UNIVERSIDAD DE CONCEPCIÓN
Dirección De Postgrado
Facultad De Ciencias Forestales
Programa Magister en Ciencias Forestales

CAPTURA DE CARBONO EN PLANTACIONES DE *PINUS RADIATA* EN UN GRADIENTE DE PRODUCTIVIDAD EN DOS SUELOS CONTRASTANTES

Tesis presentada a la Facultad de Ciencias Forestales de la Universidad de Concepción para optar al grado de Magíster en Ciencias Forestales

DANIEL IGNACIO BOZO RAMIREZ

Profesor(a) Guía: Dr. Rafael Rubilar P.
Depto. de Silvicultura,
Facultad de Ciencias Forestales
Universidad de Concepción

Marzo 2024

Concepción, Chile

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Comisión Evaluadora:

Rafael Rubilar Pons (Profesor guía)
Ingeniero Forestal, PhD. ___________________________

Rosa Alzamora Mallea (Profesor co-guía)
Ingeniera Forestal, PhD. ___________________________

Otávio C. Campoe (Comisión evaluación)
Ingeniero Forestal, PhD. ___________________________

Director de Magíster en Ciencias Forestales:
Vicente Hernández Castillo
Ingeniero en Maderas, PhD. ___________________________

Decano Facultad de Ciencias Forestales:
Eugenio Sanfuentes Von Stowasser.
Ingeniero Forestal, PhD. ___________________________

DEDICATORIA

“A mi madre, Mario, hermanos y a Emilia”

AGRADECIMIENTOS

Al profesor Dr. Rafael Rubilar, por su apoyo en mi formación profesional como investigador.

Al Centro Nacional de Excelencia para la industrial de la Madera (CENAMAD) por el apoyo financiero del proyecto ANID BASAL FB210015 para realizar las actividades de campo y análisis de laboratorio, y por la Beca de estipendio otorgada.

A la empresa CMPC, en especial a Matías Pincheira, por apoyar constantemente al desarrollo de trabajo de campo. A la Cooperativa de Productividad Forestal (FPC), a Facultad de Ciencias Forestales de la Universidad de Concepción y al Laboratorio de Investigación de Agua y Suelo (LISAB), por apoyar tanto al trabajo de campo como en el análisis de muestras y de datos.

A los profesores co-guías Dr. Rosa Alzamora y Dr. Otávio Campoe, por los comentarios tanto al proyecto de tesis como en el desarrollo de ésta.

A mi familia que desde siempre me han apoyado en todo sentido, y los amigos que he conocido en Concepción por su ayuda y motivación a desarrollar este proyecto.

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RESUMEN

Pinus radiata es la especie forestal más plantada en Chile, siendo relevante mejorar el conocimiento sobre su acumulación de carbono (C). Se planteó: i) cuantificar los stocks de C en la biomasa aérea y subterránea (TBC), en el piso forestal (FFC), en el suelo mineral (SOC) y a nivel total del rodal (TCS) en rodales adultos de esta especie en suelos de arena y cenizas volcánicas (trumaos); ii) modelar el efecto de la productividad y del tipo de suelo en los stocks de C; y iii) modelar el stock de C respecto a variables ambientales, del suelo y del sitio. Se seleccionaron 10 sitios con plantaciones de *Pinus radiata* en un gradiente de productividad en suelos contrastantes de arenas y trumaos. En cada sitio, se instalaron 3 parcelas de 1000 m^2, cuantificando el TBC mediante ecuaciones alométricas, muestreando el SOC hasta 1 m de profundidad, y tomando muestras de hojarasca y residuos para determinar el FFC. Sitios de trumao presentaron un mayor SOC y TCS que arenas ($p < 0.01$), con TCS medios de 473.2 Mg ha^{-1} y 330.9 Mg ha^{-1} respectivamente. Hubo una fuerte relación entre la productividad con el SOC y TCS ($r^2 = 0.91$, $p < 0.01$) al considerar el tipo de suelo. Las variables relacionadas con mejores condiciones nutricionales e hídricas del suelo tuvieron un efecto positivo en el stock total de C; y hubo un efecto negativo las variables relacionadas a estrés hídrico. Las diferencias en C stock según el tipo de suelo y el clima mostraron la importancia de desarrollar modelos específicos al sitio para estimar adecuadamente las reservas de C.

ABSTRACT

Pinus radiata is the most planted forest species in Chile, so it is relevant to improve knowledge about its carbon (C) accumulation. It was proposed: i) determinate the aboveground and belowground biomass (TBC), the forest floor (FFC) and the mineral soil (SOC) and total (TCS) C stocks, in adult stands of this species in sandy and volcanic ash soils sites; ii) model the effect of stand productivity and soil type on C stock; and iii) model the C stock with respect to environmental, soil and site variables. Ten sites were selected with *Pinus radiata* plantations along a productivity gradient in contrasting sandy and recent ash soils sites. At each site, 3 plots of 1000 m^2 were installed, quantifying the TBC using allometric equations, sampling the SOC up to 1 m deep and sampling litter and woody debris to determine the FFC. The recent ash sites had higher SOC and TCS than the sandy ($p < 0.01$) soil sites, with an average TCS of 473.2 Mg ha^{-1} and 330.0 Mg ha^{-1} respectively. There was a strong relationship between productivity with SOC and TCS ($r^2 = 0.91$, $p < 0.01$) when considering soil type. The variables related to better nutritional and soil water conditions had a positive effect on the total C stock; and there was a negative effect on the variables related to water stress. Differences on C stocks according soil type and climate showed the importance of developing site-specific models to adequately estimate C stocks.

INTRUCIÓN GENERAL

Debido a las actividades antrópicas se ha producido un aumento en las concentraciones de gases de efecto invernadero (GEI), tales como dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O) en la atmósfera. Esto ha significado un aumento para el 2011 de más de un 40% de las concentraciones de CO_2 respecto a la edad preindustrial (IPCC, 2013), generando una serie de problemas ambientales como el aumento de temperaturas y disminución de las precipitaciones (Zhang *et al.*, 2019). Debido a ser el CO_2 el principal GEI, para reducir su concentración en la atmósfera, se pretende disminuir y evitar sus emisiones, además de aumentar el secuestro y absorción terrestre de carbono (C) (Keller *et al.*, 2018). Por ello, a nivel global los bosques son un gran sumidero almacenando C, y así compensando las emisiones de CO_2 (Pan *et al.*, 2011). A pesar de que la mayor parte del secuestro de carbono ocurren en bosques no manejados (Payn *et al.*, 2015), las plantaciones forestales son una potencial estrategia para la mitigación del cambio climático, ya que las prácticas silvícolas intensivas aumentan el crecimiento y la productividad forestal (Albaugh *et al.*, 2015) permitiendo una mayor tasa de absorción de CO_2 y almacenamiento de carbono en los bosques (McKinley *et al.*, 2011).

En los bosques, la mayor proporción del carbono acumulado se encuentra en el suelo mineral (SOC) (Pan *et al.*, 2011; Vogel *et al.*, 2022). Entre las entradas de carbono al suelo mineral, se encuentra la materia orgánica proveniente de la hojarasca caída y de la biomasa radicular (Jobbágy and Jackson, 2000). Entre los factores que determinan el SOC, se encuentra el clima, tipo de hojarasca, disponibilidad de agua y nutrientes y el tipo de suelo (Scherer-Lorenzen *et al.*, 2007; Tessema *et al.*, 2022); siendo este último factor muy relevante en la acumulación de carbono en profundidad. Los suelos con mayor cantidad de arcilla y limo retienen materia orgánica (OM) dentro de sus agregados, ralentizando su descomposición, lo que promueve la acumulación de carbono en el suelo (Bronick and Lal, 2005). Además el contenido de arcillas se asocia a factores como son el crecimiento de plantas, fertilidad, humedad y mayor retención de SOC que suelos arenosos (Van Veen and Kuikman, 1990). Los suelos de arenas, al presentar un mayor tamaño de poros, retienen menos humedad y nutrientes en el suelo, afectando las tasas de descomposición de la materia orgánica, resultando en menor SOC por el menor crecimiento del rodal al ser suelos más restrictivos (Rubilar *et al.*, 2013; Chendev *et al.*, 2014; Olmedo *et al.*, 2020).

El stock de C en la biomasa (tanto aérea y subterránea) es el segundo reservorio más grande de C en los ecosistemas forestales (Pan *et al.*, 2011; Zhang *et al.*, 2019). La acumulación de biomasa en el tiempo es un proceso de equilibrio entre la fotosíntesis y respiración de los bosques, el que se ve afectado por variables climáticas, nutrientes del suelo y características del rodal como la especie, edad y silvicultura (Noormets *et al.*, 2015; Díaz Villa *et al.*, 2022; Giberti *et al.*, 2022; Ni *et al.*, 2022).

El piso forestal es el componente de menor proporción del stock total de carbono de los rodales. Éste comprende el material vegetal muerto sobre el suelo mineral (hojarasca acumulada, material leñoso y frutos) en distintos grados de descomposición (Harmon *et al.*, 1986). Algunos estudios han relacionado el carbono del piso forestal con variables ambientales, encontrando las mejores relaciones con la latitud (por efecto positivo de la temperatura en tasas de descomposición de hojarasca), cobertura de copa (por reducir la temperatura del suelo y disminuir tasas de descomposición) y la precipitación de verano (por mayor humedad y temperatura al aumentar las tasas de descomposición), mientras que en menor medida el déficit hídrico (López-Senespleda *et al.*, 2021; Díaz Villa *et al.*, 2022).

Pinus radiata D. Don es una especie forestal de rápido crecimiento, la cual es ampliamente cultivada en el hemisferio sur, principalmente en Nueva Zelanda, Chile, Australia y Sudáfrica (Mead, 2013; Dash *et al.*, 2019). Las plantaciones de esta especie se encuentran entre las más productivas, y su crecimiento depende principalmente de los clones, silvicultura y medio ambiente (Alvarez *et al.*, 2013; Albaugh *et al.*, 2015; Ojeda *et al.*, 2018; Dash *et al.*, 2019). En Chile, *P. radiata* constituye la especie forestal más importante en cuanto a superficie plantada, en torno a 1,3 millones de ha de los aproximadamente 2,3 millones de ha de plantaciones (Soto *et al.*, 2021). La mayoría de esas plantaciones son manejadas intensivamente, con una productividad de media de 28.3 millones m^3 yr^{-1} (Soto *et al.*, 2021). Según reuniones de los consejos de Ministros de Chile (NDC, 2020) el país se ha comprometido a ser carbono neutral al 2050, por lo que optimizar las superficies plantadas con especies de rápido crecimiento es una forma de lograr este compromiso (Gonzalez-Benecke *et al.*, 2021).

Dada la importancia de los bosques como sumidero de C, se requieren buenas estimaciones en todos los componentes del rodal (tanto biomasa, como piso forestal y suelo mineral). Especialmente en un contexto de cambio climático, para evaluar potenciales efectos de las variaciones en temperatura y precipitaciones.

Por lo anterior, planteamos como hipótesis que:

“Los rodales de *Pinus radiata* a edad de precosecha acumularán mayor carbono en los sitios con de mayor productividad (mayor volumen); y estas relaciones mejorarán al considerar variables ambientales y el tipo de suelo, por el efecto limitante que tienen las arenas respecto a las cenizas volcánicas en el crecimiento de los árboles”

Para evaluar dicha hipótesis, plantamos como objetivos:

Objetivo general:

Modelar el stock de carbono total y por componentes aéreos y subterráneos en plantaciones de *Pinus radiata* en edad de precosecha respecto a un gradiente de productividad en suelos contrastantes de arenas y cenizas volcánicas.

Objetivos específicos:

1. Determinar el carbono acumulado en la biomasa aérea y subterránea, en el piso forestal y en el suelo mineral en plantaciones de *Pinus radiata* en edad de precosecha respecto a un gradiente de productividad en suelos contrastantes de arenas y cenizas volcánicas.

2. Modelar los stocks de carbono por componentes del rodal y total en función dede la productividad del sitio en rodales de *Pinus radiata* en edad de precosecha en suelos contrastantes de arenas y cenizas volcánicas.

3. Modelar los stocks de carbono por componentes del rodal y total en función de variables ambientales, del suelo y del sitio en rodales de *Pinus radiata* en edad de precosecha en suelos contrastantes de arenas y cenizas volcánicas.

Para cumplir con los objetivos planteados, la Tesis se ha estructurado en dos capítulos:

El primero capítulo "Soil and Site Productivity Effects on Above and Belowground Radiata Pine Carbon Pools at Harvesting Age", cuantifica el stock de carbono en los componentes biomasa aérea y subterránea, piso forestal y suelo mineral, realizando una comparación entre los tipos de suelo arenas y cenizas volcánicas recientes. Y, además, se modelan estos stocks de carbono en función del volumen acumulado al momento a edad de precosecha de estos rodales. De esta forma, se cumple con los objetivos específicos 1 y 2. Este capítulo, al momento de la presentación de la Tesis, ha sido enviado y está en proceso de revisión en la revista "*Forest Ecology and Management*" (Q1).

El segundo capítulo “Modeling of climatic, soil, and site effects on the carbon stocks of radiata pine plantation in contrasting environmental condition in Chile”, explora variables ambientales, del suelo y del sitio, para luego modelar (utilizando regresiones lineales múltiples) el stock de carbono en la biomasa total, piso forestal y suelo mineral con las variables más significativas resultantes de análisis multivariados y correlaciones. Cumpliendo, con el objetivo 3 y sumando nuevos modelos al objetivo 2. Este capítulo, al momento de la presentación de la Tesis, está en preparación para ser potencialmente enviado a la revista “*Plants*” (Q1).

1. SOIL AND SITE PRODUCTIVITY EFFECTS ON ABOVE AND BELOWGROUND RADIATA PINE CARBON POOLS AT HARVESTING AGE

Daniel Bozo*[1,2]; Rafael Rubilar[1,2]; Otávio Campoe[3]; Rosa Alzamora[2,4]; Juan Pedro Elissetche[2,3]; Juan Carlos Valverde[1]; Roberto Pizarro[2,5,6,7]; Matías Pincheira[8]; Juan Carlos Valencia[8]; Claudia Sanhueza[2].

[1] Cooperativa de Productividad Forestal, Departamento de Silvicultura, Fac. Ciencias Forestales, Universidad de Concepción, Concepción, Chile.

[2] Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Santiago, Chile.

[3] Forest Productivity Cooperative, Universidade Federal de Lavras, Departamento de Ciências Florestais, Lavras, Minas Gerais, Brazil.

[4] Departamento de Manejo de Bosques y Medio Ambiente, Fac. Ciencias Forestales, Universidad de Concepción, Concepción, Chile.

[5] UNESCO Chair Surface Hydrology, University of Talca, Talca.

[6] Instituto Interdisciplinario Para la Innovación, Universidad de Talca, Talca.

[7] Facultad de Ciencias Forestales y de la Conservación de la Naturaleza, Universidad de Chile, La Pintana, Chile.

[8] Forestal Mininco S.A., Avenida Alemania 751, Los Ángeles, Chile.

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*Corresponding Author. *In Review*: Forest Ecology and Management.

