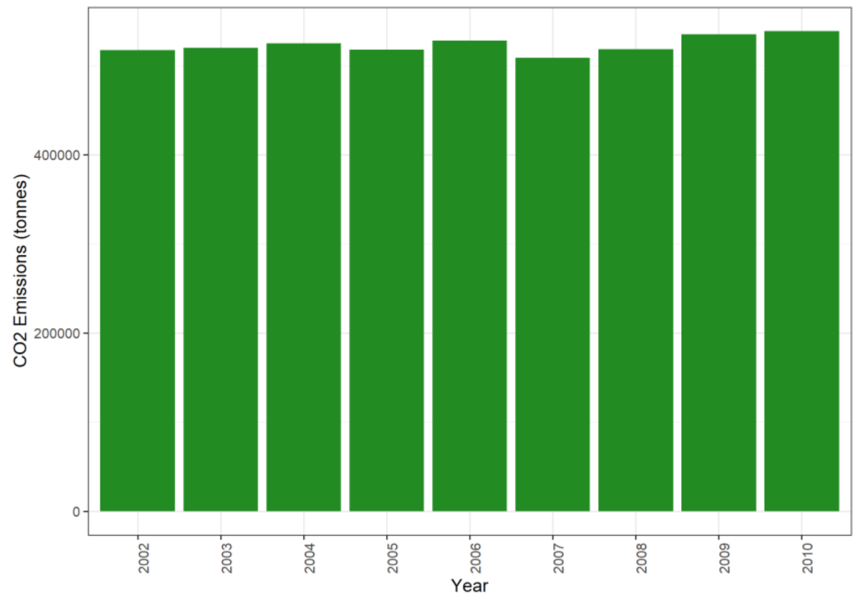


Figure 3. CO2 emissions due to forest degradation in the GCBM implementation

The calculus of the yearly emission due to degradation activities in permanent forest lead to 523073.1 tCO2 per year, 11.70% less yearly emissions than the ones reported in the FREL (Table 4)

Table 4. Comparison of CO2 emissions from degradation between the FREL and the GCBM

Indicator	GCBM estimated emissions (tCO2/year)	FREL estimated emissions (tCO2/year)	Differences between FREL and GCBM estimations (tCO2/year)	Differences between FREL and GCBM estimations (%)
Total CO2 Emissions	523076.1	592372.7	-69296.6	-11.70%

The difference between the FREL and the GCBM results can be explained by the variation in the mapping methodology of the inventory data (land use cadastre) and the degradation mapping. While the land use maps that were used for the inventory data provide fine grained information, the permanent forest methodology uses 100 x 100 m pixels (1 ha). This difference in spatial resolutions leads to lower emissions figures in the GCBM, as part of the degraded areas are classified as non-forest (as seen in Figure 4), thus not producing emissions from disturbance. Moreover, as part of the permanent forest methodology of the national FREL, the product that is used to calculate the stock-difference between 2001 and 2010 is filtered using a permanent forest mask, leaving only the pixels that present permanent forest in their center. Then, the emissions registered in degradation pixels are calculated without considering the land use inside them. This approach is different from the spatially explicit approach that can be implemented in the GCBM, that integrates all layers of information (Kurz *et al*., 2009).

