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Climate Change and Agriculture

Greenhouse gasses potential offset by forest species and CO_2 balance in integrated forestry-livestock systems in Uruguay

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Abstract

Uruguay's livestock methane is a mayor source of greenhouse gas (GHG) emissions, despite the country's low overall emissions. A case study was conducted on Forestal Caja Bancaria (FCB), a commercial farm in Uruguay's central region, with an integrated production system covering 5,802 hectares. The study aimed to estimate GHG emissions from livestock, crops and forestry, CO_2 captured by eucalypt and pine plantations, and soil organic carbon for all land uses. Results showed that cattle enteric fermentation accounted for 54 $kg.ha^{-1}.yr^{-1}$ of methane (CH_4), and total emissions accounted for 1,746 $kg.ha^{-1}.yr^{-1}$ of CO_2 equivalent. *E. grandis*, *E. dunnii*, and *Pinus spp*. captured 31, 38, and 17 $Mg.ha^{-1}.yr^{-1}$ CO_2 equivalent during their pre-harvest growth cycles. According to $GWP_{100\ AR6}$, this capture rates could offset emissions from 17.6, 21.6 and 9.9 hectares of livestock production, respectively. Using a real system approach considering staggered plantating, harvesting, and subsequent resprouting or replanting, the estimated potential offsets are adjusted to 9.6, 11.8, and 5.1 hectares, respectively, until the first harvest. After this point, there is not further net biomass accumulation, and mitigation relies on the depletion of the remaining carbon stock in the forest area, which exceeds the carbon needed to offset livestock emissions from the previous phase. $GTP_{100\ AR6}$ and GWP* metrics indicated significantly lower CO_2-eq emission values. This study aims to provide technical coefficients to quantify how forest plantations can offset livestock emissions, contributing to the goal of "carbon-neutral" meat. This information will help to asses forest systems' mitigation potential and explore livestock-forestry combinations.

Keywords: forestry, carbon stock, climate change, livestock, mitigation

Potencial de mitigación de gases de efecto invernadero por plantaciones forestales y balance de CO_2 en sistemas integrados ganadería-forestación en Uruguay

Resumen

Aunque Uruguay tiene muy bajas emisiones absolutas de gases de efecto invernadero (GEI), el metano entérico del ganado es la principal fuente. Los sistemas integrados de producción forestal/ganadera podrían contribuir a reducir las emisiones netas al capturar CO_2 en la biomasa arbórea. Se realizó un estudio de caso en Forestal Caja Bancaria (FCB), predio comercial en el centro de Uruguay que abarca 5.802 hectáreas. El objetivo fue estimar las emisiones de GEI de la ganadería, cultivos y forestación, el CO_2 capturado por la biomasa forestal y el carbono orgánico presente en el suelo. Los resultados indicaron que la fermentación entérica del ganado representó 54 $kg.ha^{-1}.año^{-1}$ de metano (CH_4) y las emisiones totales representaron 1,746 $kg.ha^{-1}.año^{-1}$ de CO_2-eq. *E. grandis, E. dunnii* y *Pinus spp*. capturaron 31, 38 y 17 $Mg.ha^{-1}.año^{-1}$ de CO_2-equivalente durante sus respectivos turnos de crecimiento precosecha. Basado en $GWP_{100\ AR6}$, estas capturas podrían mitigar emisiones de 17.6, 21.6 y 9.9 hectáreas de producción ganadera, respectivamente. Al realizar las estimaciones considerando un sistema real (plantación escalonada, cosecha y posterior rebrote o replantación), estos valores se reducen a 9.6, 11.8 y 5.1 ha, respectivamente, hasta la primera cosecha, a partir de la cual ya no hay acumulación neta de biomasa y la mitigación se realiza con base en el stock de C remanente. Las métricas $GTP_{100\ AR6}$ y GWP* determinaron emisiones de CO_2-eq sustancialmente menores. Este estudio tiene como objetivo proporcionar coeficientes técnicos para cuantificar el potencial de compensación de emisiones ganaderas por las plantaciones forestales, aportando a la producción de carne “carbono-neutral”.

Palabras clave: forestación, secuestro de carbono, cambio climático, ganadería, mitigación

Potencial de mitigação de gases de efeito estufa a partir de plantações florestais e balanço de CO_2 em sistemas integrados pecuária-floresta no Uruguai

Resumo

Embora Uruguai tenha emissões absolutas de gases de efeito estufa (GEE) muito baixas, o metano entérico proveniente da pecuária é a fonte mais importante. Sistemas integrados floresta/pecuária podem contribuir para reduzir as emissões líquidas por meio da captura de CO_2 na biomassa das culturas florestais. Um estudo de caso foi conduzido na Forestal Caja Bancaria (FCB), uma propriedade comercial com 5,802 hectares. O objetivo foi estimar emissões de GEE da pecuária, das culturas e da silvicultura, o CO_2 capturado pela floresta e o carbono orgânico presente no solo. Os resultados indicaram que a fermentação entérica do gado representou 54 $kg.ha^{-1}.ano^{-1}$ de metano (CH_4), e as emissões totais representaram 1,746 $kg.ha^{-1}.ano^{-1}$ de CO_2-eq. *E. grandis*, *E. dunnii* e *Pinus spp.* capturaram 31, 38 e 17 $Mg.ha^{-1}.ano^{-1}$ de CO_2-equivalente, durante seus respectivos períodos de crescimento pré-colheita. Baseado no $GWP_{100\ AR6}$, essas capturas poderiam mitigar emissões de 17.6, 21.6 e 9.9 hectares de produção pecuária, respectivamente. Ao aplicar estes coeficientes com uma abordagem sistêmica (plantio escalonada, colheita e subseqüente rebrote ou replantio), esses valores potenciais são reduzidos para 9.6, 11.8 e 5.1 ha, respectivamente, até a primeira colheita. Após isso, não há acumulação líquida de biomassa, e a mitigação ocorrerá exclusivamente com base no estoque de carbono restante. As métricas $GTP_{100\ AR6}$ e GWP* determinaram emissões de CO_2-eq substancialmente mais baixas. Este estudo busca fornecer coeficientes técnicos que permitam quantificar o potencial das plantações florestais para neutralizar as emissões da pecuária, como uma contribuição ao processo de geração de carne "neutra em carbono".

Palavras-chave: floresta, seqüestro de carbono, alterações climáticas, pecuária, mitigação

1. Introduction

The reports on greenhouse gas (GHG) emissions highlight that in the AFOLU section (Agriculture, Forestry, and Other Land Use) the highest emissions come from bovine animal production, while the highest rates of carbon sequestration come from forest plantations[(1)]. In Uruguay, both production chains are relevant in the country's economy. In 2024, meat exports (including beef, sheep meat, and other types) generated $2.57 billion, representing approximately 18% of Uruguay's total exports[(2)(3)(4)]. Beef remains a key export product, with China being the largest market, accounting for nearly half of beef exports[(3)]. The forestry sector, including cellulose, wood products, pulp, and paper, contributed $2.5 billion annually, which accounts for 15-20% of Uruguay's total exports[(4)(5)]; and has recently surpassed beef as Uruguay's top export item with cellulose, driven by strong demand from European and Asian markets[(5)(6)].

In recent years, negotiations have emerged pointing towards the sale of certified "carbon neutral" products. Several companies are actively involved in this initiative. Mosaica Company has been at the forefront of carbon-neutral beef exports, with shipments to Switzerland and other European markets. Mosaica achieved carbon neutrality through practices like using natural pastures and conserving native forests[(7)(8)(9)]. Uruguayan Unit of BPU Meat (NH Foods) aims to have 15-20% of its processed cattle certified as carbon-neutral by 2025. The company started shipping carbon-neutral beef to Japan, Uruguay, and Germany[(10)]. Minerva Foods has also initiated carbon-neutral beef exports from Uruguay, with shipments to Israel[(11)]. The trend towards carbon-neutral beef is expected to grow as more consumers demand sustainable products. Uruguay's strategy to certify its beef as carbon-neutral is part of broader efforts to enhance the environmental credentials of its agricultural sector, aligning with global targets to reduce emissions[(7)(10)]. This approach not only helps differentiate Uruguayan beef in international markets but also supports the country's commitment to reducing greenhouse gas emissions[(11)]. Currently, there is no estimate of the forested area required to offset the emissions produced by each head of livestock within various production systems. This essential information, which is demanded by the export sector and relevant markets for different eco-labels, is a key strategic topic that this work aims to address.

Estimates of GHG emissions from a system, product, or service are expressed in standardized units of CO_2-equivalent (CO_2-eq) to normalize the global warming potential of all greenhouse gases emitted per functional unit (system, units of product, or service provided). This estimate involves conducting a life cycle inventory (LCI) that encompasses all consumption, infrastructure, and emissions associated with the evaluated system. Additionally, it is essential to establish the temporal scope of the calculation (for example, a one-year operation) and the management scope (which may include only the farm, the farm along with the electrical energy consumed, or the entire process from the development of inputs to their final use). Therefore, for each item included in the LCI, an impact is assessed using specific coefficients published by the IPCC[(12)].

Various metrics are used to convert non-CO_2 greenhouse gases into their CO_2 equivalent in order to compare their impact.. The global warming potential (GWP), the most widely used, is a relative measure of how much heat can be retained by a GHG in a given period (radiative forcing) compared to CO_2. Global temperature change potential (GTP) refers to the change in global mean surface temperature induced by a given GHG relative to CO_2[(12)]. Both metrics are international standards currently used by Uruguay's national GHG inventory[(1)]. A temporal scope of 100 years was considered for the global warming potential (GWP) emissions according to the IPCC Sixth Assessment Report[(13)], with a GWP of 1, 27, and 273 for CO_2, CH_4, and N_2O, respectively.