1.1.ABSTRACT

Due to the increase in atmospheric CO_2 concentrations by anthropogenic activities, efforts have been made to reduce its emission and increase its capture, with forests being an important alternative by their role as a carbon sink. *Pinus radiata* is the forest species most planted in Chile, therefore it becomes relevant to improve the understanding of above and belowground carbon pools in adult plantations of this species. The objective of our study was to evaluate the effect of soil type and site productivity on the carbon stock of above and belowground biomass, forest floor and mineral soil in radiata pine plantations at harvesting age, considering contrasting sites in water and nutritional availability. In 10 sites on sandy and recent ash soils selected by a productivity gradient of harvesting age radiata pine plantations, 3 plots of 1000 m^2 were installed in which the carbon stock of above and belowground biomass was quantified using allometric equations, and with in situ carbon assessments of forest floor (litter and coarse debris) and mineral soil (up to 1 meter deep). Results showed that recent ash soil sites presented a slightly higher carbon stock than sandy in the total biomass (178.5 Mg ha^{-1} vs 172.4 Mg ha^{-1} respectively), and significant higher carbon stock in the mineral soil for recent ash sites (281.4 Mg ha^{-1}) than sandy soil sites (139.9 Mg ha^{-1}). In both soil types, forest floor represented the lowest carbon stock of stands, with 2.9 % for recent ash and 5.8 % for sandy soil sites. Total carbon stock of site (carbon on total biomass, forest floor and mineral soil), was significant higher in recent ash soil sites (473.2 Mg ha^{-1}) than sandy soil sites (330.9 Mg ha^{-1}). A strong relationship was found between the stand productivity (considering cumulative stand volume at harvesting age) with the soil organic carbon ($r^2=0.88$, $p < 0.01$) and with total carbon stock of site ($r^2=0.91$, $p < 0.01$) when the soil type is considered. High carbon stocks in mineral soil emphasize the importance of including these assessments until to 1 m depth for C stock estimates, and differences on C pools according soil type show the importance of developing soil type-specific models to adequately estimate C stocks.

Keywords: *Pinus radiata*, Carbon stock, Biomass, Forest floor, Soil organic carbon.

1.2.INTRODUCCIÓN

In the last century, atmospheric carbon dioxide (CO_2) concentrations have increased by 10 to 20% due to anthropogenic activities (Masson-Delmotte *et al.*, 2021). Greenhouse gasses emissions have triggered severe environmental changes such as increased temperatures and intense and prolonged droughts worldwide (Zhang *et al.*, 2019). Strategies to reduce emissions and promote carbon sequestration consider forest plantations as a short-term option for carbon (C) capture (Pan *et al.*, 2011; Keller *et al.*, 2018). This option may also improve ecosystem services such as hydrological cycle regulation, reducing desertification, and providing wood and fiber as an action to mitigate climate change (Tricallotis *et al.*, 2018)

Given the importance of forests on mitigating climate change, a correct understanding and estimation of carbon stocks across ecosystems is required. Carbon accumulation in forest plantations is strongly linked to specie (s), age and management (Zha *et al.*, 2013; Zhang *et al.*, 2019; Diao *et al.*, 2022) but also to abiotic factors (e.g. climate and soil) (Olmedo *et al.*, 2020; López-Senespleda *et al.*, 2021; Díaz Villa *et al.*, 2022; Watt and Kimberley, 2022). Previous studies of Pan *et al.* (2011), Georgiou *et al.* (2022) and Nandal *et al.*

(2023) estimated that global forest resources accumulate between 861 and 899 Pg C, where a 44% is distributed in soils (up to 1m of depth), 42% in living above- and below-ground biomass, 8% in deadwood and 5% in litterfall. Most studies worldwide provide precise and detailed aboveground carbon estimates. However, carbon accumulation in forest residues, forest floor and mineral soil may represent more than 60% of global carbon reserves in forests (Pan *et al.*, 2011), which demonstrates the importance of including these components in the study of carbon estimations. In fact, the highest proportion of carbon is found in mineral soil organic carbon pools (SOC) (Pan *et al.*, 2011; Vogel *et al.*, 2022), in particular in the first 10 cm of the soil, and where the first 40 cm accumulate more than 50% of the total soil carbon (López-Díaz *et al.*, 2017; Zhang *et al.*, 2019). Soil carbon from fallen leaf litter and underground biomass decomposition (Jobbágy and Jackson, 2000) increases over time with the age of the stand (Litton *et al.*, 2007; Zhang *et al.*, 2019) until reaching a maximum defined by soil and site dynamics if no disturbance exists. On this regard soil type is a key factor in the accumulation of carbon in depth (Georgiou *et al.*, 2022). Clay soils retain organic matter within their aggregates, slowing down their decomposition, which promotes long-term carbon accumulation in the soil (Bronick and Lal, 2005). Sandy soils in turn, having larger pores, retain less moisture and nutrients, and have faster rates of organic matter decomposition. These factors reduce tree and stand growth but also potential accumulation of carbon in the soil (Rubilar *et al.*, 2013; Chendev *et al.*, 2014; Olmedo *et al.*, 2020). Soil texture affects soil fertility and soil moisture together, both key factors defining site productivity and carbon sequestration withing a given climate (Van Veen and Kuikman, 1990; Georgiou *et al.*, 2022).

Tree above- and below-ground biomass is the second largest C stock in forest ecosystems (Pan *et al.*, 2011; Zhang *et al.*, 2019). Stem biomass is the largest carbon sink and as trees age carbon accumulation increases (Zhang *et al.*, 2019). Similarly, but less know, belowground biomass become the major source of soil organic matter as it decompose over time (Prescott and Vesterdal, 2021). However, alive root biomass estimates are usually limited and uncertain for most ecosystems, and constant generalized estimates as a fraction of aboveground biomass have been proposed for accounting for this pool (IPCC, 2013).

Another important carbon pool in forest ecosystems is forest floor, a layer of dead and decomposing plant material on top of the mineral soil, which includes accumulated leaf litter, woody material, and fruits in varied degrees of decomposition (Harmon *et al.*, 1986). Although this pool usually represents a lower proportion of all aboveground carbon in forests, it is estimated that it may represent around 5 % of all aboveground biomass (Pan *et al.*, 2011), and play a key role in the contribution of organic matter and nutrients to the mineral soil from aerial biomass (López-Senespleda *et al.*, 2021; Prescott and Vesterdal, 2021).

Pinus radiata D. Don (radiata pine) is one of the most important pine fast growing cultivated in the southern hemisphere, mainly in New Zealand, Chile, Australia, and South Africa (Mead, 2013; Dash *et al.*, 2019). Plantations are among the most productive species, and its high productivity depends on advanced genotypes, silviculture, and environmental conditions (Alvarez *et al.*, 2013; Albaugh *et al.*, 2015; Ojeda *et al.*, 2018; Dash *et al.*, 2019; Rubilar *et al.*, 2023). In Chile, *P. radiata* represents the most important forest species with more than 1.3 million ha of the approximately 2.3 million ha of total commercial planted forests (Soto *et al.*, 2021). According to the Council of Ministers of Chile (NDC, 2020), the country has committed to being carbon neutral by 2050, so optimizing land planted with fast-growing species is one the most effective and efficient ways to achieve this commitment (Gonzalez-Benecke *et al.*, 2021).

Olmedo *et al.* (2020) evaluated radiata pine plantations C accumulation in Chile and showed that plantations with the highest C stock were found at sedimentary and volcanic ash soils with high water resource availability. Contrastingly, water-restricted sites of lacustrine and sandy soils showed the lowest C stocks. Carbon stock estimates of radiata pine plantations require soil and productivity information for the development of models that may be able to accurately estimate above and belowground biomass carbon and mineral soil and forest floor pools. Our objective was to develop and evaluate specific versus generalized soil site-productivity-based C stock estimation models estimating biomass, mineral soil, and forest floor C pools of intensively managed radiata pine plantations at harvesting age at contrasting soil sites.

1.3.MATERIALS AND MEHODS

1.3.1. Study area

Sites were selected representing a productivity gradient of *Pinus radiata* plantations (15.2 to 28.1 m^3 ha^{-1} yr^{-1}) under intensive management at harvesting age (20-23 years-old), covering a part of the productive area of radiata pine plantations in Chile (Table 1). The sites were located in the Central Valley and the Foothills of the Andes in central and south-central Chile and spread from the Ñuble (36°59′S) to the Biobio region (37°50′S), and west to east from 72°35′W to 71°43′W . Altitudes ranged from 106 to 849 m above sea level and soils considered five stands located in coarse volcanic sands and five stands were in recent volcanic ash soil sites (CIREN, 1999; Stolpe, 2006) (Figure 1). Selected stands at each soil-site condition were planted between 1999 to 2001 with initial planting density ranging from 1000 to 1250 trees ha^{-1}. All sites were established with soil preparation considering a router at 60 cm deep plus disking. Recent volcanic ash soils received traditional operational fertilization considering 100 to 150 g per plant of NPK mix (10 to 15 g N + 10.9 to 13.2 g P + 8.3 to 12.5 g K) plus 2 to 3 g per plant of boron applied after planting. For sandy soil sites only, boron was applied. Operational weed control of stands considered pre-planting total area and 2 years banded weed control after planting in most conditions. All selected stands were pruned at least to 5.5 m height and thinned with 1 or 2 commercial thinning according to the silvicultural program applied to the stand of each site. Final stands stockings at harvesting reached 400 to 500 trees ha^{-1}.

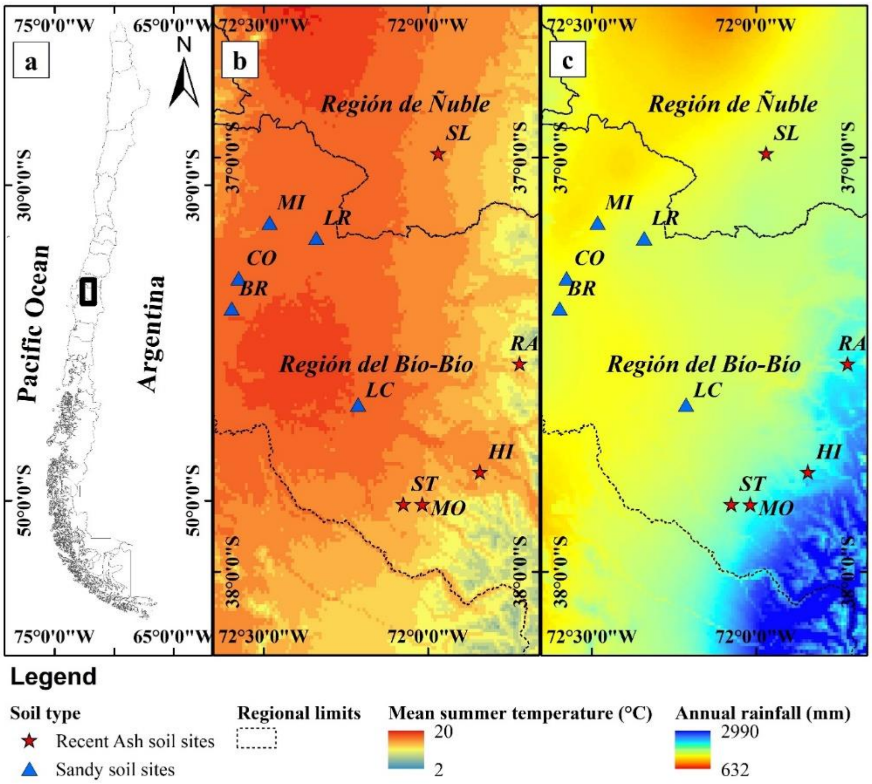

Figure 1. (a) Study area in Central South Chile, (b) Study area and site locations mean summer (January to March) temperature (°C), (c) Study area and site locations mean annual rainfall (mm yr^{-1}) (site code name is presented in Table 1).

Table 1. Site characteristics of selected locations that consider range of productivity for contrasting sandy and recent ash soils.

Site code	Soil type	Soil order[a]	Soil taxonomy[a,b]	Soil serie[b]	Drainage[b]	MAT (°C)	MAP (mm)	Age (years)	MAI (m^3 ha^{-1} yr^{-1})
Hijuelas (HI)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	11.	1585	21	18.5
Montpellier (MO)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	11.4	1521	20	25.6
Ramadillas (RA)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	9.8	1492	22	25.0
Santa Lidia (SL)	Recent Ash	Andisol	Medial, Thermic Humic Haploxerands	Mayulermo	Well drained	12.5	1207	21	20.6
Santa Teresa (ST)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	11.7	1460	23	28.1
Brasil (BR)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Arenales	Excessively drained	13.6	1131	21	20.5
Coyanco (CO)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Arenales	Excessively drained	13.7	1105	23	27.2
Los Cuartos (LC)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Coreo	Well drained to excessively drained	13.4	1182	23	22.5
La Reforma (LR)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Coreo	Well drained to excessively drained	13.6	1103	22	15.2
Misque (MI)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Arenales	Well drained	13.7	1055	22	21.4

[a] Soil Survey Staff, (2022).

[b] (CIREN, 1999; Stolpe, 2006).

MAT = mean annual temperature; MAP = Mean annual precipitation.

1.3.2. Data collection and sampling

Inventory measurements and samplings were carried out between March and May 2022. At each site, three 1000 m^2 inventory plots were established to measure diameter at breast height (DBH, cm at 1.3 m height) and total height (H, m) for all trees, and forest floor and mineral soil was sampled within each inventory plot. (Figure 2). A total of 30 plots were measured considering all site locations.

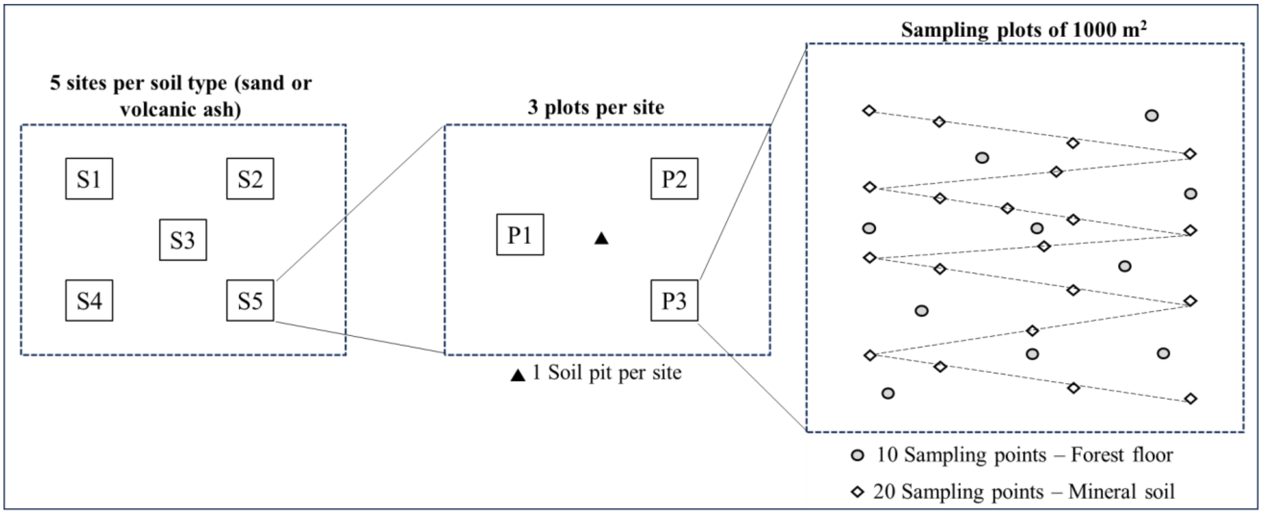

Figure 2. (a) Layout representing the number of sampled sites per soil type (S1-S5), plots at each site (P1-P3) and sampling scheme within each plot.