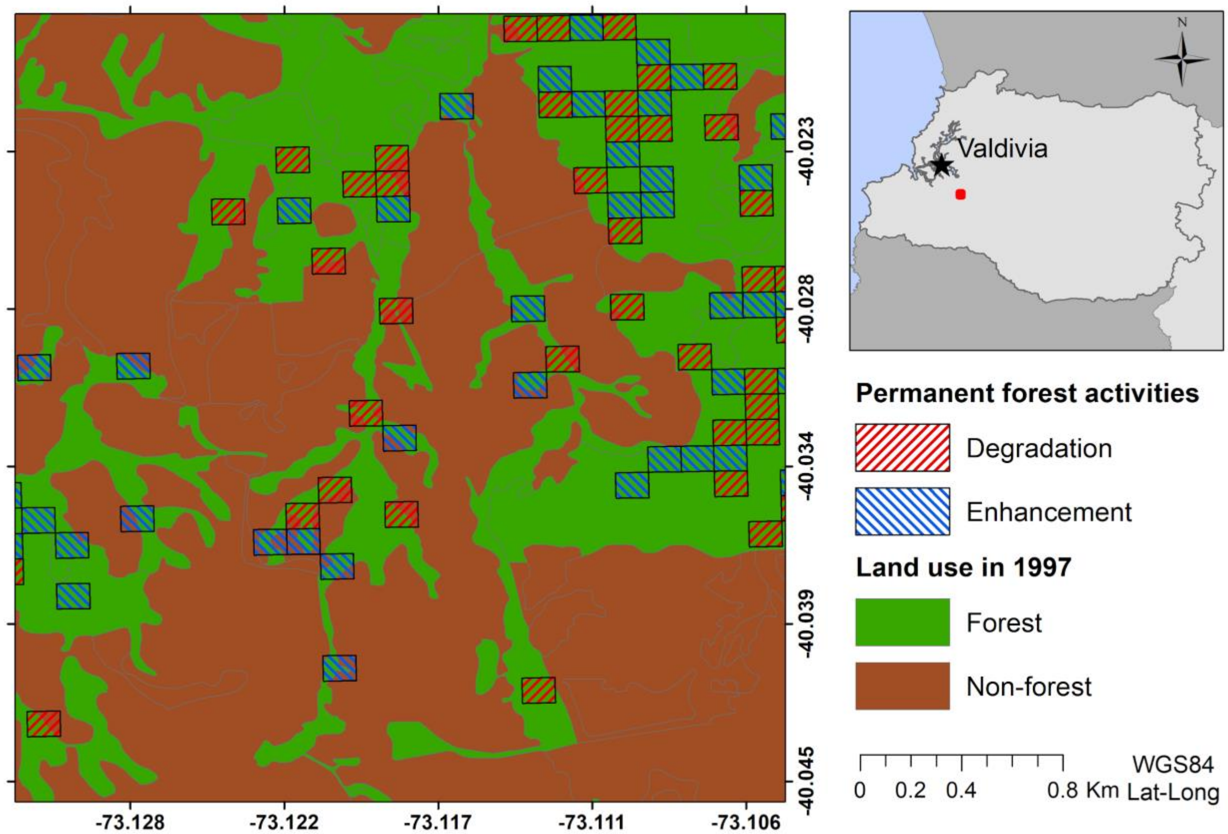


Figure 4. Land use and permanent forest layers example.

When analyzing the forest types that are subject to degradation, it is possible to see that 4.83% of the areas under degradation correspond to non-forest, thus not producing emissions. Additionally, 4.1% of the degraded forests correspond to the *Matorral Arborescente* forest type (Table 5), that contains a much smaller biomass content, producing less emissions. These two figures explain a big portion of the differences between the GCBM and the FREL.

Table 5. Yearly degraded areas by forest type in the GCBM

Forest Type	GCBM affected area (ha/year)	Percentage of the total area
Alerce	80.08	1.68%
Araucaria	12.24	0.26%
Bosque Mixto	82.99	1.74%
Cipres de la Cordillera	2.90	0.06%
Cipres de las Guaitecas	1.46	0.03%
Coihue - Rauli - Tepa	991.35	20.81%
Coihue de Magallanes	72.86	1.53%
Esclerofilo	6.89	0.14%

Lenga	395.48	8.30%
Matorral Arborescente	195.23	4.10%
Non Forest	230.31	4.83%
Roble - Rauli - Coihue	1184.71	24.87%
Siempreverde	1507.72	31.65%

One possible solution for this mismatch in emissions figures can be to obtain the stock-difference rasters without filtering for permanent forest. Although this solution does not ensure completely equal results, it would add forest remaining forest areas under degradation, that are currently being filtered out as they are not located at the center of the pixel. On the other hand, the problem that the *Matorral Arborescente* forest type is causing is currently being fixed in new historical land use maps.