Some years ago, GWP* was developed, considering the half-life of methane as point emissions (pulse) and its unique characteristic of being a short-lived gas that is reduced to CO_2 after 10-12 years. Unlike other metrics, the GWP* is not a mere calculation coefficient, but a model that estimates the CH_4 contribution in year "t" minus the value of the methane contribution in year t-12[(12)].

This research aims to understand the relationship between GHG emissions and capture of the integrate livestock farming and forest system. We hypothesize that there is a ratio livestock farming area/planted forest area that allows producing carbon-neutral beef. GHG neutrality means an entity's gross emissions of all GHG must be balanced by the removal of an equivalent amount of CO_2 from the atmosphere[14]. For this assessment, two production systems (*Pinus spp* for solid wood and *Eucalyptus spp* for pulp mill*)* were evaluated using growth models. Emissions and captures of GHGs were estimated for both systems. Due to the ongoing debate regarding the different metrics used to estimate the CO_2-eq of enteric methane and the significant variability in their results[15], a comparison of three metrics has been conducted.

2. Materials and Methods

The research was conducted in 2021 and 2022 at the "El Carmen" farm, owned by Forestal Caja Bancaria (FCB). The farm is located in the Department of Durazno, latitude 33.21° S and longitude 56.06° W (**Figure 1**). The climate is temperate and humid, without a dry season (Cfa) according to the Köppen–Geiger classification[16], and has the highest rainfall within the country (**Table 1**).

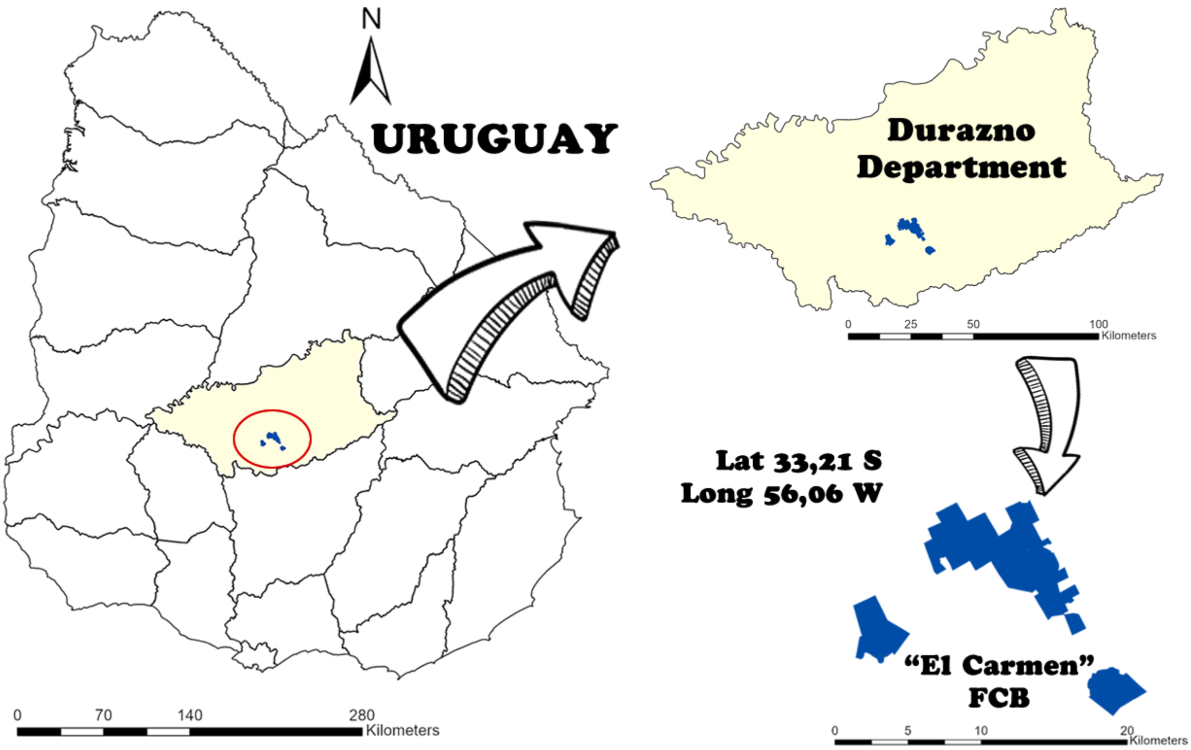

Figure 1. Spatial location of the "El Carmen" farm where the research was conducted

Table 1. Climate characteristics of the northeast region of Uruguay for the period 1980-2009[17]

CLIMATIC VARIABLE	MEAN	MINIMUM	MAXIMUM
Rainfall (mm)	1,400	1,200	1,600
Temperature (◦C)	17.7	12.9	22.6
Accumulated days with frosts	30	20	40
Radiation ($h.d^{-1}$)	7.0	5.0	9.5
Annual air relative humidity (%)	74	70	78
Potential evapotranspiration ($mm.\ month^{-1}$)	1,100	1,000	1,200

According to the Soil Atlas of Latin America and the Caribbean[18], the main soils of Uruguay are phaeozems, leptosols, vertisols, acrisols, and luvisols. Parent material of soils is sandy stones and sedimentary rocks.

To understand the relationship between GHG emissions and carbon capture in the integrated forestry and livestock system, four steps were followed: (a) characterization of the production system; (b) estimation of greenhouse gas (GHG) emissions by livestock system and forestry; (c) estimation of carbon capture by forests; and (d) assessment of the overall carbon balance.

2.1 Production System Characterization

2.1.1 Beef Cattle System

The studied system integrates livestock and forestry production in 5,802 ha, as described in **Table 2** and **Figure 2**.

Table 2. Land use of Forestal Caja Bancaria (FCB) farm “El Carmen”

LAND USE	AGE (YEARS)	AREA (ha)
Forest plantations	-	3105.4
E. dunnii	9	27.2
	3	85.3
	2	535.3
	1	635.7
E. globulus	9	9.3
	8	15.1
E. grandis	13	19.2
	9	94.3
	8	725.
	3	80.7
	2	111.5
	1	205.7
E. maidenii	8	16.4
P. taeda / P. elliottii	28	544.1
Infrastructure and native forest	-	75.0
Forage crops for beef cattle	-	817.0
Native pastures for livestock feeding	-	1,638
Other areas	-	167.0
Total area	-	5,802

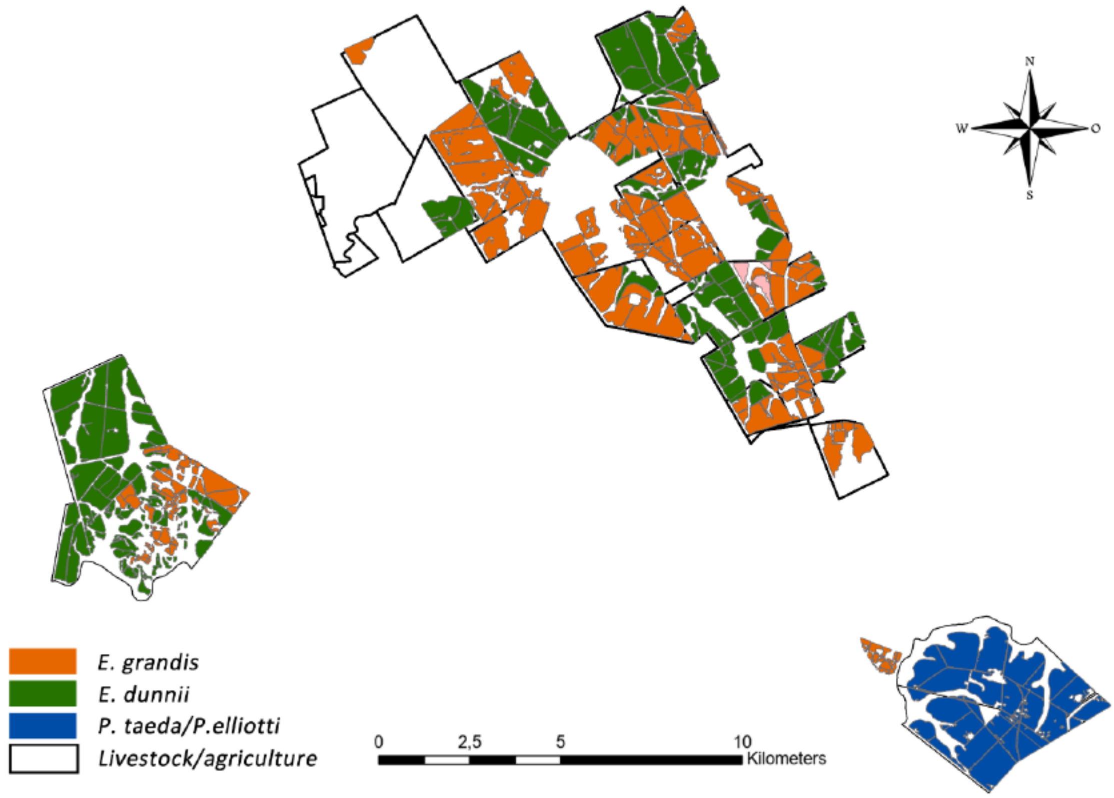

Figure 2. Land use of "El Carmen" Forestal Caja Bancaria farm

The livestock system accounts for 42% of the total area of the FCB farm. It is characterized as a complete open-cycle livestock system that includes a breeding herd responsible for producing male and female calves and heifers for replacement. Castrated male calves are raised and fattened on the farm, while surplus female calves –those exceeding the necessary number for replacing culled cows due to age or non-pregnancy in autumn– are sold. The rearing and finishing process takes place over an area of approximately 817 hectares, which is also used for crop production. This crop production provides grain supplements that help to speed up the rearing and finishing processes. Additionally, intensive forage is produced from perennial pastures and annual forage crops. Recently, the farm has adopted feedlot fattening for steers and heifers, primarily using grain produced on the farm. The decision to implement feedlot fattening depends on the price ratios of beef to feeding costs. Table 3 presents the cattle stock, sales, and various livestock productivity and efficiency indicators that are used to evaluate the production system.