1.3.2.1. *Volume and Carbon stocks of Above and Belowground Biomass estimations*

Published and local allometric equations, developed for radiata pine plantations (Zerihun and Montagu, 2004; Sandoval *et al.*, 2021), were used to estimate individual tree aboveground (AGB) and belowground (BGB) biomass carbon stock. Individual tree inventory measurements from each plot considering number of trees, DBH and HT were used to estimate tree over bark volume, adding tree volume estimates at a plot level and scale estimates to an hectare level. Calculations considered an individual tree local volume equation (V) developed by CMPC Forestal Mininco Forest Company MININCO (1995):

$$V = -0.00214 + 0.0000295 * D^2 + 0.001349 * H + 0.00002486 * D^2 * H \qquad (1)$$

where V=individual tree over bark volume (m^3 tree^{-1}), D=DBH (cm), H=height (m).

Aboveground biomass of each component (stem, bark, branch and needle) of trees was calculated using the following published (Sandoval *et al.*, 2021) allometric equations (eq. 2, eq. 3, eq. 4 and eq. 5) developed for radiata pine:

$$AGB_{stem} = 0.02389 * (D^2 * H)^{0.93216} \qquad (2)$$

$$AGB_{bark} = 0.00127 * (D^2 * H)^{0.99646} \qquad (3)$$

$$AGB_{branch} = 0.00431 * (D^2 * H)^{0.92709} \qquad (4)$$

$$AGB_{needles} = 0.19428 * (D^2 * H)^{0.48666} \qquad (5)$$

Where AGB_{stem}, AGB_{bark}, AGB_{branch} and $AGB_{needles}$ are the aboveground biomass for stem, bark, branch and needles (kg $tree^{-1}$) respectively, D=DBH (cm), H=height (m). Subsequently, the total aboveground biomass (AGB_{total}, kg $tree^{-1}$) was calculated as the sum of the biomass of each individual tree component (eq. 6) as:

$$AGB_{total} = AGB_{stem} + AGB_{bark} + AGB_{branch} + AGB_{needles} \tag{6}$$

Belowground biomass (BGB) was calculated using (Zerihun and Montagu, 2004) allometric equation (eq. 7) developed to estimate weight of total root biomass for radiata pine as:

$$l\,n(BGB) = 0.902 * ln\ (AGB_{total}) - 0.7368 \tag{7}$$

Where BGB=individual tree root biomass (kg $tree^{-1}$).

Carbon stock of each individual tree biomass component was estimated multiplying AGB_{total} and BGB by a carbon factor (CF), corresponding to the fraction of carbon of each biomass component. We used a CF of 0.48 according to what is recommended for IPCC (2013).

Finally, individual plot stocking (NHA, trees ha^{-1}), stand volume (VHA, m^3 ha^{-1}), basal area (BA, m^3 ha^{-1}), aboveground biomass carbon stock (AGBC, Mg ha^{-1}) and belowground biomass carbon stock (BGBC, Mg ha^{-1}) were estimated by adding and scaling to an hectare level numbers of trees per plot, and individual tree volume, basal area, CAGB and CBGB.

1.3.2.2. Soil organic carbon sampling and calculations

Soil organic carbon (SOC) estimates were obtained considering a composite sample for 20 distributed systematically within each plot (Figure 2). Composite mineral soil samples were obtained with a soil auger at 3 depths: 0- 20 cm, 20-40 cm and 40-100 cm. A total of 90 composite mineral soil samples were obtained for all evaluated sites in our study. Soil samples were air-dried at 30 °C, passed through a 2 mm sieve to remove all root and plant debris, and a 10 g. subsample aliquot was taken and dried at 65 °C for 24 hours and ground. A final 5 g. aliquot was obtained for the determination of organic carbon using an IRMS (Infrared Mass Spectroradiometer, SERCON Scientific Inc.).

At each site, 1 m depth soil pit was dug to describe visual soil profile characteristics and bulk density (BD) samples were obtained using a metal cylinder of 100 cm^3 volume at 0-20, 20-40 and 40-100 cm depths. Each soil sample was stored and taken to the laboratory to be dried at 105°C until constant weight. A total of 30 soil bulk density samples were obtained for all sampled sites. Additionally, for each sampled depth, a bulk 0.5 kg soil sample was taken for subsequent Boyoucos soil texture analyses, soil organic matter (O.M.) content determination (Sadzawka *et al.*, 2006), and to estimate permanent wilting point and field capacity moisture retention curve points using a pressure plate apparatus (Soil Moisture Inc., USA). Soil water holding capacity (SWHC) for each soil sample was estimated as the difference between permanent wilting point (PWP) and field capacity point (FC). All soil laboratory analyses were carried out in the Soil, Water and Forest Research Laboratory (LISAB) at the Faculty of Forest Sciences of the University of Concepción, Chile.

Soil Organic Carbon Stock (SOC_D) at each depth (d_1=0-20, d_2=20-40 and d_3=40-100 cm depth) was calculated using (eq .8):

$$SOC_{\mathrm{d}} = C_d * D_d * BD_d * 0.1 \tag{8}$$

Where: SOC_d= Soil Organic Carbon Stock of depth d (Mg ha^{-1}), C_d= Soil Organic Carbon concentration by depth d (g kg^{-1}), D_d=soil thickness of depth d (cm), BD_d= bulk density of depth d (gr cm^{-3}).

Total Soil Organic Carbon Stock (SOC) until 1 m of depth of each plot, was calculated summing the SOC_d estimates at each depth.

Table 2. Mean physical and chemical soil properties values evaluated at 0-20, 20-40 and 40-100 cm depths from soil pits representing each selected site.

Soil type	Site code	Depth (cm)	B.D. (gr cm3)	C total	O.M.	SWHC	Clay	Silt	Sand
				%					
Recent Ash	HI	0 - 20	0.56	6.21	14.55	25.52	5.34	42.45	52.21
		20 - 40	0.61	4.02	12.43	22.75	2.76	32.51	64.73
		40 - 100	0.69	3.04	9.17	17.23	2.89	34.96	62.15
	MO	0 - 20	0.53	7.86	16.17	28.05	10.30	35.88	53.82
		20 - 40	0.59	5.36	13.14	17.38	2.67	29.82	67.51
		40 - 100	0.63	3.97	11.25	14.69	2.05	24.35	73.60
	RA	0 - 20	0.68	7.38	10.08	26.77	17.83	29.35	52.82
		20 - 40	0.71	5.56	10.00	22.20	20.15	26.85	53.00
		40 - 100	0.67	3.31	11.54	16.70	19.49	23.96	56.55
	SL	0 - 20	0.53	7.05	15.82	37.94	2.67	59.84	37.49
		20 - 40	0.64	4.76	10.91	36.03	7.13	65.34	27.53
		40 - 100	0.66	3.01	10.20	37.86	4.65	56.93	38.42
	ST	0 - 20	0.67	6.61	14.32	28.51	7.84	47.59	44.57
		20 - 40	0.65	4.72	12.11	18.24	4.18	33.71	62.11
		40 - 100	0.66	3.75	10.42	34.10	2.76	37.41	59.83
Sandy	BR	0 - 20	1.07	2.80	2.67	17.21	4.19	73.40	22.41
		20 - 40	1.09	1.74	2.21	19.84	4.05	52.92	43.02
		40 - 100	1.16	1.31	3.00	16.89	5.71	11.56	82.73
	CO	0 - 20	1.18	1.68	2.50	5.99	2.75	29.51	67.74
		20 - 40	1.19	1.55	2.93	6.92	2.66	19.51	77.82
		40 - 100	1.13	1.42	2.91	5.99	2.57	22.22	75.21
	LR	0 - 20	1.32	0.89	1.34	2.87	2.74	7.15	90.10
		20 - 40	1.54	0.62	1.69	3.53	2.59	4.78	92.63
		40 - 100	1.52	0.27	1.93	1.17	2.70	2.14	95.16
	LC	0 - 20	1.06	1.16	2.87	3.45	2.66	17.45	79.89
		20 - 40	1.19	1.03	2.62	5.69	5.22	1.92	92.85
		40 - 100	1.36	1.06	1.81	4.34	2.61	2.07	95.32
	MI	0 - 20	1.03	2.04	2.14	4.85	2.47	7.20	90.33
		20 - 40	1.35	1.20	2.08	6.74	0.26	9.46	90.28
		40 - 100	1.52	0.67	1.11	4.42	2.67	2.37	94.96

Site codes are = HI: Hijuelas, MO: Montpellier, RA: Ramadillas, SL: Santa Lidia, ST: Santa Teresa, BR: Brasil, CO: Coyanco, LC: Los Cuartos, LR: La Reforma, MI: Misque; B.D. = Soil Bulk density; C total = Total carbon; SWHC = Soil water holding capacity; O.M. = Organic matter.

1.3.2.3. Forest floor carbon sampling and estimates

Forest floor carbon stock samples from organic horizons (Oi+Oe+Oa layers) were collected using a circular 25 cm in diameter cutting frame (490.9 cm^2) at 10 systematically selected points within each plot (Figure 2). At each point, litter (pine needles in all stages of decomposition) and coarse woody debris were collected separately, for a total of 600 forest floor samples from all evaluated plots. Each forest floor sample was stored in paper bags, labeled, and taken to the laboratory for drying at 65°C until constant weight. Forest floor and woody debris dry weight was recorded for each sample using a 0.01 g precision balance. After weighing the 10 organic horizons samples and the 10 woody debris residue samples were composited and homogenized separately for each plot. Each pair of composite samples per plot was independently ground using a 250 µm sieve blade mill to obtain two independent 5 g subsample aliquots that were used for final carbon analysis. Analysis of all forest floor samples were carried out on a free ash basis in order to remove mineral soil potential contamination.

The carbon stock of the organic horizons and coarse woody debris was obtained by multiplying the biomass dry weight of each component at each sample point by the average plot carbon concentration of each component (%), expanded to an hectare level (Mg ha^{-1}) and averaged for each plot. Total forest floor carbon stock (FFC) was finally estimates summing the carbon stock of the organic horizons and the coarse woody debris estimated from each plot.

1.3.2.4. Total Carbon stock calculation

Total carbon stock (TCS) for each plot was estimated as the sum of all evaluated components (AGBC, BGBC, SOC and FFC).

1.3.3. Data analysis

Data was evaluated for normality using a Shapiro–Wilk test (PROC UNIVARIATE) and a Levene's test for heteroscedasticity. Non-normal distributed data was transformed using a BoxCox transformation (PROC TRANSREG). Analysis of variance (ANOVA) for each above and belowground component, total carbon stock and for all stand inventory estimates were applied to evaluate differences among sites (PROC REG). A simple t-test was used to compare volcanic sand and recent ash soil types (PROC TTEST). Linear and nonlinear regression analyses were used to evaluate the relationship between stand cumulative volume and SOC, forest floor, above and belowground biomass, and site total carbon stocks. Models were compared using the coefficient of determination (r^2), the Akaike Information Criteria (AIC), and RMSE values. Linear models were adjusted with and without dummy variables considering soil types, and by using a log normal transformation of stand productivity estimates. Statistical analysis and regression models were fitted in SAS (SAS version 9.4, SAS Institute, Inc., Cary, NC). All tests were considered significant at a level of $\alpha=0.05$.

1.4.RESULTS

1.4.1. Stand growth metrics and Carbon Stocks of Above and Belowground Biomass

Recent ash soil sites presented higher DBH and HT than sandy sites ($p < 0.05$). Average individual tree DBH was 36.7 for recent ash vs 34.1 cm in diameter for sandy soil sites. Similarly, recent ash sites showed a higher HT of 33.6 vs 30.5 m for sandy sites (Table 3). Stocking (NHA) was the only variable for which sandy sites showed larger values than recent ash sites (492 vs 399 trees ha^{-1}). No differences in BA, VHA and MAI were observed in average between sandy and recent ash sites ($p > 0.05$) (Table 3).

Table 3. Mean of stand growth metrics by site. Lowercase letters indicate significant differences among site means (Tukey´s HSD test) considering an ANOVA analysis ($p < 0.05$). Capital letters indicate a significant difference ($p < 0.05$) between the means of recent ash and sandy soil sites (two-sample t-test analysis).

Soil type	Site Code	NHA (trees ha^{-1})	DBH (cm)	HT (m)	BA (m^2 ha^{-1})	VOL (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})
Recent Ash	HI	353.3 ns	35.5 abc	31.3 bc	36.3 bc	387.6 bc	18.5 bc
	MO	420.0 ns	34.8 abc	37.1 a	41.1 abc	512.6 ab	25.6 ab
	RA	370.0 ns	41.1 a	30.5 c	44.4 abc	549.1 ab	25.0 ab
	SL	416.7 ns	33.8 bc	32.0 abc	39.2 abc	432.2 bc	20.6 abc
	ST	433.3 ns	38.2 a	37.0 a	51.9 a	646.3 a	28.1 a
Sandy	BR	493.3 ns	34.3 bc	27.4 c	46.1 abc	431.4 bc	20.5 abc
	CO	466.7 ns	36.9 ab	36.3 ab	51.3 a	625.4 a	27.2 a
	LC	520.0 ns	34.4 c	30.0 c	49.6 ab	517.5 ab	22.5 abc
	LR	503.3 ns	29.2 c	28.3 c	34.4 c	333.8 c	15.2 c
	MI	476.7 ns	35.6 c	30.2 c	45.5 abc	470.8 abc	21.4 abc
Recent Ash Soils (Mean)		398.7 B	36.7 A	33.6 A	42.6 ns	505.5 ns	23.5 ns
Sandy Soils (Mean)		492.0 A	34.1 B	30.5 B	45.4 ns	475.8 ns	21.4 ns

Site codes are = HI: Hijuelas, MO: Montpellier, RA: Ramadillas, SL: Santa Lidia, ST: Santa Teresa, BR: Brasil, CO: Coyanco, LC: Los Cuartos, LR: La Reforma, MI: Misque; NHA = stocking, DBH = diameter at breast height; HT = total height; BA = basal area; VOL = over bark stand volume; MAI = mean annual increment. ns = not significant.

No significant differences were observed in average total biomass carbon stock ($p = 0.66$), or either for above ($p = 0.62$) or belowground ($p = 0.87$) estimates between sandy and recent ash sites. However, a slightly higher total biomass carbon stock was observed in recent ash sites (178.5 Mg ha^{-1}) compared to sandy sites (172.4 Mg ha^{-1}) (Figure 3 and Table 4). A direct relationship between site productivity and carbon stock in total biomass was observed, which suggested a positive effect of site productivity on carbon stock accumulation ($p < 0.05$) (Figure 3).