4.3.2 Forest enhancement removals

The enhancement activities produced constant CO2 removals (delta aboveground biomass) from 2002 to 2010, as the new growth curves of the forest under enhancement activities are linear. The estimated annual removals in the GCBM are 1,921,618 tCO2, being only 2.39% inferior to the removals reported in the FREL for Los Rios Region (Table 6). This difference can be explained by the same abovementioned mismatch between spatial resolutions between the land use maps and the stock difference rasters, as to calculate the removals only the forest remaining forest pixels were considered.

Table 6. Comparison of CO2 removals from forest enhancement between the FREL and the GCBM

Indicator	GCBM estimated removals (tCO2/year)	FREL estimated removals (tCO2/year)	Differences between FREL and GCBM estimations (tCO2/year)	Differences between FREL and GCBM estimations (%)
Total CO2 removals	1921618	1968685	-47066.8	-2.39%

As shown in Table 7, the forest enhancement activities mostly executed in *Coihue-Rauli-Tepa* and *Roble-Rauli-Coihue* forest types, with 2.72% of the area under enhancement being executed in non-forest areas, that are not being included in the calculus of the removals, that only considers “forest remaining forest” lands, explaining the differences between the FREL and GCBM.

Table 7. Yearly enhanced areas by forest type in the GCBM

Forest Type	GCBM affected area (ha/year)	Percentage of the total area
Alerce	121.22	1.35%
Araucaria	84.54	0.94%
Bosque Mixto	91.82	1.02%

Cipres de la Cordillera	1.31	0.02%
Cipres de las Guaitecas	1.41	0.02%
Coihue - Rauli - Tepa	3114.30	34.72%
Coihue de Magallanes	112.62	1.26%
Esclerofilo	5.67	0.06%
Lenga	1040.84	11.60%
Matorral Arborescente	239.96	2.68%
Non Forest	244.22	2.72%
Roble - Rauli - Coihue	1723.22	19.21%
Siempreverde	2189.05	24.40%

4.3.3 Forest conservation flux

The conservation activity fluxes were calculated with the results of the degradation and enhancement activities in conservation areas. In Figure 5, it is possible to see that the CO2 removals produced by forest enhancement in conservation areas are more than four times greater than the degradation, causing net removals for the conservation REDD+ activity.

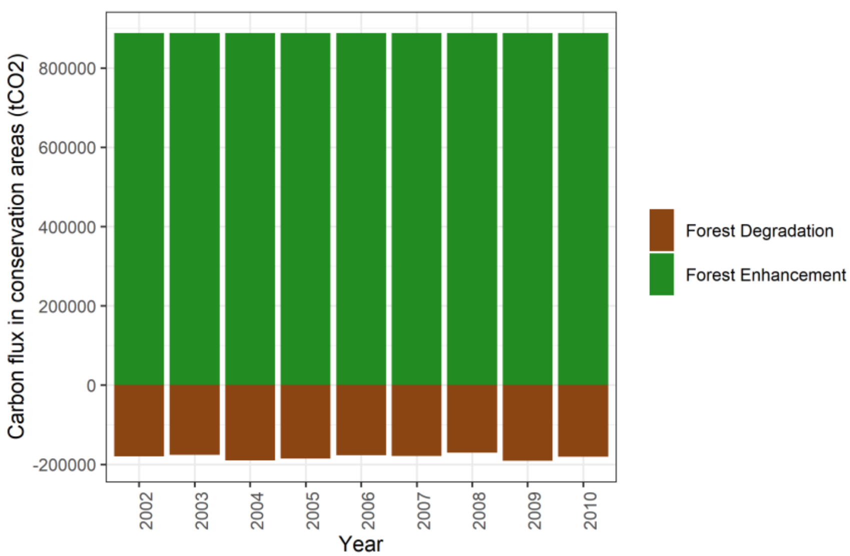


Figure 5. Carbon fluxes due to forest enhancement and degradation in conservation areas