Table 3. Beef cattle stock, sales, purchases and livestock productivity, and efficiency indicators of FCB farm

Cattle stock (June 2022)		Annual sales (n°)		Annual purchases (n°)		Simulated livestock system productivity and efficiency indicators	
Bulls	42	Steers	626	Male calves	400	Beef cattle area (ha)	2,200
Cows	620	Cows	176			Improved pastures (%)	33
Culled cows	52	1-2 yr heifers	52			Stocking rate (AU/ha)[a]	0.83
+2 yr heifers	127					Livestock production (kg LW.ha^{-1}.yr^{-1})	161
1-2 yr heifers	99						
1-2 yr steers	617						
Calves	907						

[a] AU (Animal Unit) represents the dry matter requirements of a 380 kg cow that is rearing and weaning one calf each year.

2.1.2 Forest Plantations

Forest plantations are developed in stands of *E. dunnii* and *E. grandis* oriented to the production of cellulose pulp. These stands are managed with plantation densities greater than 1,200 trees per hectare and rotation ages of 11 years on average. Additionally, smaller proportions of *Pinus taeda* and *Pinus elliottii* are planted for sawn wood, managed as unpruned stands with a density of 600 trees per hectare and a rotation period of 25 years. The spatial distribution of forest species is illustrated in **Figure 2**.

2.2 Estimated Emissions

2.2.1 GHG Emissions from Livestock

Livestock emissions were estimated using a dynamic and deterministic model[19] to simulate the behavior of a livestock production system in all its stages (breeding, rearing and fattening), considering animal performance, herd dynamics and management strategies. The time step is one month, and the model run through iterations until all outputs reach stabilization. The model adjusts the animal requirements, and the feed offered through a metabolizable energy balance based on the equations developed in Australia by the CSIRO Institute[20]. The decision to use this source of equations for the developed model is because these equations were specifically designed for grazing systems. In contrast, models like NRC[21] and ARC[22] primarily focus on grain diets and byproducts.

The model incorporates actual data from the farm, averaging three years of stock and sales information along with other relevant indicators. It establishes population parameters that define a theoretical system for maintaining stable stock and sales values over the years. The model considers the available forage and additional feed based on the current situation. It adjusts weight gain rates to correspond with the age at which the steers are sold, as well as the age and weight at calving, among other parameters sourced from the FCB farm. The productive parameters estimated by the model are utilized to determine the dry matter intake of animals, which is categorized based on their consumption of different feeds. The methane conversion factor (Ym) is derived from the dry matter digestibility (DMD) of the feed, as proposed by Gere and others[23]:

$$Ym = 11.555 - 0.091 \times DMD\ (\%) \qquad \text{[Equation 1]}$$

This approximation integrates variations between different consumed pastures more accurately instead of using a single coefficient for pastures, as proposed by the IPCC[24]. The amount of feed consumed, the quality of each type of feed, and the estimated emission factor will all contribute to the level of enteric methane emissions. These emissions are calculated using the equations provided by the Intergovernmental Panel on Climate Change[24]. Furthermore, this information source provides the equations for estimating methane emissions in manure and nitrous oxide emissions from manure. Based on the information provided by the FCB, it is possible to establish the dry matter intake from native pastures, artificial pastures and supplements for the different categories and, thus, to analyze this intake (and based on this, the emissions) attributable to the different livestock subsystems in the farm. The cow-calf subsystem (COW-CALF) includes breeding cows, bulls, and replacement females (calves and heifers) and calves and heifers produced until they are weaned. These categories usually graze in native grasses that have a high fiber content but lower digestibility. The rearing and fattening subsystem (R+FAT) takes male calves from the breeding subsystem, culled cows, and some female calves, fattening them for sale to the meat processing industry. This process is carried out on annual or perennial pastures known for their high quality and low fiber content; it can also be conducted in a feedlot to fatten steers and heifers.

The emissions from crops used for livestock feed are included in this section. The carbon footprint of these crops is based on studies by Bustamante-Silveira and others[25].

2.2.2 Global Warming Coefficients

The three global warming coefficients analysed were computed as follows. Related to GWP*, the following equation[26] models the process of converting methane into CO_2 equivalent over time:

$$E_{CO_2eq(t)} = \left(4.53 \text{ x } E_{CH_4(t)} - 4.25xE_{CH_4(t-20)}\right) \text{ x } GWP_{100}$$ [Equation 2]

where:

$E_{CO_2eq(t)}$= CO_2 equivalent emissions in year t
$E_{CH_4(t)}$= CH_4 emissions in year t
$E_{CH_4eq(t-20)}$= CH_4 emissions in year t-20
$GWP_{100} = 27 =$ Global warming potential value normalization (AR6)

If no changes in the livestock production system are assumed, i.e. a system stabilized over time, gross emissions will also be stabilized. Consequently:

$$E_{CO_2eq(t)} = 7.56xE_{CH_4(t)}$$ [Equation 3]

The different coefficients to express the impact of GHG emissions are presented in **Table 4**.

Table 4. Descriptions of coefficients for common GHG emission values normalization[13]

	GWP_{100} (AR6)	GTP_{100} (AR6)	GWP*
Carbon dioxide (CO_2)	1	1	1
Methane (CH_4) (non fossil)	27	4.7	Equation 3 = 7,56 (at stable emissions)
Nitrous oxide (N_2O)	273	233	273

2.2.3 GHG Emissions from Forest Plantations

The life cycle inventory (LCI) was performed for each type of plantation, from the growth of the trees in the greenhouse up to their harvest, with a cradle-to-gate scope. The LCIs of forest plantations were developed according to Rachid-Casnati and others[27] without considering soil erosion. These inventories were transferred to the OpenLCA software, where the respective ecodesigns[28] were developed for plantations intended to produce solid wood (25-year-old pines) and cellulose pulp (11-year-old eucalypts). The GWP coefficients for these carbon footprint estimations were IPCC 1997 available in the Agribalyse database (OpenLCA Nexus). Estimates of emissions related to forestry activities were expressed in kilograms of CO_2-eq per cubic meter of harvestable wood, with IPCC GWP impact coefficients for 100. Wood production values were obtained as explained in 2.3.2.

2.3 Carbon Stock Estimations

2.3.1 Characterization of Soil Organic Carbon

To characterize organic matter levels across various soil uses and types, samples were collected for chemical analysis of organic carbon (0-15 cm). This was done alongside the collection of a corresponding number of bulk density samples from the same site to calibrate the resulting organic carbon values. A total of sixty samples were processed at INIA Soil Laboratory for each analysis (chemical and bulk density), where each sample analysed consisted of 5 subsamples. In **Supplementary Material 1** locations where soil sampling was conducted and the soil characterization according to classification[29] are presented.

2.3.2 Forestry Production and Carbon Accounting

Estimation of carbon stock of forest plantations included two steps: a) characterization of stands at current age, and b) growth projection until harvest age and aboveground biomass estimation. For the first step a stratified random sampling (forest inventory) was carried out to estimate stand variables (diameter at breast height, total height and number of trees per hectare) at the current age. Only plantations older than two years (inclusive) were inventoried. A circular plot of 314 m^2 was established every 5.5 hectares, with 85 plots measured in *E. grandis* stands and 56 plots measured in *E. dunnii* stands. The activity was carried out by the Planning and Inventories Area of UPM-Forestal Oriental. Measurements for the initial characterization of the *P. taeda* and *P. elliottii* plantations at 18 years of age were provided by the management department of FCB (**Figure S2**, Supplementary Material).

Using information from the forest inventory as a characterization at the current age, the growth of *E. grandis*, *P. taeda* and *E. dunnii* was projected at the final rotation age. For this, simulation models developed by INIA were used[30][31][32][33]. In the case of *Pinus elliottii,* the *P. taeda* simulator was used. Those forest simulators provide total aboveground biomass (stem, bark, branches and leaves) along with equivalent CO_2 calculated by multiplying dry biomass weight by 0.49 $MgC.MgDM^{-1}$ and then by 3.67 $MgCO_2.MgDM^{-1}$. Each plot was projected based on mean top height (MTH), basal area per hectare (BA), standard deviation of diameters at breast height (SDdbh), and number of trees per hectare (N). The MTH was calculated as the average of the 100 trees with the greater diameter at breast height (DBH) of the hectare. The site index (SI) was calculated through the growth and yield models as the mean top height at the key age for each species. For *E. dunnii* the key age was 8 years, 10 years for *E. grandis,* and 15 years for pines. Root biomass was assumed as 11% and 13% of total dry weight of aboveground biomass for eucalypts and pines, respectively, based on reported values for ages 11 and 24 (harvest age)[34][35][36].

Plantations of 1 year old and younger were estimated as a weighted average of adult plantations. Those corresponding to *E. globulus* and *E. maidenii* were quantified in the same way. This criterion was assumed given the small area occupied by these species and the decision to replant those areas with *E. grandis* and *E. dunnii* by the company. A cutting period of 11 years was assumed for eucalypts and 25 years for pine trees.

2.4 Carbon Emissions Offset

The carbon balance of the system was calculated by considering the GHG emissions from the livestock system and the forest plantations. The total emissions and carbon captures were then used to determine the overall carbon balance.