A wide range of carbon stock in the total cumulative biomass at harvesting age was observed among sites where LR, a sandy soil site, showed the lowest volume (333.8 m^3 ha^{-1}) that also showed the lowest carbon stock in total biomass (124.3 Mg ha^{-1}). On the other hand, ST, a recent ash soil site, showed the highest stand volume (646.3 m^3 ha^{-1}) and carbon stock in total biomass (226.7 Mg ha^{-1}) (Figure 3 and Table 4).

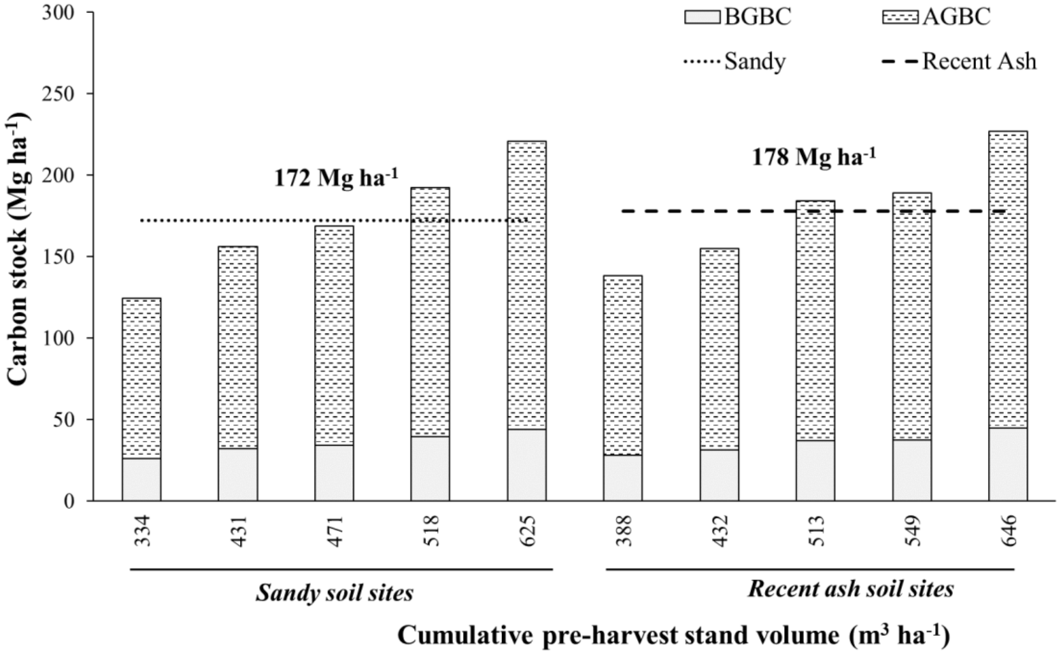

Figure 3. Aboveground biomass carbon stock (AGBC) and belowground biomass carbon stock (BGBC) at each site by soil type and by cumulative over bark stand volume at harvesting age.

Table 4. Average aboveground, belowground, total biomass, soil, forest floor and total site carbon stock for all sites. Lowercase letters indicate significant differences among site means (Tukey´s HSD test) considering an ANOVA analysis within each soil type. And different capital letters indicate significant difference among soil type mean considering a two-sample t-test analysis.

Soil type	Site code	AGBC (Mg ha^{-1})	BGBC (Mg ha^{-1})	TBC (Mg ha^{-1})	SOC (Mg ha^{-1})	FFC (Mg ha^{-1})	TCS (Mg ha^{-1})
Recent Ash	HI	110.2 bc	27.9 cd	138.1 bc	244.6 ab	10.7 b	393.4 bc
	MO	147.1 abc	36.9 abcd	183.9 abc	296.8 a	13.7 ab	494.5 ab
	RA	151.6 ab	37.3 abcd	188.9 ab	312.3 a	11.8 b	512.9 ab
	SL	123.4 bc	31.3 cd	154.7 bc	255.0 ab	16.9 ab	426.6 abc
	ST	182.2 a	44.5 a	226.7 a	298.3 a	13.7 ab	538.7 a
Sandy	BR	123.9 bc	32.1 bcd	156.0 bc	188.9 bc	8.9 b	353.8 c
	CO	176.9 a	43.9 ab	220.8 a	172.7 bc	22.7 ab	416.2 abc
	LC	153.2 ab	39.3 abc	192.5 ab	135.2 cd	27.7 a	355.3 c
	LR	98.2 c	26.1 d	124.3 c	67.7 d	17.3 ab	209.4 d
	MI	134.3 abc	34.2 abcd	168.5 abc	135.1 cd	16.5 ab	320.2 cd
Recent Ash Soils (Mean)		142.9 ns	35.6 ns	178.5 ns	281.4 A	13.4 B	473.2 A
Sandy Soils (Mean)		137.3 ns	35.2 ns	172.4 ns	139.9 B	18.6 A	330.9 B

Site codes are = HI: Hijuelas, MO: Montpellier, RA: Ramadillas, SL: Santa Lidia, ST: Santa Teresa, BR: Brasil, CO: Coyanco, LC: Los Cuartos, LR: La Reforma, MI: Misque; AGBC = carbon stock in the aboveground biomass; BGBC = carbon stock in the belowground biomass; TBC = carbon stock in the total (aboveground + belowground) biomass; SOC = carbon stock in the organic soil; FFC = carbon stock in the forest floor; and TCS = total carbon stock of the stands. ns = not significant.

1.4.2. *Soil Carbon Stock results*

Recent ash soils presented a higher SOC than sandy soils ($p < 0.05$) (Figure 4a and Table 4) and showed 29.5 % of the SOC accumulated at 0-20 cm depth, 22.2 % at 20-40 cm depth, and the remaining 48.2 % accumulated between 60-100 cm depth (Figure 4b). Similarly, sandy sites accumulated 27.7 and 22.4% at 0-20 and 20-40 cm depth, respectively; and its remaining 49.9 % at 40-100 cm depth (Figure 4b).

The LR site (the least productive sandy soil), according to what was observed for carbon stock in total biomass, was the site with the lowest SOC up to 1 m depth (67.7 Mg ha^{-1}) and showed significant differences with most other sites of higher productivity ($p < 0.05$) (Table 4 and Figure 4). The RA site (the most productive recent ash soil) was the site with the highest SOC (312.3 Mg ha^{-1}) but showed the second highest volume (549.1 m^{3} ha^{-1}) and was significantly higher than most other sites ($p < 0.05$) (Table 4 and Figure 4).

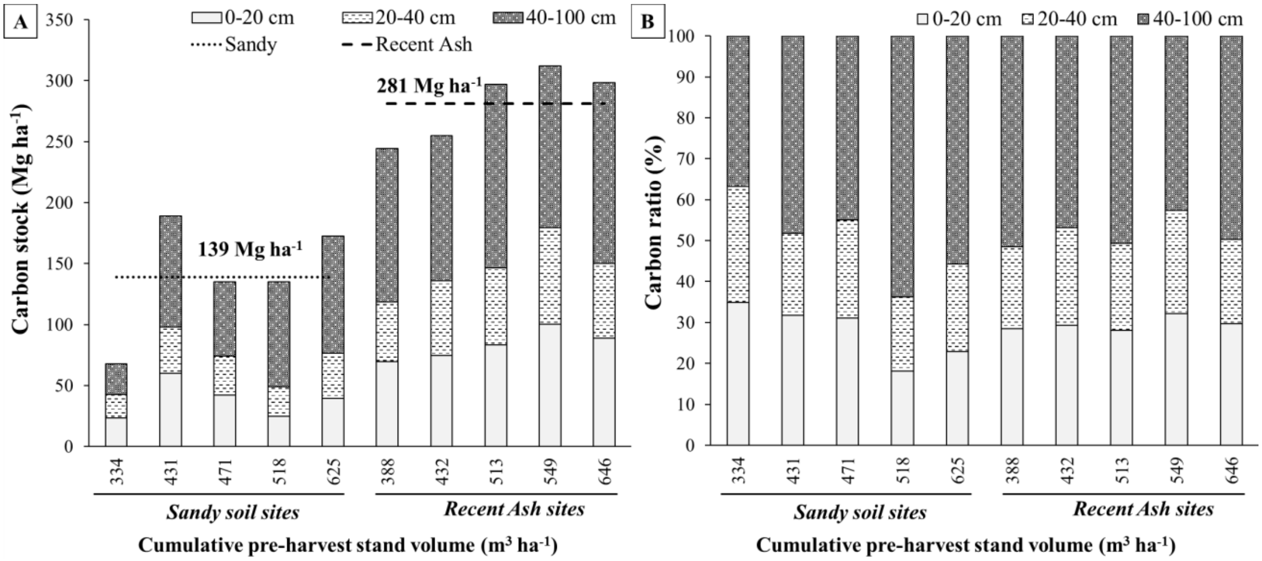

Figure 4. (a) Soil carbon stock up to 1 m depth, and (b) proportion of carbon for each soil depth (b), at each site by soil type and by cumulative over bark stand volume at harvesting age.

A positive relationship was observed a between site productivity and SOC, suggesting that increase on SOC could be explained from site stand over bark volume at harvesting age for each soil type (Figure 4a and 5, Table 4). Regression analysis of productivity again SOC for all selected soil sites showed a significant but weal relationship between both variables ($p < 0.05$, $r^2=0.16$) (Table 5). When considering soil type as a *dummy* variable in the regression model, the coefficient of determination of the model increased up to $r^2=0.88$ ($p < 0.001$). The adjusted model had the form: SOC= 3.61+0.26*(VOL)+148.45*(0=Sand or 1=Ash) (Table 5, Figure 5a and 5b). This model suggests that although regression lines for the sand and ash soil types have the same slope, they differ in the intercept as an effect of soil type on SOC (an increase of 148.9 Mg ha^{-1} was observed for recent ash soils regarding sandy soils).

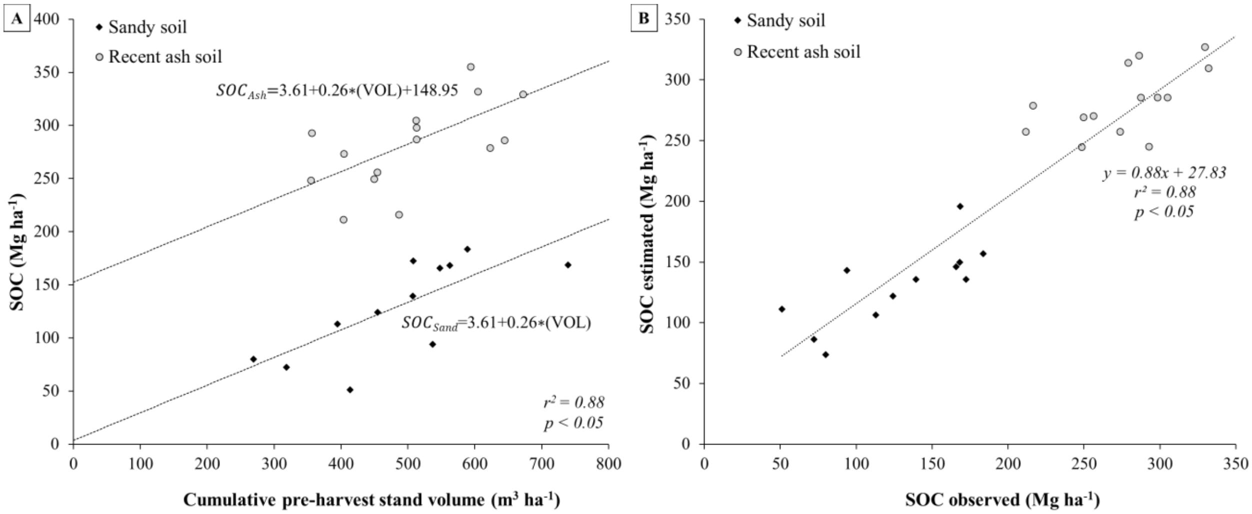

Figure 5. (a) Relationship between site productivity (cumulative over bark stand volume at harvesting age, VOL) and Soil Organic Carbon (SOC) using soil type as dummy variable; and (b) relationship between observed SOC and estimated SOC estimated using the dummy variable regression adjusted model.

Table 5. Adjusted models between cumulative over bark stand volume at harvesting age (VOL) and Soil Organic Carbon until 1 m depth (SOC). Model 1 represent the generalized model considering all evaluated sites, Model 2 represent the dummy variable regression model.

Model	r^2	*RMSE*	*AIC*	*Parameter*	*Estimate*	*S.E.*	*t*	*p*
SOC = a + b * VOL	0.16	82.8	319.05	a	58.39	73.45	0.80	0.43
				b	0.31	0.14	2.16	0.041
SOC = a + b * VOL + c * Soil (0=Sand or 1=Ash)	0.88	32.04	268.66	a	3.61	28.78	0.13	0.901
				b	0.26	0.06	4.55	< 0.001
				c	148.95	12.45	11.96	< 0.001

r^2: coefficient of determination; *RMSE*: root mean square error; *AIC*: Akaike information criterion values; *a*, *b* and *c* regression coefficients; *S.E.*: standard error; *t*: t-Statistics; *p*: p-values of regression coefficients.

1.4.3. *Forest Floor Carbon results*

Sandy soil sites presented higher forest floor carbon stock than recent ash soils ($p < 0.05$) (Figure 6a and Table 4). In average, sandy soil sites had 82.8 % of the forest floor carbon accumulated in organic horizons and only 17.2 % in coarse woody debris (Figure 6b). In comparison, recent ash soil sites had 75.6 % of the forest floor carbon stock accumulated in organic horizons and 24.4 % in coarse woody debris (Figure 6b). For forest floor carbon pool, no significant relationship was found between site productivity and carbon accumulation in this pool ($p = 0.25$), and no effect of soil type was observed for adjusted models (Table 4).

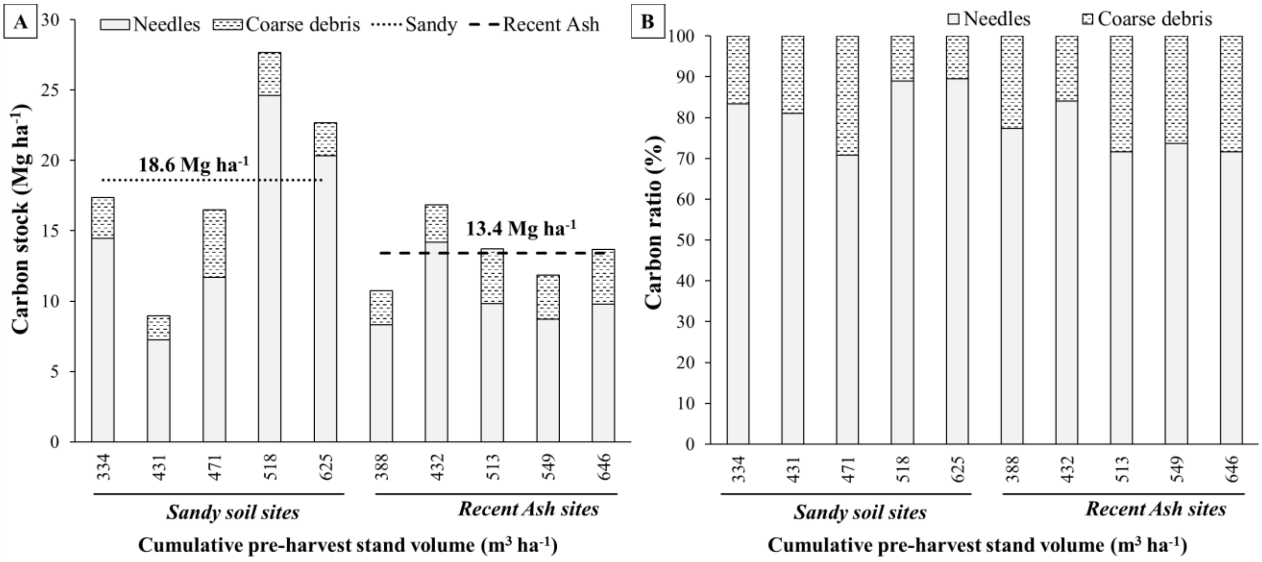

Figure 6. (a) Forest floor carbon stock in organic horizons and coarse woody debris, and (b) proportion of carbon stock in forest floor and coarse woody debris at each site by soil type and by cumulative over bark stand volume at harvesting age.