As most part of the conservation areas in Los Rios Region are covered by forests, the differences between the GCBM implementation and the FREL results are small (-1.01% in the case of forest enhancement and -3.28% in forest degradation), the net flux results in conservation areas is also very close to the figures of the FREL, showing yearly removals of 707165 tCO2, a difference of -0.41% with the FREL results (Table 8).

Table 8. Comparison of CO2 fluxes in conservation areas between the FREL and the GCBM

Indicator	GCBM estimated flux (tCO2/year)	FREL estimated flux	Differences between FREL	Differences between FREL

		(tCO2/year)	and GCBM estimations (tCO2/year)	and GCBM estimations (%)
Forest Enhancement removals in conservation areas	888313.95	897372.7	-9058.75	-1.01%
Forest Degradation emissions in conservation areas	181148.85	187292	-6143.15	-3.28%
Net flux in conservation areas	707165.10	710080.7	-2915.60	-0.41%

In the case of the degradation and enhancement activities in conservation areas, the most represented forest types are the *Coihue-Rauli-Tepa* and *Roble-Rauli-Coihue* forest types, while in this case the non-forest areas under degradation and enhancement are much smaller than outside the conservation areas, representing 1.76% in the case of degradation and 0.97% in the case of enhancement. Additionally, the *Matorral Arborescente* areas under degradation are much smaller, representing only 0.43% of the total (Table 9), explaining why in this case, the differences between the GCBM and FREL are minor.

Table 9. Areas under forest degradation and enhancement inside conservation areas by forest type

	Degradation		Enhancement	
Forest Type	**GCBM affected area (ha/year)**	**Percentage of the total area (%)**	**GCBM affected area (ha/year)**	**Percentage of the total area (%)**
Alerce	70.36	4.32	138.0	3.77%
Araucaria	1.28	0.08	9.78	0.27%
Bosque Mixto	7.22	0.44	5.74	0.16%
Coihue - Rauli - Tepa	316.39	19.40	1088.24	29.73%
Coihue de Magallanes	8.28	0.51	14.70	0.40%
Esclerofilo	0.18	0.01	0	0%
Lenga	281.50	17.26	817.61	22.33%
Matorral Arborescente	7.07	0.43	10.74	0.29%
No forestal	28.77	1.76	35.50	0.97%
Roble - Rauli - Coihue	132.65	8.13	245.07	6.69%
Siempreverde	776.95	47.65	1295.36	35.39%

5 Inclusion of foliage, bark and branch components

In the first stage of the pilot project, the proportions of branches, foliage and bark in the Chilean trees species was set to zero, with the objective of simplifying the calibration of the conversion of the merchantable volume to biomass, as the equations described by Boudewyn *et al*. (2007), that the GCBM uses internally, were fitted for the specific Canadian inventory data and are not easy to adapt. This simplification allowed the Chilean implementation to obtain good results regarding emissions from biomass due to land use change activities, but produced underestimation in emissions from Dead Organic Matter (DOM) (Cabezas *et al*., 2020)

As part of the improvements planned for the second stage of the GCBM implementation, a more realistic approach to represent the different components of the Biomass was proposed. For this purpose, information about the proportions of foliage, bark and branches in Chilean forest were requested to CONAF professionals via a letter. However, meanwhile the information is collected, tests using the parameters of the species included in the database of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3 ; the same as the GCBM) were carried out.