Harvested wood for cellulose pulp or solid wood is not carbon sequestration, as the useful life of both forest products is negligible within a 100-year time frame. For solid wood, there is currently no clear criterion to define what portion of that biomass could realistically remain intact for 100 years. However, in this study all the wood was accounted for to serve to the purpose of the analysis.

The analysis of the livestock emissions offset process is based on two approaches:

a) Potential emissions offset: This approach focuses solely on growth rates and the accumulation of biomass in the standing forest crop, which is directly related to the capture of atmospheric CO_2. It evaluates the biomass accumulation in a specific area from planting to harvest, considering the entire rotation period (11 years for eucalyptus and 25 years for pine), based on the conditions observed at the farm.

b) Carbon offset through a dynamic system approach: Involves an annual staggered plantation across an area equivalent to the total forest area divided by the rotation period for each species, and it is assumed that at the end of each rotation the respective plot is harvested, followed by resprouting or replanting, which ensures a perpetual plantation. The conceptual framework presented here addresses a real forestry system and encompasses two distinct periods:

1) Active CO_2 removal period: This phase includes the net growth of the forest stand, starting from planting until the annual harvest area matches the growth of the remaining plots. These plots may consist of those planted subsequently or those that have resprouted following harvest. The duration of this interval is contingent upon various factors, including the number of plots planted each year and the cutting schedule. During this period, the CO_2 capture rate by different forest species, determined by their growth capacity and biomass accumulation, establishes the potential for offsetting emissions from alternative sources, such as livestock.

2) Stationary offset emissions period: Following the previous period, the atmospheric CO_2 removal balance of the forest reaches a steady-state phase. This is where the amount of CO_2 sequestered by the growing areas matches exactly the biomass that has been harvested. As was noted, since the biomass is primarily intended for cellulose pulp production, it does not provide a permanent form of carbon sequestration and is therefore theoretically considered an emission due to its temporary nature. However, if this afforestation continues over time, the carbon stored in the biomass –including trunks, branches, leaves, and roots– can be recognized as a potential mechanism for offsetting livestock emissions, as it retains carbon which contributes to the greenhouse effect in the form of CO_2. It is essential to note that this carbon stock is finite, which limits the livestock area (or cattle heads) and the time needed to effectively offset emissions.

2.4.1 Potential Emissions Offset

As described on item 2.3.2, the amount of carbon accumulated over 11 years (eucalypts) or 25 years (pine) minus the emissions generated by the plantation during this period determines the quantity of carbon removed from the atmosphere by the trees. The ratio of this carbon volume to the livestock emissions –converted to CO_2 equivalent using three different metrics– will establish how many units of livestock (grazing hectares or cattle heads) can be neutralized by one hectare of forest of each species.

Calculated offset coefficients will be used for estimations in a real system, such as the FCB farm in the following sections.

2.4.2 Carbon Offset through a Dynamic System Approach

Active Carbon Stocking Period

During the first 11 years (until harvest), each plot accumulates carbon until, by year 10, all plots have been growing for different periods.

The total accumulated carbon stock in year 10 can be calculated as the sum of the carbon capture of each plot P*i*, considering that a plot planted in year *i* has been accumulating carbon for 11 – *i* years.

$$CS_{10} = \frac{CC * TFA}{11} * \sum_{i=0}^{10}(11 - i) \quad \text{[Equation 4]}$$

where:

CS_{10} = Carbon stock on year 10 (Mg)
CC = Carbon capture ($Mg.ha^{-1}.year$)

i = year from 0 to 10
TFA = Total forested area (ha)

solving the summation:

$$\sum_{i=0}^{10}(11-i) = (11+10+9+\cdots+1) = 66 \qquad \text{[Equation 5]}$$

Thus, the total accumulated carbon stock in year 10 is:

$$CS_{10} = \frac{CC * TFA}{11} * 66$$

$$CS_{10} = CC * TFA * 6 \qquad \text{[Equation 6]}$$

The accumulated carbon emissions for the livestock area in year 10 can be calculated as the sum of the annual carbon emissions over the 11 – i years.

$$CE_{10} = \sum_{i=0}^{10}(LA * LAE)$$

where:

CE_{10} = Total carbon emissions on year 10 (Mg)
LA = Livestock area (ha)
LAE = Livestock annual emissions (Mg/ha)
i = year from 0 to 10

$$CE_{10} = 11 * LA * LAE \qquad \text{[Equation 7]}$$

In the **Supplementary Material 2.1**, the equations for the case of pines are presented, which differ in having a harvest rotation of 25 years.

Stationary Carbon Stock Period

The period to consider for carbon stock to offset livestock emissions is influenced by the quantity of carbon stock, the designated area for livestock to offset, and the specific metric used to convert methane emissions to CO_2. This relationship can be represented mathematically as follows:

$$RCS_{10} = LA * LAE * TZB$$

where:

RCS_{10} = Remaining carbon stock (Mg)
LA = Livestock area (ha)
LAE = Livestock annual emissions ($Mg.ha^{-1}$)
TZB = Time to zero balance (years)

Therefore, the duration until the stock of C is depleted (TZB) will be:

$$TZB = \frac{RCS_{10}}{LA * LAE_{10}}$$

In the **Supplementary Material 2.2**, the equations for the case of pines are presented, which differ by a 25-year harvest rotation.

By considering the factors mentioned in each period, estimates can be integrated to determine for how long a specific forest area can offset livestock emissions.

3. Results

3.1 Emissions

3.1.1 Livestock Emissions

The results from simulating the FCB livestock system using the referred model[(19)] indicate that the animals consume approximately 5,200 Mg of dry matter annually from both native and improved pastures. In addition, 1,018 Mg of dry matter per year of supplements were added, based on FCB farm records. **Table 5** provides a breakdown of the feed consumed by the animals, as well as the emission factors used and the total emissions achieved, categorized by subsystem (COW-CALF vs. R+FAT).

Table 5. Cattle dry matter intake, emissions, and emission's intensity of FCB livestock system

	COW-CALF	R+FAT	Whole system
Native pasture intake (Mg $DM.yr^{-1}$)	2,157	567	2,724
Improved pastures intake (Mg DM. yr^{-1})	499	1,973	2,472
Total forage intake (Mg DM. yr^{-1})	2,656	2,540	5,196
Dry matter intake digestibility [a] (%)	54.8	64.7	60.5
Concentrate intake (Mg DM. yr^{-1})	275	743	1,018
Total feed intake (Mg DM. yr^{-1})	2,931	3,283	6,214
Average methane emission factor (Ym)	6.4	5.8	6.1
Enteric methane emissions (Mg $CH_4.yr^{-1}$)	58.2	60.5	118.7
Methane emissions from manure (Mg $CH_4.yr^{-1}$)	0.92	1.30	2.23
Manure nitrous oxide emissions (Mg $N_2O.yr^{-1}$)	0.86	1.25	2.11
Enteric methane emissions [b] (kg $CH_4.ha^{-1}.yr^{-1}$)	26.5	27.5	54.0
Methane emissions from manure [b] (kg $CH_4.ha^{-1}.yr^{-1}$)	0.42	0.59	1.01
Nitrous oxide from manure emissions [b] (kg $N_2O.ha^{-1}.yr^{-1}$)	0.39	0.57	0.96
Live weight production [b] (kg $LW.ha^{-1}.yr^{-1}$)	47	114	161
Enteric CH_4 emissions intensity (kg.100 kg LW^{-1})	56.7	24.2	33.6
Manure CH_4 emissions intensity (kg.100 kg LW^{-1})	0.90	0.52	0.63
Manure N_2O emissions intensity (kg.100 kg LW^{-1})	0.84	0.50	0.60

[a] feedlot included on R+FAT subsystem

[b] refers to total area, not effective area of each subsystem.

The total forage consumption is similar for the COW-CALF and R+FAT subsystems, but the sources are different. In the COW-CALF subsystem, 81% of the total forage comes from native pastures, while in the R+FAT subsystem, only 22% comes from this source. The remaining 78% in the R+FAT subsystem comes from annual and perennial pastures, leading to better digestion of the diet and resulting in increased productivity and lower emissions per kilogram of dry matter consumed. This is based on equation 1 and the emission factor (Ym) derived from it (5.8% vs. 6.4% in COW-CALF).

In the R+FAT system, there is a high consumption of supplements (22% of the total diet vs. 9% in COW-CALF) and highly digestible feed. This contributes to a diet with higher nutrient content, greater potential for weight gain, and lower relative potential to generate enteric methane emissions. Despite similar levels of enteric methane emissions and slightly higher methane and nitrous oxide emissions in manure, the higher production levels of the R+FAT subsystem (114 vs. 47 kgLW ha^{-1} $year^{-1}$) result in significantly lower emissions intensity for the three variables analyzed. Overall, enteric methane emissions are by far the largest source of greenhouse gas emissions. The emission values of crops destined for grain for animal supplementation were estimated based on the study by Bustamante-Silveira and others[(25)].

GHG emission values (enteric methane, manure methane, and manure nitrous oxide) generated in this study are shown in **Figure 3** based on the three global warming metrics described in item 2.2.