1.4.4. *Total Carbon Stock results*

Recent ash soils presented a higher total carbon stock (TCS) than sandy soils ($p < 0.05$), with averages of 473.2 and 330.9 Mg ha^{-1}, respectively (Figure 7a and Table 4). Recent ash soil sites had 59.6 % of the TCS in the SOC stock that accounted for 1 m depth (281.4 Mg ha^{-1}), followed by the carbon stock accumulated in total biomass with 37.5 % (178.5 Mg ha^{-1}). The lowest carbon stock for these soils was found in the forest floor pool that accounted for 2.9 % (13.4 Mg ha^{-1}). Conversely, for the sandy soil sites the highest proportion of TCS was found in total biomass with 52.7 % (172.4 Mg ha^{-1}) of the TCS, followed by the SOC with 41.5 % (139.9 Mg ha^{-1}). Again, the lowest carbon stock was found in the forest floor with 5.8 % (18.6 Mg ha^{-1}) but this pool was higher in sandy compared to recent volcanic ash soils (Figure 7b and Table 4).

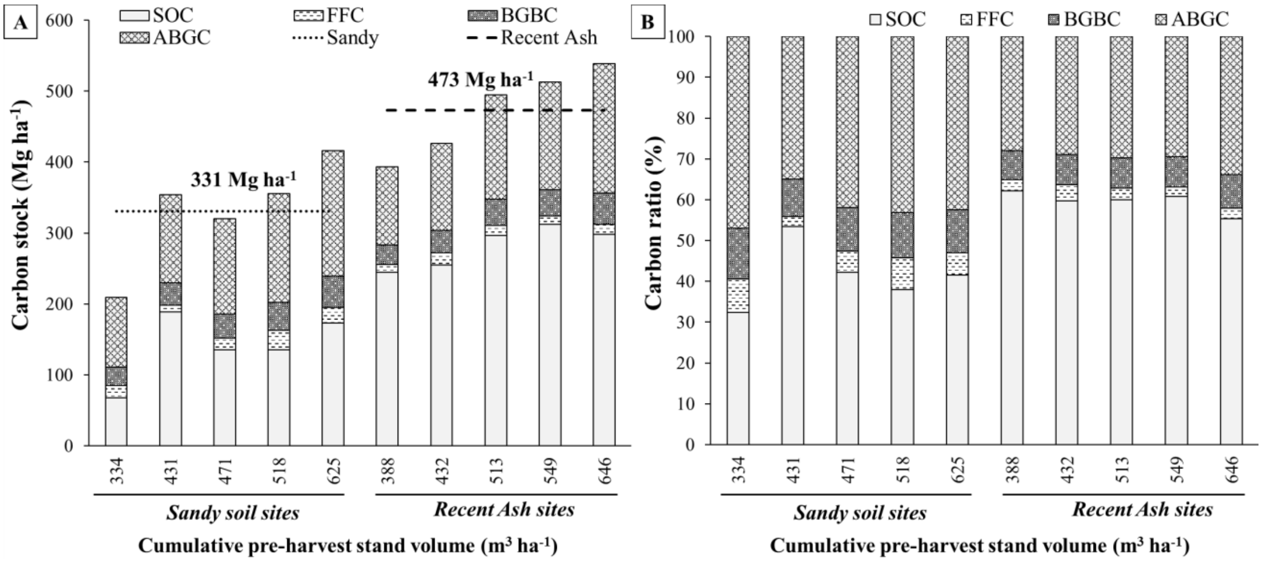

Figure 7. (a) Total carbon stock for soil organic carbon (SOC), forest floor (FFC), belowground biomass (BGBC) and aboveground biomass (ABGC), and (b) proportion of total site carbon stock at each site by soil type and by cumulative over bark stand volume at harvesting age.

For sandy soils, the LR site, the site with the lowest productivity, showed the lowest total carbon stock (209.4 Mg ha^{-1}) and showed significant differences with all other sandy sites except with the MI site (Figure 7 and Table 4). For the recent ash soils, the ST site with the highest productivity, showed the highest total carbon stock (538.7 Mg ha^{-1}), showing a significant difference with the lowest productivity ash site HI (393.4 Mg ha^{-1}) (Table 4 and Figure 4).

Similar to what was observed for the SOC pool, a positive relationship was observed between stand productivity (cumulative over bark stand volume at harvesting age) and total site carbon stock (TCS), which suggest that TCS increases as stand volume increase across for each soil type (Figure 7a and 8, Table 4). In fact, regression analysis between stand volume and TCS showed a significant relationship (r^2=0.49, $p < 0.05$) (Table 5). When regression analyses considered soil type as a dummy variable into the model, the coefficient of determination of the model increased up to r^2=0.91 ($p < 0.001$) (Figure 8a and 8b). The regression model considering soil type as a dummy variable had the form: TCS= 30.39+0.61* (VOL)+136.66*(0=Sand or 1=Ash) ($p < 0.05$) (Table 6). The dummy variable model showed the same slope (0.61) but differ in intercept parameter that was affected by the soil type dummy variable (with an increase of 136.66 Mg ha^{-1} for the ash soil type). Therefore, for the same level of site productivity, the recent ash sites presented a higher total carbon stock due to soil type but with a positive offset that was similar to the mean value difference observed between the sandy (330.9 Mg ha^{-1}) and recent ash (473.2 Mg ha^{-1}) for all locations within each soil type (Figure 7).

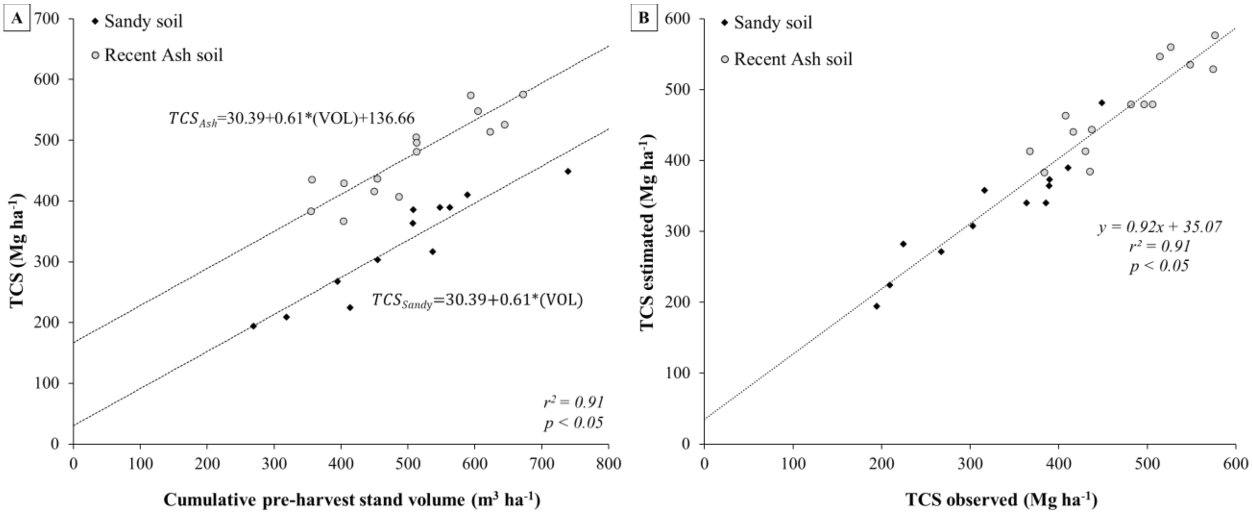

Figure 8. (a) Regression models of the relationship between cumulative over bark stand volume at harvesting age (VOL) and total site carbon stock (TCS) considering soil type as a dummy variable, and (b) relationship between observed and estimated TCS using dummy variable model.

Table 6. Adjusted models between cumulative over bark stand volume at harvesting age (VOL) and total carbon stock of stands (TCS). Model 1 represent the generalized model considering all evaluated sites, Model 2 represent the dummy variable regression model.

Model	r^2	*RMSE*	*AIC*	*Parameter*	*Estimate*	*S.E.*	*t*	*p*
TCS = a + b * VOL	0.49	76.95	315.07	a	80.65	68.23	1.18	0.25
				b	0.66	0.13	4.91	0.041
TCS = a + b * VOL + c * Soil (0=Sand or 1=Ash)	0.91	31.89	268.41	a	30.39	28.64	1.06	0.299
				b	0.61	0.06	10.87	< 0.001
				c	136.66	12.39	11.03	< 0.001

r^2: coefficient of determination; *RMSE*: root mean square error; *AIC*: Akaike information criterion values; *a*, *b* and *c* regression coefficients; *S.E.*: standard error; *t*: t-Statistics; *p*: p-values of regression coefficients.

1.5.DISCUSIÓN

1.5.1. Carbon Stock in Above and Belowground Biomass

Mean carbon stocks in above and belowground biomass (total biomass), showed no significant differences between the sandy and recent volcanic ash soil types. Similarly, no differences were observed in average stand volume, basal area or carbon stock in biomass pools between soil types, but important differences were observed in average DBH and HT. In average, larger trees were observed in recent volcanic ash sites compared to the sandy sites (Table 3). However, higher stockings were observed in sandy soils, that in average showed 93 trees ha^{-1} more than volcanic ash sites. Differences in stocking obey to differences in operational management schemes of these stands where recent volcanic ash sites are targeted to generate larger diameter for sawn timber objectives (Mendoza-Vega *et al.*, 2023) compared to multipurpose (pulp and structural sawtimber) of sandy sites. For this reason, although there were no differences in mean C stock in total biomass at stand level between sandy and recent ash soil types, differences were observed at individual tree level in aboveground biomass, with trees having greater individual C stock in recent ash soil sites

(0.74 Mg tree^{-1}), increasing the C stock at individual tree level respect to sandy soil sites by 25.5 % (0.59 Mg tree^{-1}).

Our results for total biomass C stock of radiata pine stands under intensive management were similar to those reported of Olmedo *et al.* (2020), which for stands of similar age and management schemes, showed slightly higher values of 181.2 to 214.0 Mg ha^{-1} for sandy and recent volcanic ash soils types, respectively. For the study of Ferrere and Lupi (2023), in 21-year-old radiata pine stands in Argentina, only 105.2 Mg ha^{-1} of C stock in total biomass were reported, showing lower carbon stock than our and Olmedo et al (2022) results. In that study, despite having stands of similar age (21 years) and standing volume (390.5 m^{3} ha^{-1}), higher stocking (870 trees ha^{-1}) due to less intensive management produced smaller DBH (27.5 cm) and HT (18.2 m) compared to our stands.

For sandy soils in our study and in Olmedo *et al.* (2020), the highest proportion of carbon stock was found in total biomass with 52.1% and 70.5%, respectively. Differences in the carbon proportion of stand components between both studies are due to the measured depth of soil C pool, because we measured the soil C stock up to 1 m depth, while in Olmedo's study soil C stock was measured only up to 30 cm deep. However, if we only consider our soil estimates up to 40 cm depth, our results will coincide closely with Olmedo *et al.* (2020). In fact, C in total biomass considering that approach would have reached 66.7 % of the total site C stock. In the case of recent volcanic ash sites, in our study the proportion of the C stock in total biomass decreased significantly with respect to sandy soils, corresponding to 37.7%, and being the second largest C reservoir in order of importance after SOC. In the study of Olmedo *et al.* (2020), the proportion of C in total biomass for recent ash soils was 64.3 %, much higher than our value. Again, this difference in C proportions with our study was due to the different depth of soil sampling, and if we consider only up to 40 cm depth, the proportion of C in the total biomass increases to 52.8 %, being even lower than estimated by Olmedo *et al.* (2020).

A direct relationship between stand volume and total biomass C stock was observed independent of soil type. Balboa-Murias *et al.* (2006) found an increase in aboveground biomass C with an increase in Site Index, similar to what we observed with stand productivity. They found also that thinning increased tree growth and C accumulation in stems, and reported, similar to our results, between 96.0 and 187.0 Mg ha^{-1} of C stock in aboveground biomass for

30-year-old plantations. While, in a global assessment of the effect of thinning on C accumulation in forests, Zhang *et al.* (2024) found that overall thinning significantly increased total tree aboveground biomass C stock (23.9%), but belowground biomass C stock remained unchanged; with a positive effect also in an increase in the mean DBH by 18.9 %, showing a positive effect of intensive plantation management on C stock.

1.5.2. *Soil Organic Carbon (SOC)*

Soil organic carbon concentrations were higher on volcanic ash soils than in sandy soils along the soil profiles (Table 2). Large differences between these soil types may be explained by soil texture and its effect on organic matter protection and accumulation over time (Bronick and Lal, 2005; Georgiou *et al.*, 2022). For both sites carbon concentration decreased in depth (Table 2), similar to what is reported in many studies (López-Díaz *et al.*, 2017; Zhang *et al.*, 2019; Ferrere and Lupi, 2023), and as expected due to soil matter organic accumulation from root decomposition and forest floor inputs (Jobbágy and Jackson, 2000; Prescott and Vesterdal, 2021).

For C stock in the mineral soil, Olmedo *et al.* (2020) reported in average 68.7 to 109.7 Mg ha^{-1} for sandy and volcanic ash soil types, respectively. In our study, due to our deeper sampling up to 1 m in depth, we found 139.9 and 281.4 Mg ha^{-1} for the same soil types respectively. When considering our SOC values only up to 40 cm depth, to resemble the depth measured by Olmedo *et al.* (2020), mean carbon stocks values for sandy soils are very similar between both studies, with 68.7 Mg ha^{-1} vs 68.1 Mg ha^{-1} (our study). In sandy soils, when considering only up to 40 cm, the SOC represented around 26% of the total carbon stock of the stand, however, when considering up to 1 m, it increased to 42.3%.

In another recent study carried out by Crovo *et al.* (2021) in central Chile, the C stock was compared between native forest and radiata pine plantations across five soil types, of which one site corresponded to Andisols, with characteristics similar to the Recent Ash soil sites that we evaluated on our study. In this study, the Andisol site presented the highest SOC stock, without significant differences between forest types, with a SOC accumulated up to 120 cm depth for native forest of 246.6 Mg ha^{-1} and for pine plantation of 243.7 Mg ha^{-1}, very similar values to the mean SOC stock up to 1 m depth for the Recent Ash soil sites found in our study (281.4 Mg ha^{-1}).