In order to select a suitable tree species, the proportions of the different elements of the forest were compared with information extracted from Gayoso (2001), that determined the proportions of bark, stem, branches and foliage of 17 tree species from southern Chile. As in the national FREL, the *Roble-Rauli-Coihue* forest types species were considered as representative of the forest in Los Rios Region, thus, the proportions of bark, stem, foliage and branches in the the three dominant tree species of this forest types were averaged (Table 10), and species with similar proportions were searched in the CBM-CFS3 database.

Table 10. Proportions of the total biomass in the components of the dominant tree species of the *Roble-Rauli-Coihue* forest type

	Fraction of the total biomass of the tree (%)			
Species	**Stem**	**Bark**	**Branches**	**Foliage**
Roble (*Nothofagus obliqua*)	78.02	10.41	10.67	0.9
Rauli (*Nothofagus alpina*)	73.16	12.47	12.77	1.6
Coihue (*Nothofagus dombeyi*)	72.25	7.79	16.71	3.25
Species mean	74.48	10.22	13.38	1.92

Source: Adapted from Gayoso (2001)

5.1 Testing of Species included in the CBM-CFS3

As in the GCBM, the CBM-CFS3 model simulates annual changes in living aboveground biomass at the stand level in three main carbon pools: merchantable stemwood + bark, other wood (small trees and branches including bark), and foliage.

The CBM-CFS3 provides more than 30 equations which correspond to single-species types, genus types, or generic hardwood and softwood species, from which the users outside of Canada can select the one that best represents the proportions of the aboveground biomass pool to the total tree biomass (Kurz *et al*., 2009).

Figure 6 exemplifies 15 different combinations of biomass proportions for single-species, mixed or generic species types of merchantable-sized trees at the stand level. Out of that number, only “Generic Hardwood”, seemed to be the most appropriate to represent the *Roble-Rauli-Coihue* forest types in the GCBM pilot, considering that it was the only “tree” type that allocated close to 80% to the stem component (84% in the Chilean forests), as well a small proportion to foliage (3% in Generic Hardwood while 2% in the Chilean forest).

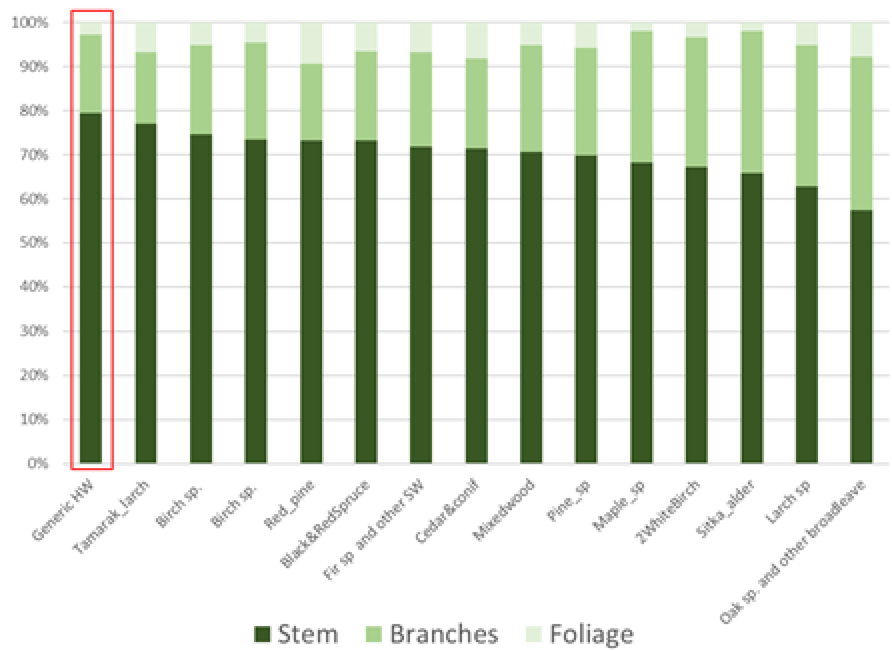


Figure 6. Living aboveground biomass allocation for 15 species/genus/generic tree types available in the GCBM. The Generic Hardwood was the only type that has a more similar distribution of biomass components in merchantable-sized trees (red rectangle).