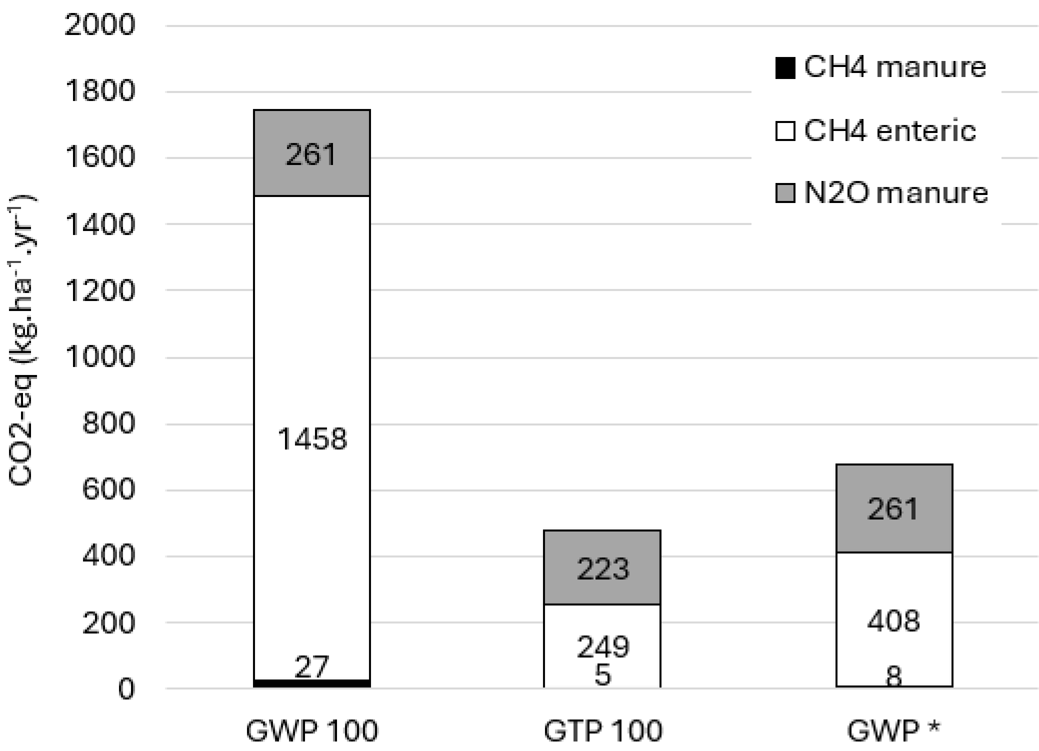

Figure 3. Livestock emissions as CO_2 eq according to three different global warming metrics used

3.1.2 Carbon Stocking by Forest Plantations

The initial sampling of forest plantations growth aimed to characterize each stratum at current age. The location of sampling plots is offered in **Supplementary Material 1**. The non-sampled area corresponded to 1-year-old plantations, which represents 27% of the planted area. Other specie's plantations represent 1.3%.

After projecting plots growth for each species from the current age to the rotation age and obtaining the dasometric variables per unit area, the variables of interest were estimated at the farm level (**Table 6**). Differences in individual growth are evident considering contrasting planting densities and rotation lengths for eucalypts and pines. Among eucalypts, the average annual increase and total volume were greater for *E. grandis*; however, the biomass per hectare of *E. dunnii* was greater. Therefore, *E. dunnii* captured the largest annual amount of carbon of the three species analyzed.

Table 6. Statistical characterization of eucalypt and pine stands at the harvest age

		FOREST SPECIES		
		E. grandis	*E. dunnii*	*Pinus spp.*
	Area (ha)	1,253	1,308	544
	Rotation age (yr)	11.0	11.0	25.0
Mean values weighted by the area of each stratum	Mean top height (m)	28.0	26.1	24.2
	Stocking (trees.ha $^{-1}$)	1,351	634	322
	Basal area (m ^{3}.ha- ^{1})	31.2	31.0	38.4
	Mean DBH (cm)	17.6	18.9	39.0
	Standard deviation of DBH (cm)	5.20	5.50	4.70
	Total volume (m ^{3}.ha $^{-1}$)	321	268	399
	Mean Annual Increment (m ^{3}.ha $^{-1}$.yr $^{-1}$)	29.0	22.7	14.0
	Above ground biomass (Mg.ha $^{-1}$)	160	211	229
	Commercial volume [a] (m ^{3}.ha $^{-1}$)	242	245	250
	Total CO_2-eq (Mg.ha $^{-1}$)	343	420	436
Values for the total forest area	Total volume (m ^{3})	402,228	350,383	217,112
	Commercial volume (m ^{3})	302,739	320,705	135,817
	Above ground biomass (Mg)	200,839	275,274	124,336
	CO_2-eq in total biomass (Mg)	429,779	549,360	209,712

[a] Small end diameters were set in 5 cm for eucalypts (pulp) and 20 cm for pines (timber)

The projected biomass distribution per hectare in the measured plots for the eucalypts was analyzed in relation to the Site Index (SI). This is considered an indicator of site quality although growth includes the adaptation of specific genetics to each site. In this sense, the relationship between SI and carbon captured for eucalypts was analyzed using the information of each plot (**Figure 3** and **Figure 4**). This was not possible for pines due to the limited number of plots used to characterize these plantations. For both eucalypt species, the SI showed a wide range of values that ranged between 19 and 34 m for *E. grandis* (at 10 years), and between 18 and 28 m for *E. dunnii* (at 8 years). For these ranges the correlation with the equivalent carbon captured was strong, with greater capture in the sites with higher productivity. The range of aboveground biomass production for the 11 years of both species is wide, although higher biomass per hectare is estimated on average for *E. dunnii*.

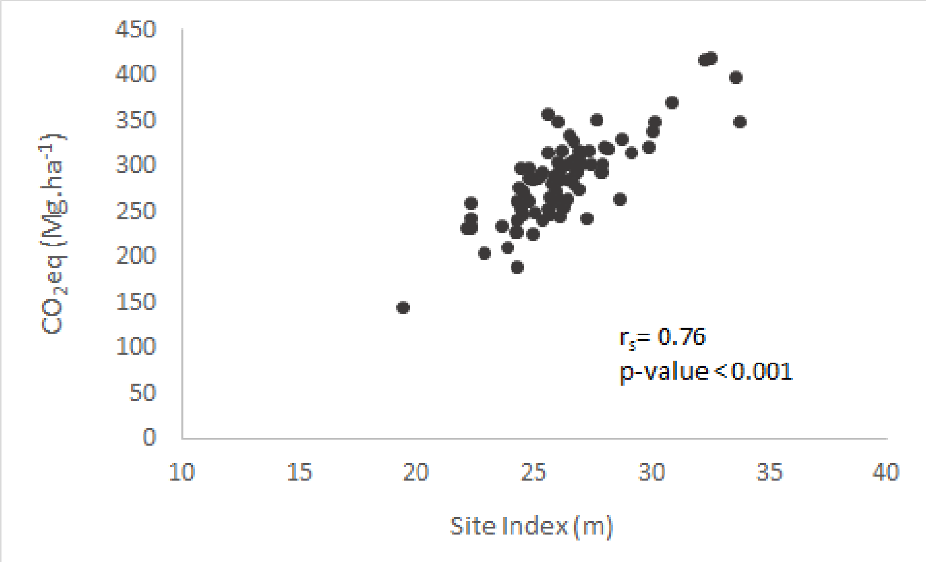

Figure 4. Variability of site quality within FCB farm assessed through the Site Index (in meters) and its relationship with carbon stocking in *E. grandis* aboveground biomass (Rs=Spearman correlation)

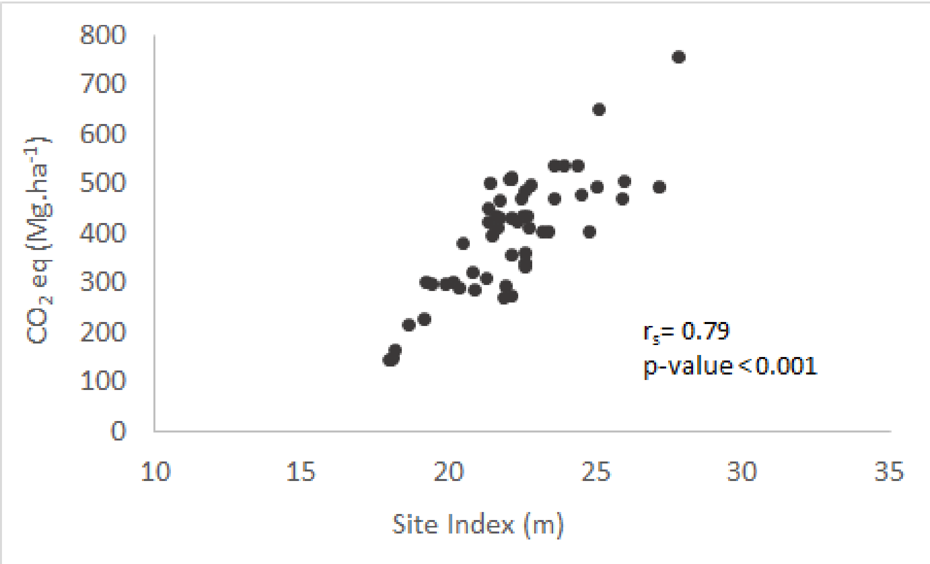

Figure 5. Variability of site quality within FCB farm assessed through the Site Index (in meters) and its relationship with carbon stocking in *E. dunnii* aboveground biomass (Rs=Spearman correlation)

3.2 Soil Organic Carbon

The analysis of soil samples showed no statistically significant differences among the land uses, including cropping, forestry, and livestock. The organic matter percentages recorded were 5.9, 5.2 and 5.0%, respectively.

3.3 Carbon Emissions Offset

3.3.1 Potential Emissions Offset

In this section, we present the potential offset focused on one hectare of forest during its active growth period, specifically from planting until harvest. Subsequent section will examine results that consider the dynamic nature of these systems using the offset coefficients introduced in this section.

Primary findings regarding the carbon footprints of forestry and livestock are offered in **Table 7**. The wood carbon footprint is characterized by a large carbon surplus from the biomass of forestry plantations.