Interestingly, in the case of recent volcanic ash soils, when considering SOC only up to 40 cm, we found 146.0 Mg ha^{-1} of C in mineral soil, much higher than those reported by Olmedo *et al.* (2020) up to 30 cm depth (109.7 Mg ha^{-1}), similar than what Crovo *et al.* (2021) reported for the same depth for radiate pine plantation (129.6 Mg ha^{-1}); but lower than what Ferrere and Lupi (2023) reported for radiata pine stands in Argentina (210.6 Mg ha^{-1} of C in mineral soil up to 50 cm depth). In our study, in recent volcanic ash soils, SOC represented in average, 59.5 % of the total site C stock. When considering only a 40 cm depth it represented 43.2%, a higher proportion than Olmedo *et al.* (2020) that reported only 33.0 %, and a smaller proportion of what was reported by Ferrere and Lupi (2023) in Argentina where it accounted for 64.9 % of the total site carbon. For recent volcanic ash soils, at the depth of 60 to -100 cm, we found 135.4 Mg ha^{-1} of C, which, like in sandy soils, suggest that a large unaccounted amount of carbon at depth needs to be considered for correct assessment of C sequestration estimates from forest plantations.

Our results emphasize what was indicated by Houghton (2007) for terrestrial ecosystems, indicating that two to three times more carbon is stored in the top meter of soils than in the living biomass. Among the soil factors that drive the C stock on soils are the parent material and soil properties, such as the aggregation of its particles, the clay and silt content, and the mineralogy of the clays and their specific surface area (Wiesmeier *et al.*, 2019; Paula *et al.*, 2021; Georgiou *et al.*, 2022), which display different capacities for soil organic matter (SOM) stabilization and protection (Torn *et al.*, 1997; Denef and Six, 2005). Recent volcanic ash soils (Andisols) present secondary minerals, including short-range-order (SRO) minerals (Wiesmeier *et al.*, 2019), as allophane and imogolite (Garrido and Matus, 2012). These clay type and soil aggregates, with high specific surface area and variable charge, provided a physical and chemical protection and stabilization for SOM (Torn *et al.*, 1997; Garrido and Matus, 2012; Wiesmeier *et al.*, 2019) resulting in higher C stocks than sandy soil sites. Our results and those of Olmedo *et al.* (2020) and Crovo *et al.* (2021) suggest that a high amount of C stock is stored and maintained in volcanic ash soils, due clay type and the higher clay and silt content, accumulating more soil organic matter (Matus *et al.*, 2014; Soto *et al.*, 2019; Paula *et al.*, 2021; Georgiou *et al.*, 2022). Therefore, the content of clays of the SRO mineral type, such as allophane and imogolite in recent volcanic ash soils, allows Andisols to accumulate one of the largest SOC stocks in temperate forest (Lal, 2014; Wiesmeier *et al.*, 2019; Paula *et al.*, 2021).

In addition, sites with finer soil textures and greater water retention capacity, such as recent volcanic ash soil sites (Table 2), also show high microbial activity that increase the rate of decomposition of organic matter in fine roots and its input into the soil (Bronick and Lal, 2005; Garrett *et al.*, 2012; Paula *et al.*, 2021; Prescott and Vesterdal, 2021). Sandy soils, having 141.5 Mg ha^{-1} less C than volcanic ash soils, have lower potential to sustain larger amounts of soil carbon because their coarse texture, larger pore size, and lower water and nutrient availability that affects stand productivity but also storage and speed of decomposition of organic matter (Rubilar *et al.*, 2013; Chendev *et al.*, 2014; Olmedo *et al.*, 2020; Ouimet *et al.*, 2023; Pinto *et al.*, 2023).

1.5.3. *Carbon Stock in the Forest Floor*

The lowest C stock in our study was found in the forest floor, and significant differences were observed between soil types. Sandy soils showed higher estimates (18.6 Mg ha^{-1}) compared to recent volcanic ash soils (13.4 Mg ha^{-1}).

Our results were similar to those reported by Oliver *et al.* (2011) in New Zealand for 15- and 16-year-old *Pinus radiata* stands, with forest floor soil C accumulation ranging between 12.4 to 16.7 Mg ha^{-1}. However, in Spain, a mean of 14.8 Mg ha^{-1} of C in the forest floor was found for radiata pine stands, but with a range of 2.5 to 42.1 Mg ha^{-1} (López-Senespleda *et al.*, 2021). Our values were higher than those reported by Olmedo *et al.* (2020), with 7.1 and 9.1 Mg ha^{-1} for sandy and volcanic ash soil types, respectively; and those reported by Ferrere and Lupi (2023) in Argentina with 8.3 Mg ha^{-1}. In our study C stock in the forest floor represented of the total carbon in the stand, 5.6 % for the sandy and 2.8 % for the recent volcanic ash soil types. Percentage wise our values were similar to what was reported by Olmedo *et al.* (2020) with 2.8 % and by Ferrere and Lupi (2023) with 2.6 %. Forest floor, despite being the smallest C reservoir, is a key component in the site C and nutrient dynamic but also on its contribution to mineral soil C and its role as a nutrient reservoir for successive rotations (López-Senespleda *et al.*, 2021; Prescott and Vesterdal, 2021).

In our study, the effect of soil type on the amount of C in the forest floor was important but not site productivity. Also, and similar to what was found by Petritan *et al.* (2023), no correlation was observed between stand volume and C stock in dead wood residues accumulation. In a previous study in Chile in *Pinus radiata* plantations at harvesting age and similar to our study, residues biomass for contrasting soil types was evaluated and similar to our results, a larger proportion of biomass residues was observed in sandy soils compared to recent volcanic ash soil types (Cartes-Rodríguez *et al.*, 2016). In this study they estimated 34.2 Mg ha^{-1} of residues for sandy and 27.3 Mg ha^{-1} for volcanic ash soil sites; so, by applying a conversion factor from residues biomass to C, values will coincide with our analysis. The greater C stock in the forest floor observed for sandy compared to recent volcanic ash soil sites may be because sandy sites have higher temperatures and lower humidity (Figure 1, Table 1), which could slow down decomposition rates of organic matter. Forest floor carbon stock is affected by precipitation, altitude, crown cover and water deficit (López-Senespleda *et al.*, 2021; Prescott and Vesterdal, 2021; Díaz Villa *et al.*, 2022).

1.5.4. *Total Carbon Stock*

Large carbon stocks were found radiata pine plantations evaluated for sandy and recent volcanic ash sites. Observed values, similar to what has been reported in previous studies, indicates that most productive sites that have less water and nutritional limitations reach the largest total carbon storage capacity (Kranabetter, 2009; Olmedo *et al.*, 2020).

Our estimated values were higher than those reported by Olmedo *et al.* (2020) in a recent study carried out in Chile in which carbon stocks were evaluated for radiata pine plantations considering different soil site types. In that study, for the same soil types and plantations of similar age, total carbon stock mean values ranged from 257.0 to 332.8 Mg ha^{-1} for sandy and volcanic ash, respectively. However, Olmedo *et al.* (2020) only estimated SOC until 30 cm of depth, resulting in a underestimation of total site carbon stock respect to our study. Ferrere and Lupi (2023), in other recent study, evaluated the C stock of radiata pine stands in Argentina, finding an average of 324.1 Mg ha^{-1} of C in stands of similar ages. However, they only measured SOC up to 50 cm depth, so again an important underestimation of total site carbon that is accumulated in forest plantations. These results indicate the importance of measuring an accounting for soil carbon in depth in order to correctly evaluate total site carbon pools. In fact, our results of C stock in volcanic ash only up to 40 cm depth (337.9 Mg ha^{-1} of C) accounts for similar values to both previous studies with soils of similar characteristics.

1.5.5. *Relation between C stocks and stand productivity.*

We found a positive linear relationship between stand over bark volume and total site C stock (soil organic carbon + carbon in the total biomass + carbon in the forest floor) ($p < 0.05$). This relationship improved significantly when models were adjusted considering soil type as a *dummy* variable ($p < 0.001$), providing independent regressions for each soil type. Interestingly, regardless of soil type, there is an increase in SOC and total C stock that depends on stand volume, and the same slopes for sandy and volcanic ash soil types of 0.26 for the C in the mineral soil and of 0.61 for C stock of all stand components suggest that site productivity, as an expression of site resource availability, has a close relationship with C accumulation.

Soil type influenced the intercept of the model, with an increase of 148.9 Mg ha^{-1} for SOC for sites recent volcanic ash compared to sandy soils (figure 5, table 5); and with an increase of 136.7 Mg ha^{-1} for total site carbon stock recent volcanic ash compared to sandy soils (figure 8, table 6). The increase in C stock found in the soil according aligned the level of productivity of the site and soil type. This also may be related with the source of organic matter entering the soil, coming mainly from the decomposition of fine roots and litterfall (Jackson *et al.*, 2017; Prescott and Vesterdal, 2021). Therefore, sites with higher stand volume will have a greater contribution of organic matter from the decomposition of the roots and forest soil, providing C to the mineral soil.

This study provides interesting equations to estimate C stocks in mineral soils and total C stock at harvesting age of radiata pine stands for sandy and recent volcanic ash soils for radiata pine plantations. Few studies have evaluated relationships between stand productivity and site C stocks. Kranabetter (2009) showed a slight trend of increase of mineral soil C (until 50 cm depth) along a productivity gradient in Canadian boreal forests. However, the trend was significant when considering all above and belowground stand components (C in the mineral soil + forest soil + residues + total biomass) and stand height. Pinto *et al.* (2023) investigating *Pinus taeda* plantations in Brazil, related soil attributes to site productivity. He found a positive relationship between stand mean annual increment (MAI) with clay content and with soil C stocks. However, another study that related C stock to site productivity, developed by van den Bor *et al.* (2023) evaluating *Pinus halepensis* plantations and *Quercus* native forest in central Spain, found a significant relationship between basal area and total C stock of stands, and for individual aboveground and belowground biomass and litter components. However, they did not find a relationship between basal areas and C stock in the mineral soil for any of the investigated species.

Since not all studies find a significant trend between C stock in the mineral soil and site productivity, this study provides a linear model that was significant ($p < 0.05$; $r^2=0.88$) and suggest that productivity could be used to estimate site and soil C stocks. Also, a linear model was developed to estimate total C stock of the stand biomass ($p < 0.05$; $r^2=0.91$) but the close relationship between volume, biomass and carbon stock has been extensively reported. Given that our study showed that C stock in the mineral soil in depth is a large proportion of the total site carbon stock, which is rarely considered in C stock calculations, it emphasizes its importance for future assessments and should be incorporated in carbon sequestration models. Our models improve current C stock estimates for radiata pine plantations at harvesting age and emphasize the importance to develop soil type specific models to appropriately estimate site C stock.

1.6.CONCLUSIONS

In the adult radiata pine plantations evaluated, we found a significantly higher amount of total C stock in the recent ash soil than in the sandy soil sites. In both soil types, a high amount of carbon in the mineral soil up to 1 m depth was found, being the main pool of C in the recent ash soil sites (59.6 %) and the second in sandy soil sites (41.5 %); which emphasize the importance of including these assessments until to 1 m depth for C stock estimates. Forest floor represented the lowest carbon stock of stands on all sites, with 2.9 % for recent ash and 5.8 % for sandy soil sites, which, however, has an important role in protecting the mineral soil, storing nutrients, and allowing inputs of C (organic matter) to the mineral soil from aerial biomass. A correlation was observed between the stand productivity with the carbon stock in the mineral soil and with the total carbon stock of the site, which increased strongly when considering the effect of soil type as dummy variables. High carbon stocks in mineral soil, and differences on C pools according soil type show the importance of developing soil type-specific models to adequately estimate C stocks.

2. MODELING OF CLIMATIC, SOIL, AND SITE EFFECTS ON THE CARBON STOCKS OF RADIATA PINE PLANTATION IN CONTRASTING ENVIRONMENTAL CONDITION IN CHILE.

Daniel Bozo[1,2]; Rafael Rubilar*[1,2]; Otávio Campoe[3]; Rosa Alzamora[2,4]; Juan Pedro Elissetche[2,4]; Juan Carlos Valverde[1]; Matías Pincheira[5]; Juan Carlos Valencia[5].

[1] Cooperativa de Productividad Forestal, Departamento de Silvicultura, Fac. Ciencias Forestales, Universidad de Concepción, Concepción, Chile.

[2] Centro Nacional de Excelencia para la Industria de la Madera (CENAMAD), Pontificia Universidad Católica de Chile, Santiago, Chile.

[3] Forest Productivity Cooperative, Universidade Federal de Lavras, Departamento de Ciências Florestais, Lavras, Minas Gerais, Brazil.

[4] Departamento de Manejo de Bosques y Medio Ambiente, Fac. Ciencias Forestales, Universidad de Concepción, Concepción, Chile.

[5] Forestal Mininco S.A., Avenida Alemania 751, Los Ángeles, Chile.

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*Corresponding Author. *In Preparation*. Plants.

2.1.ABSTRACT

Forests are an important terrestrial carbon sink, sequestering and retaining carbon in the biomass, forest floor and mineral soil. *Pinus radiata* is the most planted forest species in Chile, so it becomes relevant to improve the understanding of how climate, soil and site characteristics affect those carbon pools. The objective of our study was to evaluate the effect of environmental, site and soil variables in carbon stock of the biomass, forest floor and mineral soil in radiata pine plantations at harvesting age, considering contrasting sites in water and nutritional availability. In 10 sites on sandy and recent ash soils selected by a productivity gradient of harvesting age radiata pine plantations, 3 plots of 1000 m^2 were installed in which the carbon stock of biomass was quantified using allometric equations, and through *in situ* carbon assessments were calculated forest floor and mineral soil (up to 1 meter deep). Results showed that ash soil sites presented a slightly higher carbon stock than sandy in the total biomass (178.5 Mg ha^{-1} vs 172.4 Mg ha^{-1} respectively), and significant higher carbon stock in the mineral soil for recent ash sites (281.4 Mg ha^{-1}) than sandy soil sites (139.9 Mg ha^{-1}). In both soil types, forest floor represented the lowest carbon stock of stands, with 2.9 % for recent ash and 5.8 % for sandy soil sites. Total carbon stock of site was significant higher in recent ash soil sites (473.2 Mg ha^{-1}) than sandy soil sites (330.9 Mg ha^{-1}). PCA, correlations analysis and fitted linear models showed that variables related to soil water availability (silt + clay content, and soil water holding capacity), precipitation and stand productivity were strongly and positively related to C stock ($p < 0.05$), while variables related to drought and water stress, such as temperature, evapotranspiration and higher sand content decreased the C stock of stands.

Keywords: Carbon pools, Biomass, Forest floor, Soil organic carbon, Water stress.

2.2.INTRODUCCIÓN

Forests are a large sink that stores carbon (C) and offsets CO_2 emissions from anthropogenic activities (Pan *et al.*, 2011). Additionally, forests improve ecosystem services such as a regular hydrological cycle, help in the mitigation of climate change, and provide pulp and wood products (Tricallotis *et al.*, 2018; Díaz Villa *et al.*, 2022). The potential of forests to capture and store carbon is influenced by a variety of environmental factors, particularly soil and climate characteristics (Wiesmeier *et al.*, 2019; Olmedo *et al.*, 2020; López-Senespleda *et al.*, 2021; Díaz Villa *et al.*, 2022; Mizuta *et al.*, 2022). In the current context of climate change, in which an increase in temperatures and a decrease in precipitation is expected (Zhang *et al.*, 2019; Carrasco *et al.*, 2022), is especially important to understanding how climate, soil and site characteristics affect carbon stocks in forest plantations.