5.2 Impacts on CO2 emissions estimates

The application of the Generic Hardwood species parameters on the volume to biomass conversion of the Chilean species yielded similar results than the ones presented in the first phase of the GCBM in land use change related activities, not impacting greatly in the CO2 emissions from DOM, while the emissions from Biomass estimations were also very similar (Table 11), as the assumptions of the deforestation and substitution activities include a transfer of the 100% of the tree biomass to the atmosphere in CO2 form. The absence of changes in the DOM emissions will have to be further investigated in next iterations of the GCBM implementation, further adjusting the turnover and decomposition rates, that determine how much DOM is accumulated, to understand the differences between the GCBM and FREL estimates, that are still present. The degradation results follow the same pattern, producing the same emissions as in Table 11 (section 4 of this report).

Table 11. Comparison of deforestation and substitution emissions in the GCBM and FREL (Using the Hardwood Generic parameters).

Indicator	GCBM estimated emissions (tCO2/year)	FREL estimated emissions (tCO2/year)	Differences between FREL and GCBM estimations (tCO2/year)	Differences between FREL and GCBM estimations (%)
Deforestation				
CO2 emissions from DOM	36240.79	161591.1	-125350	-77.57%
CO2 emissions from Biomass	505603.8	483104.8	22498.99	4.66%
Total CO2 emissions	541844.6	644695.9	-102851	-15.95%
Substitution				
CO2 emissions from DOM	40881.52	197844.9	-156963	-79.34%
CO2 emissions from DOM	594993.4	576776.6	18216.75	3.16%
Total CO2 emissions	635874.9	774621.5	-138747	-17.91%

On the other hand, the inclusion of the Hardwood Generic parameters in the model produced significant changes in the removals produced by forest enhancement activities, as seen in Table 12. In this case, the changes in parameters caused an underestimation of the removals, as the increase of volume causes a decrease on the relation between volume and the sum of the biomass of all components, when applying the equations of Boudewyn *et al* 2007.

Table 12. Comparison of forest enhancement removal estimations in the GCBM and FREL (Using the Hardwood Generic parameters).

Indicator	GCBM estimated removals (tCO2/year)	FREL estimated removals (tCO2/year)	Differences between FREL and GCBM estimations (tCO2/year)	Differences between FREL and GCBM estimations (%)
Total CO2 removals outside	1399562	1968685	-569123	-28.91%

conservation areas				
Total CO2 removals in conservation areas	639475.7	897372.7	-257897	-28.74%

These changes in the emission figures are caused by the characteristics of the volume to biomass equations included in the GCBM, as the biomass of each component of the tree (bark, stem, branches and foliage), and thus the total biomass, is dependent on the merchantable volume value. As Chile uses a single factor to transform from volume to biomass (0.875), the adaptation of the equation of Boudewyn *et al* (2007) is not straightforward, causing that in this case, this factor is changed according to the total volume, producing changes in the estimation when the growth of the forest is enhanced as in this case.

6 Lessons learned and next steps

The activities performed to enhance the capabilities of the GCBM implementation made the pilot project cover all the CO2 emissions in Los Rios Region for the four REDD+ activities reported by Chile (Deforestation, Degradation, Enhancement and Conservation), with different degrees of similarity between the GCBM and FREL. This work showed several aspects of the GCBM that are different to the FREL approach, as well as the flexibility of the model to introduce these different approaches. Moreover, the work allowed the participants to visualize the differences between an integrated approach, such as the GCBM implementation, and the separated spreadsheet processes that is carried out in the elaboration of the FREL, devising possible improvements that could lead to an improved integrated MRV system in the future.