Table 7. Carbon footprint, balance, and livestock emissions potential offset (LSEPO) according to metrics used

	E. grandis	*E. dunnii*	*Pinus spp.*	Beef	Crops
Change in C soil ($Mg.ha^{-1}$)	-	-	-	-	-
Area affected (ha)	1,253	1,308	544	2,200	260
Rotation length (yr)	11	11	25	1	1
Carbon capture by planted forests (kg CO_2 eq.ha^{-1})	-342,567	-419,733	-435,502	-	-
Carbon capture by planted forests (kg CO_2 eq.ha^{-1}.yr^{-1})	- 31,142	- 38,158	- 17,420	-	-
GHG emissions (kg CO_2 eq.m^{-3})	7,313	7,384	7,482	-	-
GHG emissions (kg CO_2 eq.m^{-3}.yr^{-1})	665	671	299	-	-
GHG emissions GWP_{100} (kg CO_2 eq.ha^{-1}.yr^{-1})				1,746	
GHG emissions GWP* (kg CO_2 eq.ha^{-1}.yr^{-1})	487	494	221	677	1,702[a]
GHG emissions GTP_{100} (kg CO_2 eq.ha^{-1}.yr^{-1})				477	
Carbon balance GWP_{100} (kg CO_2 eq.ha^{-1}.yr^{-1})				1,746	
Carbon balance GWP* (kg CO_2 eq.ha^{-1}.yr^{-1})	-30,695	-37,688-	-17,219	677	1,702[a]
Carbon balance GTP_{100} (kg CO_2 eq.ha^{-1}.yr^{-1})				477	
LSEPO GWP_{100} (Livestock ha.Forestry ha^{-1})	17.6	21.6	9.9	-	-
LSEPO GWP* (Livestock ha.Forestry ha^{-1})	39.1	48.0	21.9	-	-
LSEPO GTP_{100} (Livestock ha.Forestry ha^{-1})	50.6	62.2	28.4	-	-
LSEPO GWP_{100} (heads.Forestry ha^{-1})	20	24	11	-	-
LSEPO GWP* (heads.Forestry ha^{-1})	44	54	25	-	-
LSEPO GTP_{100} (heads.Forestry ha^{-1})	57	70	32	-	-

[a] Based on Bustamante−Silveira and others[(25)]

The metric applied by IPCC for estimating GHG warming equivalences, GWP_{100}, determines CO_2 equivalent emission values higher than the other two metrics evaluated.

The results indicate that different forest species and metric used have varying potentials for offsetting emissions. In the least favorable scenario with pines and GWP_{100}, 10% of the area is needed to offset CO_2 emissions from livestock (1 hectare of pines for every 9.9 hectares of livestock). Conversely, in the most favorable case with *E. dunnii* and GTP_{100} metric, only 1.6% of forest plantations is required to offset cattle emissions, meaning 1 hectare of *E. dunnii* can offset emissions from 62.2 hectares of livestock.

Changing the indicator to avoid referencing the specific stocking rate used in this case study, 1 hectare of eucalypts can potentially offset emissions from 20 to 70 cattle heads, while pines (1 hectare) can offset emissions from 11 to 32 cattle heads.

3.3.2 Offset during the Active Carbon Stocking Period

During the initial 11 years leading up to the harvest of the first plot, annual net accumulation increases as new plots are established. Throughout this period, the carbon balance depends on the forest species, the metrics used, the available forested areas, and the livestock area intended to offset. For example, focusing on *E. grandis* and applying the GWP_{100}, a zero-carbon balance will be achieved by year 10, when the area designated for livestock is 9.62 times larger than that of the forest. In other words, one hectare of *E. grandis*, with eleven plots of $\frac{1}{11}$ hectares planted annually, can offset emissions from 9.62 hectares of livestock at year 11. **Table 8** presents the complete results of these equations, considering three species and three metrics.

Table 8. Livestock area that can be offset by each forest species and the metrics considered within a long-term systems approach

	GWP_{100}	GWP*	GTP_{100}
E. grandis	9.6	21.3	27.6
E. dunnii	11.8	26.2	33.9
P. taeda	5.1	11.4	14.8

According to previous estimates, one hectare of *E. grandis*, evaluated using the GWP_{100} metric, has the potential to offset emissions equivalent to those produced by up to 21.6 ha of livestock over an 11-year growth period (**Table 7**). This represents the offset value for a hectare cultivated for 11 years, from planting to harvest.

However, employing a systems approach that considers the dynamics of plots gradually incorporated into the forest plantation, for the same species and metric, this value decreases to 9.62 hectares, as previously indicated. If the ratio livestock-afforested area is smaller than this 9.62/1 ratio by year 11, the carbon stock will exceed the amount needed to meet the specified demand.

3.3.3 Stationary Offset Emission Period

Table 9 presents the time needed for 100 hectares of eucalypts to offset emissions from various livestock areas, considering the forest species and the metrics used.

Table 9. Time required per 100 hectares of forest plantations to offset livestock emissions, according to forest species and metrics considered

Forest species	Metric	Livestock area (ha)	Offset time (yr)
E. grandis	**GWP**	200	53
		400	26
		600	18
	GWP*	200	117
		400	59
		600	39
E. dunnii	**GWP**	200	65
		400	32
		600	22
	GWP*	200	144
		400	72
		600	48

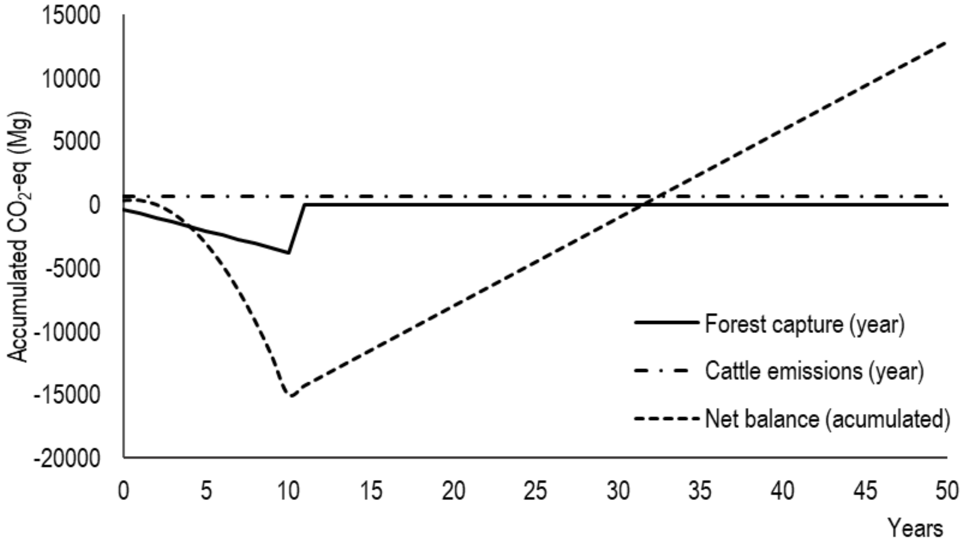

Figure 6. Cumulative carbon dioxide equivalent balance for a scenario considering 100 ha of *E. dunnii*, 400 ha livestock, and GWP_{100} as methane conversion metric

As shown in **Figure 6**, under the specified conditions –100 hectares of *Eucalyptus dunnii* and 400 hectares dedicated to livestock–, and considering the GWP_{100} metric, there is a continuous accumulation of biomass (i.e., net carbon accumulation) during the 11 years following the initial harvest. After this period, the 100 hectares that no longer accumulate biomass but remain standing can offset the emissions from the 400 hectares of livestock for an additional 21 years. This results in a total offset duration of 32 years.

4. Discussion

4.1 Livestock Emissions

As a reference, the national greenhouse gas inventory reports 50.6 kg of CH_4 emitted per animal per year. This value is derived from 601 million Mg of CH_4 emitted annually[(1)] over a stock of 11.8 million cattle heads[(37)].

The estimated value in this study was 65 kg of CH_4 emitted per head per year. This difference seems reasonable due to the intensive rearing and fattening scheme applied, which involves a low age at slaughter and higher weight gain. As a result, this system produces 79% more live weight than the country's average[(38)].

The value found in this study is also higher than the 56 kg CH_4.head^{-1} yr^{-1} suggested by the IPCC/Tier 1 for livestock in Latin America[(24)]. The same argument applies to this case as well. It is reasonable to use a lower value for methane emission levels when applying it at the country level, particularly in situations with lower production rates than the FCB case.

Researchers from Victoria University of Wellington, New Zealand, reported annual methane emissions of 95 kg CH_4 head^{-1} yr^{-1} per dairy cattle and 61 kg CH_4 head^{-1} yr^{-1} per beef cattle[(39)].

Several production systems –from different countries– have shown that the fiber content in pastures is linked to methane production at the rumen level[(40)(41)]. This is because the amount of digested plant cell walls is linked to the hydrogen release, which in turn affects the amount of the methane (CH_4) produced. Therefore, the CH_4 yield per unit of digested fiber should remain constant in diets that are primarily based on roughages[(42)].

This information supports this study findings, which show that the cow-calf system, which mainly relies on natural pasture and lower production levels (**Table 5**), produces comparable emissions but over a larger area and less live weight production, with significantly higher emissions intensity.

Similar findings have been reported in national studies[43], concluding that enteric methane emissions were significantly lower in animals grazed on higher quality pastures compared to those grazed on pastures with less quality and high fiber content.