Precipitation and temperature are two key factors in the growth of forests, which affect their leaf area index (LAI) and therefore the responses in productivity and biomass accumulation (Alvarez *et al.*, 2013; Ojeda *et al.*, 2018). In addition, they have an effect on soil respiration and decomposition rates of organic matter, affecting both the carbon present in the forest floor and the organic carbon stored in the mineral soil (SOC) (Pinto *et al.*, 2023), being SOC the largest reservoir of C in forests (Pan *et al.*, 2011). Many studies have been found that mean temperature decreases stand C stock; while annual precipitation increases it (Becknell *et al.*, 2012; Sun *et al.*, 2023; Yang *et al.*, 2023). Another important property that affects the accumulation of carbon in the soil is texture, due than clay content promotes long-term retention and protection of organic matter and the water storage capacity of the soil (Bronick and Lal, 2005; Wiesmeier *et al.*, 2019; Georgiou *et al.*, 2022; Pinto *et al.*, 2023). Otherwise, soils with high sand content have larger pores, retain less moisture and nutrients, are less fertile and have high rates of organic matter decomposition (Van Veen and Kuikman, 1990; Chendev *et al.*, 2014).

Pinus radiata D. Don (radiata pine) is one of the most important pine fast growing cultivated in the southern hemisphere, mainly in New Zealand, Chile, Australia, and South Africa (Mead, 2013; Dash *et al.*, 2019). In Chile, radiata pine represents the most important forest species with more than 1.3 million ha of the approximately 2.3 million ha of total commercial planted forests (Soto *et al.*, 2021). Forest productivity of this species depends on advanced genotypes, silviculture, and environmental conditions (Flores and Allen, 2004; Alvarez *et al.*, 2013; Dash *et al.*, 2019; Rubilar *et al.*, 2023). Some recent studies have been carried out to estimate the forest productivity and C stock in radiata pine forest plantation in Chile (Olmedo *et al.*, 2020; Crovo *et al.*, 2021; Carrasco *et al.*, 2022). The highest stand growth rates have been found in recent volcanic ash soils, and therefore the highest accumulation of biomass and C in the soil (Olmedo *et al.*, 2020; Rubilar *et al.*, 2023), being sites with lower water limitations, higher clay content, organic matter and high annual precipitation than more restrictive soils such as sandy soil sites. Therefore, in radiata pine stands, sandy soil sites reduce stand growth (Rubilar *et al.*, 2013; Rubilar *et al.*, 2023) and present lower carbon stock in the mineral soil than recent ash soil sites (Olmedo *et al.*, 2020).

Therefore, having models that allow quantifying the C stock with respect to environmental, soil and site variables is of great importance, to understand how climate change could affect forest productivity and stand carbon sequestration. Our objectives are: (1) to calculate the aboveground and belowground carbon stocks in radiata pine plantations in contrasting climate, soil, and site productivity sites; and (2) to model these C stocks with respect to climatic and soil property variables.

2.3.MATERIALS AND MEHODS

2.3.1. Study area

Sites were selected representing a productivity gradient of *Pinus radiata* plantations, under intensive management at harvesting age, covering a part of the productive area of radiata pine plantations in Chile (Table 1). The sites were in the Central Valley and the Foothills of the Andes in central and south-central Chile and spread from the Ñuble to the Biobio region. Soils considered five stands located in coarse volcanic sands and five stands were in recent volcanic ash soil sites (CIREN, 1999; Stolpe, 2006) (Figure 1). Climate varies depending on the location across the climatic and soil gradient, with sandy soil sites presenting an annual mean temperature of 13.6 °C and volcanic ash soil sites with 11.5 °C. Mean annual precipitation varies widely, ranging from values of more than 1500 mm in the most productive volcanic ash sites to less than 1110 mm in the most restrictive sandy soil sites (Figure 1 and Table 1).

Selected stands at each soil-site condition were planted between 1999 to 2001 with initial planting density ranging from 1000 to 1250 trees ha^{-1}. All sites were established with soil preparation considering a router at 60 cm deep plus disking. Recent volcanic ash soils received traditional operational fertilization considering 100 to 150 g per plant of NPK mix (10 to 15 g N + 10.9 to 13.2 g P + 8.3 to 12.5 g K) plus 2 to 3 g per plant of boron applied after planting. For sandy soil sites only, boron was applied. Operational weed control of stands considered pre-planting total area and 2 years banded weed control after planting in most conditions. All selected stands were pruned at least to 5.5 m height and thinned with 1 or 2 commercial thinning according to the silvicultural program applied to the stand of each site. Final stands stockings at harvesting reached 400 to 500 trees ha^{-1}.

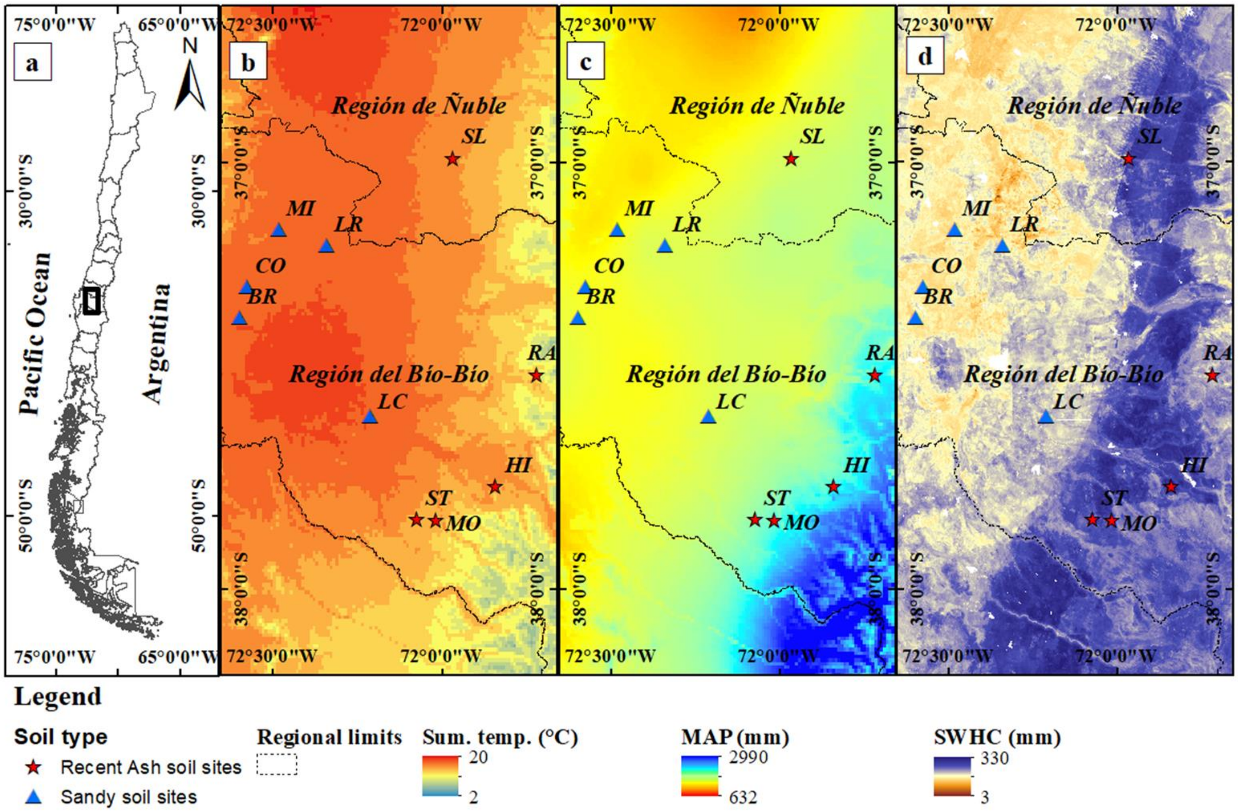


Figure 9. (a) Study area in Central South Chile, (b) Sites and mean summer (January to March) temperature (°C) (Sum. Temp.), (c) Sites and mean annual rainfall (mm yr^{-1}) MAP); and (d) Sites and soil water holding capacity up to 1 m deep (mm) (SWHC) (Dinamarca *et al.*, 2023). Site codes are presented in Table 1.

Table 7. Site characteristics of selected locations that consider range of productivity for contrasting sandy and recent ash soils.

Site code	Soil type	Soil order[a]	Soil taxonomy[a,b]	Soil serie[b]	Drainage[b]	ALT (masl)	MAT (°C)	MAP (mm)	Age (years)	MAI (m^3 ha^{-1} yr^{-1})
Hijuelas (HI)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	1217	11.9	1585.0	21	18.5
Montpellier (MO)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	1427	11.4	1521.1	20	25.6
Ramadillas (RA)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	2547	9.8	1492.0	22	25.0
Santa Lidia (SL)	Recent Ash	Andisol	Medial, Thermic Humic Haploxerands	Mayulermo	Well drained	1024	12.5	1207.8	21	20.6
Santa Teresa (ST)	Recent Ash	Andisol	Medial, Mesic Typic Haploxerands	Santa Bárbara	Well drained	1140	11.7	1460.6	23	28.1
Brasil (BR)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Arenales	Excessively drained	376	13.6	1131.7	21	20.5
Coyanco (CO)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Arenales	Excessively drained	318	13.7	1105.3	23	27.2
Los Cuartos (LC)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Coreo	Well drained to excessively drained	506	13.4	1182.4	23	22.5
La Reforma (LR)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Coreo	Well drained to excessively drained	444	13.6	1103.0	22	15.2
Misque (MI)	Sandy	Entisol	Mixed, Thermic Typic Xeropsamments	Arenales	Well drained	344	13.7	1055.1	22	21.4

[a] Soil Survey Staff, (2022).

[b] (CIREN, 1999; Stolpe, 2006).

ALT= altitude; MAT = mean annual temperature; MAP = Mean annual precipitation.

2.3.2. Study area

Inventory measurements and samplings were carried out between March and May 2022. At each site, three 1000 m^2 inventory plots were established to measure diameter at breast height (DBH, cm at 1.3 m height) and total height

(H, m) for all trees, and forest floor and mineral soil was sampled within each inventory plot. A total of 30 plots were measured considering all site locations.

2.3.2.1. *Volume and Carbon stocks of Above and Belowground Biomass estimations*

Individual tree inventory measurements from each plot considering number of trees, DBH and HT were used to estimate tree over bark volume. Calculations considered an individual tree local volume equation (V) developed by CMPC Forestal Mininco Forest Company MININCO (1995):

$$V = -0.00214 + 0.0000295 * D^2 + 0.001349 * H + 0.00002486 * D^2 * H \qquad (1)$$

where V=individual tree over bark volume (m^3 $tree^{-1}$), D=DBH (cm), H=height (m).

Published and local allometric equations, developed for radiata pine plantations (Zerihun and Montagu, 2004; Sandoval *et al.*, 2021), were used to estimate individual tree aboveground (AGB) and belowground (BGB) biomass carbon stock. Aboveground biomass of each component (stem, bark, branch and needle) of trees was calculated using the following published (Sandoval *et al.*, 2021) allometric equations (eq. 2, eq. 3, eq. 4 and eq. 5) developed for radiata pine:

$$AGB_{stem} = 0.02389 * (D^2 * H)^{0.93216} \tag{2}$$

$$AGB_{bark} = 0.00127 * (D^2 * H)^{0.99646} \tag{3}$$

$$AGB_{branch} = 0.00431 * (D^2 * H)^{0.92709} \tag{4}$$

$$AGB_{needles} = 0.19428 * (D^2 * H)^{0.48666} \tag{5}$$

Where AGB_{stem}, AGB_{bark}, AGB_{branch} and $AGB_{needles}$ are the aboveground biomass for stem, bark, branch and needles (kg $tree^{-1}$) respectively, D=DBH (cm), H=height (m). Subsequently, the total aboveground biomass (AGB_{total}, kg $tree^{-1}$) was calculated as the sum of the biomass of each individual tree component (eq. 6) as:

$$AGB_{total} = AGB_{stem} + AGB_{bark} + AGB_{branch} + AGB_{needles} \tag{6}$$

Belowground biomass (BGB) was calculated using (Zerihun and Montagu, 2004) allometric equation (eq. 7) developed to estimate weight of total root biomass for radiata pine as:

$$l\,n(BGB) = 0.902 * ln\,(AGB_{total}) - 0.7368 \tag{7}$$

Where BGB=individual tree root biomass (kg tree^{-1})

Then, the total individual tree biomass (TB, kg tree^{-1}) was finally estimates summing the AGB and BGB stocks. The individual tree carbon biomass was estimated multiplying TB by a carbon factor (CF), corresponding to the fraction of carbon of each biomass component. We used a CF of 0.48 according to what is recommended for IPCC (2013).

Finally, individual plot stocking (NHA, trees ha^{-1}), stand volume (VHA, m^3 ha^{-1}), basal area (BA, m^3 ha^{-1}) and total biomass carbon stock (TBC, Mg ha^{-1}) were estimated by adding and scaling to an hectare level numbers of trees per plot, the individual tree volume, basal individual tree area, and the individual tree carbon biomass

2.3.2.2. *Soil organic carbon sampling and calculations*

Individual tree Soil organic carbon (SOC) estimates were obtained with a soil auger considering a composite sample for 20 distributed systematically within each plot, at 3 depths: 0- 20 cm, 20-40 cm and 40-100 cm. A total of 90 composite mineral soil samples were obtained for all evaluated sites in our study. Soil samples were air-dried at 30 °C, passed through a 2 mm sieve to remove all root and plant debris, and a 10 g. subsample aliquot was taken and dried at 65 °C for 24 hours to constant weight and ground. A final 5 g. aliquot was obtained for the determination of organic carbon (C) and total nitrogen (N) using an IRMS (Infrared Mass Spectroradiometer, SERCON Scientific Inc.).

At each site, 1 m depth soil pit was dug to describe visual soil profile characteristics and to collect bulk density (BD) samples using a metal cylinder of 100 cm^3 volume at 0-20, 20-40 and 40-100 cm depths. Each soil sample was stored and taken to the laboratory to be dried at 105°C until constant weight. A total of 30 soil bulk density samples were obtained for all sampled sites. Additionally, for each sampled depth, a bulk 0.5 kg soil sample was taken for subsequent Boyoucos soil texture determination (Sadzawka *et al.*, 2006), and to estimate permanent wilting point and field capacity point from moisture retention curve points using a pressure plate apparatus (Soil Moisture Inc., USA). Soil water holding capacity (SWHC) for each soil sample was estimated as the difference between permanent wilting point (PWP) and field capacity point (FC). All soil laboratory analyses were carried out in the Soil, Water and Forest Research Laboratory (LISAB) at the Faculty of Forest Sciences of the University of Concepción, Chile.