Firstly, the stock-difference approach, used by Chile's FREL to estimate the emissions of the REDD+ activities in permanent forest, can be successfully adapted to the GCBM, yielding similar results while following the same assumptions. Differences in results are in many times explained by the use of spatial data with different spatial resolutions, that in the FREL are used separately in different spreadsheets, while in the GCBM they are integrated in a single model, that can provide a more complete visualization and understanding of the forest carbon dynamics.

On the other hand, the inclusion of the different components of the tree proved to be more difficult than expected, as the GCBM provides equations to transform volume to biomass that are specific to Canada, and can not be easily applied to local parameters. In this case, the inclusion of the parameters of species included in the GCBM alone did not provide a solution to the difference in DOM estimates, that could be applicable to all REDD+ activities, and further investigation about the turnover and decomposition rates have to be developed.

During the months between April and June 2021, the information collected from CONAF's professionals could be analyzed and new parameters could be tested for the model. Moreover, the work would take emphasis on improving the DOM emissions figures, which are still far (roughly -70-80%) from the estimates of the national FREL, and are the only component of the GCBM simulation that still produces results order of magnitude different from the FREL. Additionally, some pending issues such as the correct estimation of the removals from afforestation and the inclusion of the *Matorral arborescente* root parameters could be improved (Cabezas *et al*., 2020). This work would result in an integrated second phase report and template, containing all the CO_2 emissions for the FREL period in Los Rios Region. This work prepares the foundation from which to expand the pilot to other regions in southern Chile, as well as other reporting periods, as all the process are semi-automatized and the code is available to the public.

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Appendix 1. Letter to CONAF professionals (in Spanish)

Corporación Nacional Forestal

Gerencia de Desarrollo y Fomento Forestal

Unidad de Cambio Climático y Servicios Ambientales

Asunto: Información sobre parámetros del bosque para mejora de estimación de emisiones de gases de efecto invernadero.

Estimados Profesionales de CONAF,

Como parte de los procesos de mejora continua de las metodologías de Medición, Reporte y Verificación de las emisiones y absorciones de gases de efecto invernadero (GEI) en bosques producto de actividades REDD+, la unidad se encuentra probando modelos para la estimación de la dinámica de estas emisiones de manera espacialmente explícita. Entre los modelos en consideración e implementación se encuentra el *Generic Carbon Budget Model* (GCBM), una herramienta de código libre, basado en las guías del Panel Intergubernamental sobre Cambio Climático para el cálculo de flujos de GEI en el sector forestal. La implementación de este modelo se enmarca dentro de una colaboración con el Servicio Forestal del Gobierno de Canadá.

Como parte de la implementación de este modelo con datos del centro-sur del país (regiones del Maule a Los Lagos), una serie de parámetros específicos del bosque nativo del país son requeridos, entre los que se cuentan:

- Crecimiento corriente anual (curvas de crecimiento) por tipo forestal o especie.
- Referencias sobre la edad para alcanzar niveles máximos en volumen o en biomasa aérea por tipo forestal o especie.
- Información sobre la proporción de la biomasa total del bosque por componente aéreo (foliaje, tronco, corteza y ramas) y su relación con la edad o volumen maderable (factores de expansión).
- Información sobre tamaño del reservorio mantillo y necromasa en distintos estados del bosque (e.g. renoval y adulto), o tasas de acumulacion anuales de hojarasca (transferencia del reservorio foliaje a hojarasca).
- Tasa de mortalidad natural del bosque por tipo forestal o especie (e.g., porcentaje anual)

Cualquier información sobre estos parámetros, ya sea a nivel regional o subnacional será útil para su inclusión en el modelo, por lo que recurrimos a ustedes para recabar posibles reportes o información de terreno realizados al interior de la Corporación de los cuales estos parámetros se pudiesen derivar. Paralelamente, el equipo a cargo de la implementación realizará una búsqueda bibliográfica de la literatura disponible públicamente.

Saluda atentamente a ustedes,

Equipo MRV, UCCSA, CONAF