4.2 Forestry Plantations as Carbon Sinks

Forest plantations (e.g. pines and eucalypts) use carbon dioxide from the atmosphere to create sugars and energy for growth and life functions through their lifespan until harvest. This process allows offsetting GHG generated by enteric and nitrous oxide sources from livestock. The area needed overtime to offset livestock emissions depends on several factors, including tree species, agro-ecological region where they are located, growth rates, and forest management practices[39]. Depending on the species and varying growth rates, carbon sequestration changes by the harvest age. In our study, mean annual increments ranged between 14 and 29 $m^{-3}.ha.yr^{-1}$. These differences, due to site characteristics, management practices, and genetics, allow for variations in carbon stock in live forest biomass, ranging from 100 to 700 $Mg.ha^{-1}$ of CO_2 (as shown in **Figure 4** and **Figure 5**). For this reason, the comparison of forest plantation's carbon-capture to livestock's GHGs net emissions should consider specific characteristics of production systems including stand variability. This highlights the importance of developing adequate inventories to capture such variability when evaluating these systems.

Loza-Balbuena[44] reported the greater carbon sequestration of *E. grandis* compared to *P. taeda* due to the higher growth rate of the first species. The same author estimated higher carbon stocking compared to the present study: 512 Mg CO_2-eq at 25 years for *P. taeda*, while for *E. grandis* estimations corresponded to 519 Mg CO_2-eq at 11 years[44]. In both cases, mulch and root biomass were considered, and the analysis was carried out for the northern area of Uruguay, where growth rates are higher in response to better growing conditions such as greater soil depth and annual rainfall. This study conservatively assumed an 11-13% proportion of root biomass to the total biomass, while other studies mention a proportion of 20%[45]. Among eucalypts analyzed, both with similar rotation ages and growth rates, the production of dry matter and biomass differs, probably due to the differences in wood density between *E. grandis* and *E. dunnii*, greater in the latter[46]. This is enhanced by the high proportion of stem biomass in the total aerial biomass[34][47][48]. On the other hand, the variability of sites was reflected in the production of biomass and carbon sequestration for the eucalypt species studied, coinciding with previous studies[34][49].

The forestry component in our analysis represents a common arrange of species and production cycles in Uruguay. *E. grandis* is the most planted eucalypt species, occupying just over 250,000 hectares with a large proportion of that area dedicated to pulp production. It is followed by *E. dunnii* with almost 217,000 hectares and destined entirely for pulp production, followed by *P. taeda* and *P. elliottii* as the third most planted exotic species (together)[50], to produce boards and sawn wood.

Alternatively to the fast-growing species assessed, *Eucalyptus tereticornis* deserves attention as a potential forest component in integrated systems oriented to produce carbon-neutral beef. This species, along with *Eucalyptus camaldulensis*, is usually planted in small patches throughout the country for providing shed and shelter for cattle and sheep production, given the resistance of the species to a wide range of microsite conditions. Moreover, their durable wood is used for fencing and for building many rural structures. However, biomass production and potential carbon storage in Uruguayan conditions need to be assessed for this species. National studies report stem volumes per hectare of *E. tereticornis* at 9 years ranging from 146 $m^3.ha^{-1}$[51] in the North of Uruguay and 93 $m^{-3}.ha^{-1}$ in the same region of FCB farm (El Carmen in Durazno), considering total stem volumes over bark and 700 stems.ha^{-1}. Under these conditions and considering wood density as 680 kg.m^{-3}[(52)], stem biomass would range from 69.2 to 99.3 MgDM.ha^{-1} corresponding to 12.2 and 19.8 MgCO$_2$-eq.ha^{-1}.year^{-1}. Those values are comparable to the pine species, but if total biomass is considered, captured CO_2 would approach to values found for *E. grandis* and *E. dunnii*. Although the growth rate and volumes of the latter species are larger, their wood density is considerably smaller: 423 and 499 kg.m^3 (basic apparent density) for *E. grandis* and *E. dunnii*, respectively[(53)(54)].

The interest in native forests as carbon sinks in carbon-neutral beef production is also growing. A recent study reported that native forests in expansion removed in average 9.76 MgCO$_2$-eq.ha^{-1}.year^{-1}, corresponding to 35.7 MgCO$_2$-eq of above and belowground biomass[(55)]. Challenges and opportunities of native forest integration are under discussion[(56)], however, local information of biomass production and carbon capture is still scarce.

The effectiveness of forestry plantations as a greenhouse gas emissions offsetting technology alternative should be further assessed in future studies. This should consider various regions of Uruguay, the composition and structure of livestock systems, the layout and use of forest plantations (including species, proportions, and purpose), and the overall aim of the proposal. In other countries it was suggested that in a phased approach, fast-growing eucalyptus will be utilized as a quick response to help offset livestock emissions, while slower-growing pine will serve as a longer-term and more sustainable solution. Additionally, promoting the inclusion of native forests in cattle farming can also be part of this long-term strategy[(57)].

4.3 Livestock-Forestry Integration for Carbon-Neutral Beef and Dairy Production

Our results showed that *E. grandis*, *E. dunnii*, and *P. taeda* plantations capture 64, 77, and 79 times the emissions from forestry activities, respectively. This creates a significant surplus of carbon that can help offset emissions in other kind of productions, such as cattle farming. For the livestock system assessed, one hectare of afforested area with *E. grandis*, *E. dunnii* and *P. taeda* can compensate the GHG emissions of 39.1, 48 and 21.9 hectares of cattle production, respectively (through GWP*).

The significance of calculating these potential offset parameters is underscored by the possibility that stem wood may eventually be used for durable materials, such as construction materials or insulators, instead of cellulose pulp. In this case, calculating the carbon stock in plantations similar to the one assessed would involve applying the potential offset coefficients over the time forests remain in place, since harvesting would no longer result in a loss of carbon to atmosphere.

Forest arrays other than high tree stockings for pulp can be considered. Dieguez Cameroni and others[(58)] assessed livestock capacity and carbon balance during the steer fattening phase in an integrated system including *Eucalyptus dunnii* planted in two different arrays: traditional pulp-oriented (1,100 trees.ha^{-1}) and silvopastoral spacing of (2×3) + 18 (526 trees.ha^{-1})[(58)]. For both plantations arrays, forest growth rate was lower than the recorded at FCB farm. Cattle emissions for the conditions assed were also lower than the emissions reported for the complete cycle analyzed in this study. The mentioned study reports that 13% of afforested areas allow neutralizing cattle emissions during one forestry rotation, without considering tree harvest emissions.

In New Zealand, approximately in 30 years, a study reported that one hectare of pine plantation stored approximately 6.4 Mg of carbon. The study showed that to achieve the same thermal effect as a 24% reduction in methane emissions from the beef cattle herd, 373,000 hectares of pine plantations would be needed. This highlights the potential of forests in reducing greenhouse gas emissions in that country[(39)]. Another study in the same country[(59)] found that for an average 695 ha sheep and beef farm, 62.6 hectares of *Pinus radiata* are needed to neutralize 50% of GHG emissions, while 125.2 hectares are needed to neutralize

100%. For dairy farms, 37.2 hectares are needed to compensate 50% of GHG emissions, and 74.4 hectares for 100% neutralization. These values vary with tree species, and afforestation on the farm itself can participate in New Zealand's carbon market credits.

In Australia it was found that afforestation of 20% of the area of sheep or beef farms with *Corymbia maculata* could reduce emissions over 25 years[(60)]. Another study in the same country[(61)] identified afforestation and reforestation as effective methods for sequestering carbon in the Australian red meat sector, suggesting that 5 to 11% of the current grazing area would need to be occupied with trees, depending on the tree species used.

Modeling strategies were also applied to estimate the area of eucalypt and pine plantations needed to offset 1,000 Mg of CO_2 equivalent in different regions of Queensland, Australia[(62)]. Findings pointed out that between 0.9 and 8.8 hectares of eucalypt plantations would be necessary, depending on various factors such as season and soil fertility. Compared to our findings, 1,000 Mg of CO_2-eq would be equivalent to emissions from 574 hectares of livestock similar to FCB farm. For comparison, 1 hectare of eucalypts could offset between 65 and 638 hectares of livestock emissions considering a similar production system to the FCB farm, which are significantly higher than the values found in our study (between 10 and 22 hectares; **Table 7** and **Table 8**).

In Amazonia (Brazil), Monteiro and others[(63)] found 224 kg ha^{-1} of enteric methane emissions in a livestock system with higher live weight gains (0.630 kg $LW.day^{-1}$) and a greater stocking rate (2.5 $AU.ha^{-1}$). Adjusting these results to a similar stocking rate of our case study, the equivalent value would be 72 kg $CH_4.ha^{-1}.yr^{-1}$, higher than the 54 kg $CH_4.ha^{-1}.yr^{-1}$ found in our work. However, the cited authors focused exclusively on fattening, with live weight gains significantly higher than those recorded for FCB farm.

Experiments focused on the evaluation of different crop-forestry-cattle combinations in the Cerrado region in Brazil showed that only 15% of the production area devoted to a mixed integrated system would be sufficient to offset all methane emissions from cattle and nitrous oxide (from soil and cattle excrement) in addition to the initial emissions from the crop phase (N_2O)[(64)]. Another study in the same country[(65)] reported that silvopastoral systems help neutralize the impact of enteric CH_4 emissions by facilitating carbon storage in soil organic carbon.

4.4 Challenges for Carbon Accounting

For long-lived greenhouse gases that accumulate in the atmosphere, such as carbon dioxide, cumulative GWP_{100} emissions are roughly proportional to global warming. However, this relationship does not hold for short-lived greenhouse gases, such as methane, as the GWP_{100} approximates the average warming from an emissions pulse over the next 100 years but not the warming at any given time. The GWP* is proposed as an alternative to GWP_{100} for better representing the climate effects of short-lived greenhouse gases, as it equates to an increase or decrease in the annual emission rate of a short-lived greenhouse gas with a one-off emission or removal of carbon dioxide[(39)]. Thus, cumulative GWP* emissions are ensured to be proportional to the additional warming of a time series of methane emissions relative to warming at the start of the time series. Cumulative GWP* emissions give similar results to those obtained using a climate model to assess the additional warming of a time series of methane emissions[(66)]. Although several studies show that it is possible to offset greenhouse gas emissions by sequestering CO_2 in growing forest biomass, great concern has arisen in recent years about how to avoid double counting, audited only by carbon markets developed between private parties[(67)(68)].

Given that global warming is of public interest due to its environmental impacts that affect the entire human population, the need for tools for monitoring and verification of public policies has emerged as a line of technological research[(66)]. In this framework, the lack of reliability in emissions compensation has generated doubts in the international market[(67)(69)] and, in some cases, about the use of exotic forest plantations[(70)].

Potential impacts on soil quality and water availability of large-scale forest plantations with exotic species must be analyzed in each case and balanced with CO_2 capture[(70)(71)].

Developing a system that allows traceability and avoids double-counting is necessary. New strategies, such as the application of blockchain technology, could prevent duplicate carbon sequestration from entering the market[(72)] and a more precise international audit for national livestock production systems that intend to declare carbon neutrality.

Integration of forest plantations in livestock systems can be implemented on a small proportion of beef farms to diversify income and promote certification of carbon-neutral meat through eco-labeling systems, as shown by some national ventures that have successfully exported verified carbon-neutral beef overseas[(73)].

The results obtained can be used to analyze various mitigation scenarios and discuss the information needs for designing new eco-friendly systems strategies. This involves combining different livestock systems or subsystems (such as breeding, rearing, and fattening) with forest plantations of diverse species, such as the ones analyzed in this study or alternative tree components.

5. Conclusions

The current results support the hypothesis that forest plantations with eucalypts and pines enable carbon-neutral beef production considering a ratio of cattle production and afforested area in a limited timeframe.

For this study case, forest units ranging from 3% to 20% of the total area could potentially offset emissions from beef cattle, depending on the species, rotation age, and metric used.

The carbon footprint related to planting and harvesting forests is less than 0.02% of the carbon stored in trees in the case study.

Substantial variability considering mitigation potential of the studied tree species was found in the area assessed associated with the differences in growth rates, wood properties, and management practices which influence biomass production per hectare.

Different global warming measures used to calculate livestock emissions had a significant impact on the overall offsetting of the livestock system. This emphasizes the importance of including GWP* and GTP calculations for a comprehensive analysis in integrated forestry and livestock systems in Uruguay.

The potential values provided in this study allow further understanding of the relationships between components (cattle production and forestry) required for offsetting livestock emissions, and the duration in which beef produced could be considered “carbon neutral beef”. This information would help to discuss alternative models at production unit level in the future.

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Transparency of data

Data not available: The data set that supports the results of this study is not publicly available.

Author contribution statement

	Soares de Lima JM	Rachid-Casnati C	Montossi F	Carrasco-Letelier L
Conceptualization	■	■	■	■
Formal analysis		■		■
Funding acquisition			■	
Investigation	■	■		■
Methodology		■		■
Project administration	■			
Writing – review and editing	■	■	■	■

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Supplementary Material

Supplementary Material 1. Figures

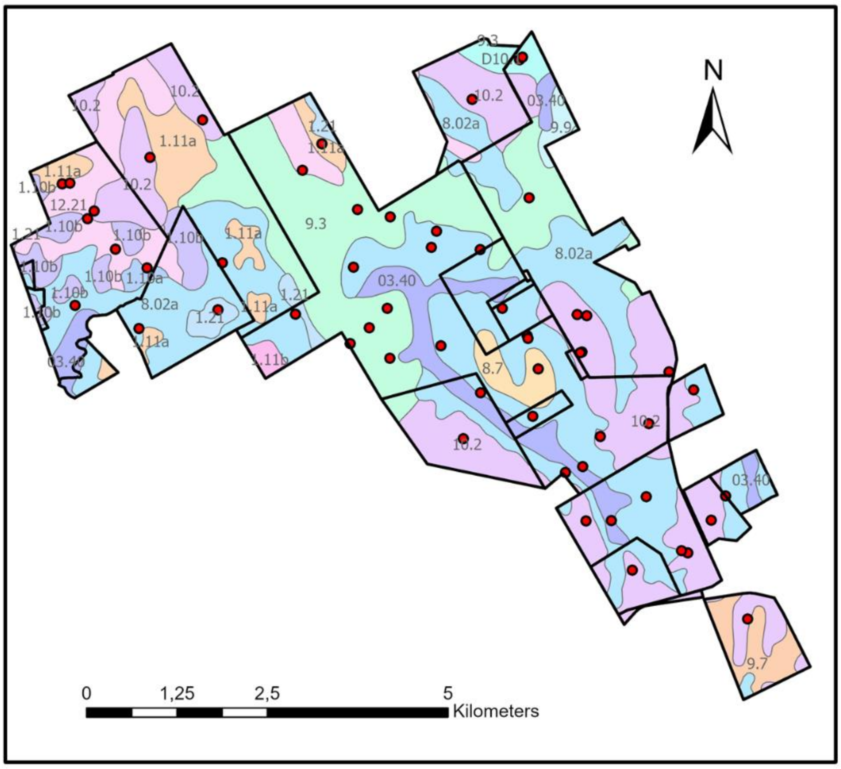

Figure S1. CONEAT soil groups (1:100.000) and soil organic carbon sampling points

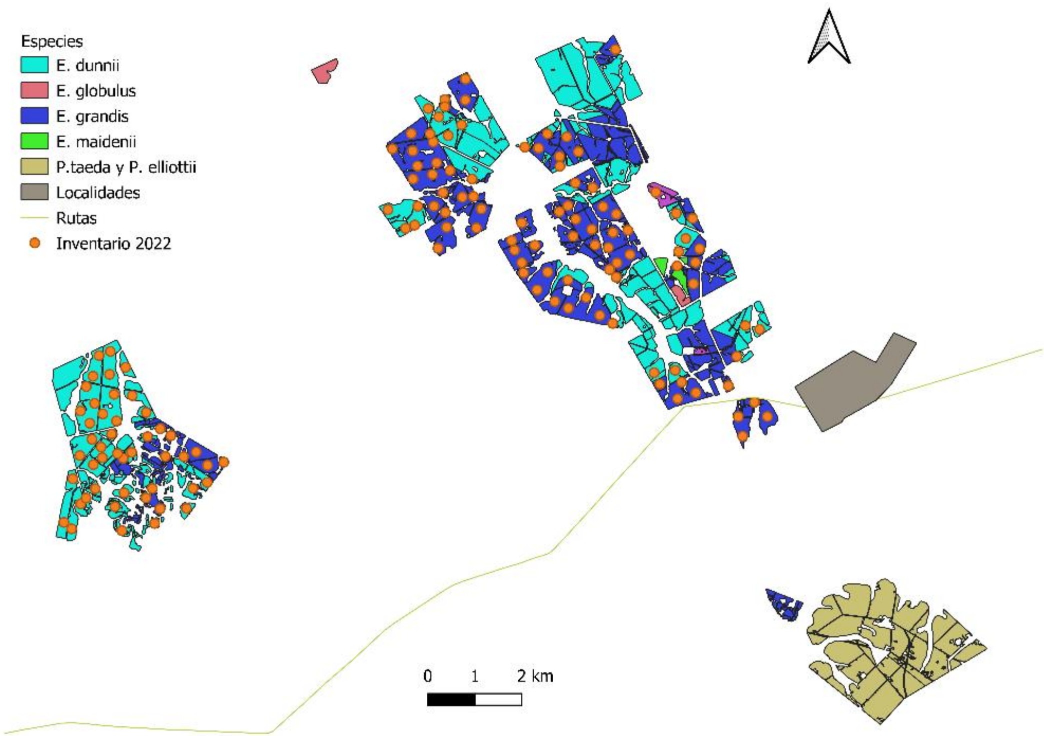

Figure S2. Distribution of inventory plots for sampling and estimating population variables of *E. grandis* and *E. dunnii*

Supplementary Material 2. Equations for Estimating Carbon Stock before Harvest for *Pinus* Spp.

Supplementary Material 2.1 (Active CO_2 removal period)

$$CS_{24} = CC * \frac{TFA}{25} * \sum_{i=0}^{25}(25 - i)$$ [Equation 8]

where:

CS_{24} = Carbon stock on year 24 (Mg)
CC = Carbon capture (Mg/ha/year)
i = year from 0 to 24
TFA = Total forested area (ha)

solving the summation:

$$\sum_{i=0}^{24}(25 - i) = (25 + 24 + 23 + \cdots + 1) = 325$$ [Equation 9]

Thus, the total accumulated carbon stock in year 24 is:

$$CS_{10} = CC * \frac{TFA}{25} * 325$$

$$CS_{10} = CC * TFA * 13$$ [Equation 10]

The accumulated carbon emissions for the livestock area in year 10 can be calculated as the sum of the annual carbon emissions over the 25 – *i* years.

$$CE_{10} = \sum_{i=0}^{24}(LA * LAE)$$

where:

CE_{24} = Total carbon emissions on year 24 (Mg)
LA = Livestock area (ha)
LAE = Livestock annual emissions (Mg/ha)
i = year from 0 to 24

$$CE_{24} = 25 * LA * LAE$$ [Equation 11]

Supplementary Material 2.2 Stationary offset emission period

$$RCS_{24} = LA * LAE * TZB$$

where:

RCS_{24} = Remaining carbon stock (Mg)
LA = Livestock area (he)
LAE = Livestock annual emissions (Mg/ha)
TZB =Time to zero balance (yr)

Therefore, the duration until the stock of C is depleted will be:

$$TZB = \frac{RCS_{24}}{LA * LAE_{24}}$$