Soil Organic Carbon Stock (SOC_D) at each depth (d_1=0-20, d_2=20-40 and d_3=40-100 cm depth) was calculated using (eq .8):

$$SOC_{\mathrm{d}} = C_d * D_d * BD_d * 0.1 \tag{8}$$

Where: SOC_d= Soil Organic Carbon Stock of depth d (Mg ha^{-1}), C_d= Soil Organic Carbon concentration by depth d (g kg^{-1}) (Table 2), D_d=soil thickness of depth d (cm), BD_d= bulk density of depth d (gr cm^{-3}). Total Soil Organic Carbon Stock (SOC) until 1 m of depth of each plot, was calculated summing the SOC_d estimates at each depth.

Table 8. Mean physical and chemical soil properties values evaluated at 0-20, 20-40 and 40-100 cm depths from soil pits representing each selected site.

Soil type	Site code	Depth (cm)	B.D. (gr cm3)	C total	O.M.	SWHC	Clay	Silt	Sand
				%					
Recent Ash	HI	0 - 20	0.56	6.21	14.55	25.52	5.34	42.45	52.21
		20 - 40	0.61	4.02	12.43	22.75	2.76	32.51	64.73
		40 - 100	0.69	3.04	9.17	17.23	2.89	34.96	62.15
	MO	0 - 20	0.53	7.86	16.17	28.05	10.30	35.88	53.82
		20 - 40	0.59	5.36	13.14	17.38	2.67	29.82	67.51
		40 - 100	0.63	3.97	11.25	14.69	2.05	24.35	73.60
	RA	0 - 20	0.68	7.38	10.08	26.77	17.83	29.35	52.82
		20 - 40	0.71	5.56	10.00	22.20	20.15	26.85	53.00
		40 - 100	0.67	3.31	11.54	16.70	19.49	23.96	56.55
	SL	0 - 20	0.53	7.05	15.82	37.94	2.67	59.84	37.49
		20 - 40	0.64	4.76	10.91	36.03	7.13	65.34	27.53
		40 - 100	0.66	3.01	10.20	37.86	4.65	56.93	38.42
	ST	0 - 20	0.67	6.61	14.32	28.51	7.84	47.59	44.57
		20 - 40	0.65	4.72	12.11	18.24	4.18	33.71	62.11
		40 - 100	0.66	3.75	10.42	34.10	2.76	37.41	59.83
Sandy	BR	0 - 20	1.07	2.80	2.67	17.21	4.19	73.40	22.41
		20 - 40	1.09	1.74	2.21	19.84	4.05	52.92	43.02
		40 - 100	1.16	1.31	3.00	16.89	5.71	11.56	82.73
	CO	0 - 20	1.18	1.68	2.50	5.99	2.75	29.51	67.74
		20 - 40	1.19	1.55	2.93	6.92	2.66	19.51	77.82
		40 - 100	1.13	1.42	2.91	5.99	2.57	22.22	75.21
	LR	0 - 20	1.32	0.89	1.34	2.87	2.74	7.15	90.10
		20 - 40	1.54	0.62	1.69	3.53	2.59	4.78	92.63
		40 - 100	1.52	0.27	1.93	1.17	2.70	2.14	95.16
	LC	0 - 20	1.06	1.16	2.87	3.45	2.66	17.45	79.89
		20 - 40	1.19	1.03	2.62	5.69	5.22	1.92	92.85
		40 - 100	1.36	1.06	1.81	4.34	2.61	2.07	95.32
	MI	0 - 20	1.03	2.04	2.14	4.85	2.47	7.20	90.33
		20 - 40	1.35	1.20	2.08	6.74	0.26	9.46	90.28
		40 - 100	1.52	0.67	1.11	4.42	2.67	2.37	94.96

Site codes are = HI: Hijuelas, MO: Montpellier, RA: Ramadillas, SL: Santa Lidia, ST: Santa Teresa, BR: Brasil, CO: Coyanco, LC: Los Cuartos, LR: La Reforma, MI: Misque; B.D. = Soil Bulk density; C total = Total carbon; SWHC = Soil water holding capacity; O.M. = Organic matter.

2.3.2.3. *Soil organic carbon sampling and calculations*

Forest floor carbon stock samples were collected using a circular 25 cm in diameter cutting frame (490.9 cm^2) at 10 systematically selected points within each plot (Figure 2). At each point, litter and coarse woody debris were collected separately, for a total of 600 forest floor samples from all evaluated plots. Each forest floor sample was stored in paper bags, labeled, and taken to the laboratory for drying at 65°C until constant weight. Forest floor and woody debris dry weight was recorded for each sample using a 0.01 g precision balance. After weighing the 10 organic horizons samples and the 10 woody debris residue samples were composited and homogenized separately for each plot. Each pair of composite samples per plot was independently ground using a 250 µm sieve blade mill to obtain two independent 5 g subsample aliquots that were used for final carbon analysis. Analysis of all forest floor samples were carried out on a free ash basis to remove mineral soil potential contamination.

The carbon stock of the organic horizons and coarse woody debris was obtained by multiplying the biomass dry weight of each component at each sample point by the average plot carbon concentration of each component (%), expanded to an hectare level (Mg ha^{-1}) and averaged for each plot. Total forest floor carbon stock (FFC) was finally estimates summing the carbon stock of the organic horizons and the coarse woody debris estimated from each plot.

2.3.2.1. *Total Carbon stock calculation*

Total carbon stock (TCS) for each plot was estimated as the sum of all evaluated components (TBC, SOC and FFC).

2.3.3. Climate data

Temperature, precipitation, and solar radiation data (from 1998 to 2022) were acquired from climate dataset of Google Earth Engine platform (https://earthengine.google.com). The climatic data were previously correlated and validated with climatic stations close to each sampling site, belonging to Chilean government agencies Dirección General de Aguas (https://snia.mop.gob.cl/BNAConsultas/reportes) and Instituto de Investigaciones Agropecuarias, (https://agrometeorologia.cl/). For precipitation, we calculated cumulative annual precipitation (Pp) and cumulative precipitation on growing season (September to April) (Ppgs). Vapor pressure deficit (VPD, mBar) was estimated using the eq. 9 (Allen *et al.*, 1998):

$$VPD \quad = \left(\frac{6.1078 * e^{\left(\frac{17.269 * T_{max}}{\left(237.3 + * T_{max})\right)}\right)} - 6.1078 * e^{\left(\frac{17.269 * T_{min}}{\left(237.3 + * T_{min})\right)}\right)}}{2} \right) \tag{9}$$

Where VPD is the vapor pressure deficit (mBar), T_{max} is the maximum daily temperature (°C) and T_{min} is the minimum daily temperature (°C).

We estimated the reference evapotranspiration of the sites using the method described by Hargreaves and Samani (1985). Finally, we estimated the soil water deficit index (SWDI) using (eq. 10):

$$SWDI = P_p - ET + SWC \tag{10}$$

Where SWDI is the water deficit index during the year (mm $year^{-1}$), P_p is the cumulative annual precipitation (mm $year^{-1}$), ET is the evapotranspiration during a year (mm $year^{-1}$) and SWC is the soil water holding capacity (mm) (Table 2).

2.3.4. Canopy estimates

Leaf area index is a key ecophysiological parameter highly related with stand growth, productivity, and physiological process in stand canopies (Ojeda *et al.*, 2018; Parker, 2020; Brito *et al.*, 2021). Due to the high correlation between LAI and the spectral vegetation index (VIs) (Cohrs *et al.*, 2020), we estimated some VIs from Sentinel-2 images. We download a one Level-1C Sentinel-2 image from the Copernicus Open Access Hub online repository, with < 10 % cloud cover, that was acquired close to the sampling date (April 13, 2022).

Digital numbers (DN) from Santinel-2 image were converted to at-sensor spectral radiance (Chavez, 1996), and then we calculated the top-of-atmosphere (TOA) reflectance (Chander *et al.*, 2009). From multispectral image, only bands 4 (Red: 0.665 µm) and 8 (near infrared band, NIR: 0.834 µm) with a 10 m spatial resolution were used in this analysis. For each plot, we calculated simple ratio index (SR) as (NIR/Red) (Birth and McVey, 1968), normalized difference vegetation index (NDVI) as ((NIR-Red)/(NIR+Red)) (Rouse *et al.*, 1973) and soil adjusted vegetation index (SAVI) as ((NIR-Red)/(NIR+Red+0.5)*(1.5)) (Huete, 1988).

2.3.5. Data analysis

Carbon stocks (TBC, FFC, SOC and TCS) data was analyzed with simple t-test was used to compare sandy and recent ash soil types. These carbons stocks were considered as dependent variables for regression analysis. The independent variables were grouped into climate (mean annual precipitation and cumulative precipitation on the growing season; soil water deficit index; minimum, mean and maximum temperatures; mean and summer VPD), stand attributes (stand volume; spectral vegetation indices), soil properties (soil N; C:N ratio at 20 cm and 1 m depth; percentage of sand; soil water holding capacity) and site locations (latitude; elevation; distance from sea) groups.

An exploratory analysis was performed to identify outliers (observations distanced more than 2.5 times the standard deviation from the mean value) and remove them. Principal component analysis (PCA) was performed to avoid multicollinearity of possible predictor variables, and to identify variables that contributed with more significant variability. Then, we performed a correlation analysis to evaluate the effect of the most relevant independent variables from PCA, against each dependent variable (carbon stock). Multiple linear regressions were then performed to examine the effects of the independent variables (climate, soil, site and stand attributes) for each carbon pool (TBC, SOC and FFC) and total (TCS). For each carbon pool, linear models were adjusted in two steps: a complete model was fitted using all the variables selected from PCA and correlation analysis.

Then, a stepwise process was used to fit a reduced model including only significant ($p < 0.05$) variables. Fitted models were evaluated and diagnosed through graphical and analytical analysis, verifying the assumptions of linearity (graphic analysis), normality (Kolmogorov-Smirnov test), homoscedasticity (Breusch-Pagan test), and residual independence (Durbin-Watson test).To identify the best model and compare the performance of each approach, the adjusted coefficient of determination (Adj-r^2), root mean square error (RMSE) and the Akaike's Information Criteria (AIC) values were calculated in the fitting process. All the statistical analysis and fitting procedures were carried out using SAS software (version 9.4, SAS Institute, Inc., Cary, NC)). All tests were considered significant at a level of $\alpha=0.05$

2.4.RESULTS

2.4.1. Variation in carbon stocks of stands

No significant differences were observed in the means of total biomass carbon stock (TBC) between sandy and recent ash sites ($p = 0.66$). However, the mean values revealed that TBC was slightly higher in recent ash sites (+ 6.1 Mg ha^{-1}) compared to sandy sites (Table 3). For carbon stock in the mineral soil (SOC), recent ash soils presented a higher SOC (+ 141.5 Mg ha^{-1}) than sandy soils sites ($p < 0.05$); with a difference of more than 132.4 Mg ha^{-1} between the site with the highest SOC (in recent ash soil) compared to the site with the lowest SOC (in sandy soil). Carbon stock in the forest floor (FFC) was the lowest carbon pool on all sites, with a higher FFC stock in sandy soil (+5.2 MG ha^{-1}) than recent ash soils ($p < 0.05$). At total stand level, ash soils presented a higher total carbon stock (TCS) than sandy soils ($p < 0.05$), with averages of 473.2 and 330.9 Mg ha^{-1}, respectively.

Recent ash soil sites had 59.6 % of the TCS in the SOC stock that accounted for 1 m depth, followed by the carbon stock accumulated in total biomass with 37.5 % (Table 3). The lowest carbon stock for recent ash soils sites was found in the forest floor pool that accounted for 2.9 %. Conversely, for the sandy soil sites the highest proportion of TCS was found in total biomass with 52.7 % of the TCS, followed by the SOC with 41.5 %. Again, the lowest carbon stock was found in the forest floor with 5.8 %.

Table 9. Average aboveground, belowground, total biomass, soil, forest floor and total site carbon stocks for all sites. Different capital letters indicate significant difference among soil type mean considering a two-sample t-test analysis.

Soil type	Site code	AGBC (Mg ha^{-1})	BGBC (Mg ha^{-1})	TBC (Mg ha^{-1})	SOC (Mg ha^{-1})	FFC (Mg ha^{-1})	TCS (Mg ha^{-1})
Recent Ash	HI	110.2	27.9	138.1	244.6	10.7	393.4
	MO	147.1	36.9	183.9	296.8	13.7	494.5
	RA	151.6	37.3	188.9	312.3	11.8	512.9
	SL	123.4	31.3	154.7	255.0	16.9	426.6
	ST	182.2	44.5	226.7	298.3	13.7	538.7
Sandy	BR	123.9	32.1	156.0	188.9	8.9	353.8
	CO	176.9	43.9	220.8	172.7	22.7	416.2
	LC	153.2	39.3	192.5	135.2	27.7	355.3
	LR	98.2	26.1	124.3	67.7	17.3	209.4
	MI	134.3	34.2	168.5	135.1	16.5	320.2
Recent Ash Soils (Mean)		142.9 ns	35.6 ns	178.5 ns	281.4 A	13.4 B	473.2 A
Sandy Soils (Mean)		137.3 ns	35.2 ns	172.4 ns	139.9 B	18.6 A	330.9 B

Site codes are = HI: Hijuelas, MO: Montpellier, RA: Ramadillas, SL: Santa Lidia, ST: Santa Teresa, BR: Brasil, CO: Coyanco, LC: Los Cuartos, LR: La Reforma, MI: Misque; AGBC = carbon stock in the aboveground biomass; BGBC = carbon stock in the belowground biomass; TBC = carbon stock in the total (aboveground + belowground) biomass; SOC = carbon stock in the organic soil; FFC = carbon stock in the forest floor; and TCS = total carbon stock of the stands. ns = not significant.

2.4.2. Selected environmental variables.

Principal component analysis (PCA) explained 72.8% of the data variability (Figure 2). The first component of the PCA represented 62.9% of the variation, with the contribution in this axis being high of those variables directly related to stand growth (such as stand volume, total biomass carbon, nutrients), close to the ash soil type group. This axis had a negative relationship with those variables related to soils with fewer nutrients (Sand content and high C:N ratio). While the second PCA component explained 10.9 % of data variability, with a clear trend of those variables relates with water availability (precipitation and soil water holding capacity) near of ash soil type group, and the variables relates with water stress (VPD, evapotranspiration and temperatures) close to sandy soil type group.

With PCA test, it was possible to reduce the dimensionality of the data set that would be used as predictor variables, and greatly reducing the multicollinearity of some highly correlated variables. From PCA test, we found 14 continuous independent variables with a high score, corresponding to: Alt (altitude, m.a.s.l.), NDVI (normalized difference vegetation index), N (soil nitrogen, %), CN20 (C:N ratio on the 20 cm depths), Sand (sand content, %), SWHC (soil water holding capacity, mm), Pp (mean annual precipitation, mm), Ppgs (cumulative precipitation on the growing season, mm), ET (evapotranspiration, mm), SWDI (soil water deficit index, mm), Tmed (mean annual temperature, °C), VPDsum (mean VPD of summer season, kPa), VPDmed (mean VPD, kPa) and Vol (stand volume, m^3 ha^{-1}). In addition, the type of soil was considered as a factor (Sandy or Ash), due to the clear grouping of the plots between sandy and volcanic ash soils sites ($p < 0.05$).

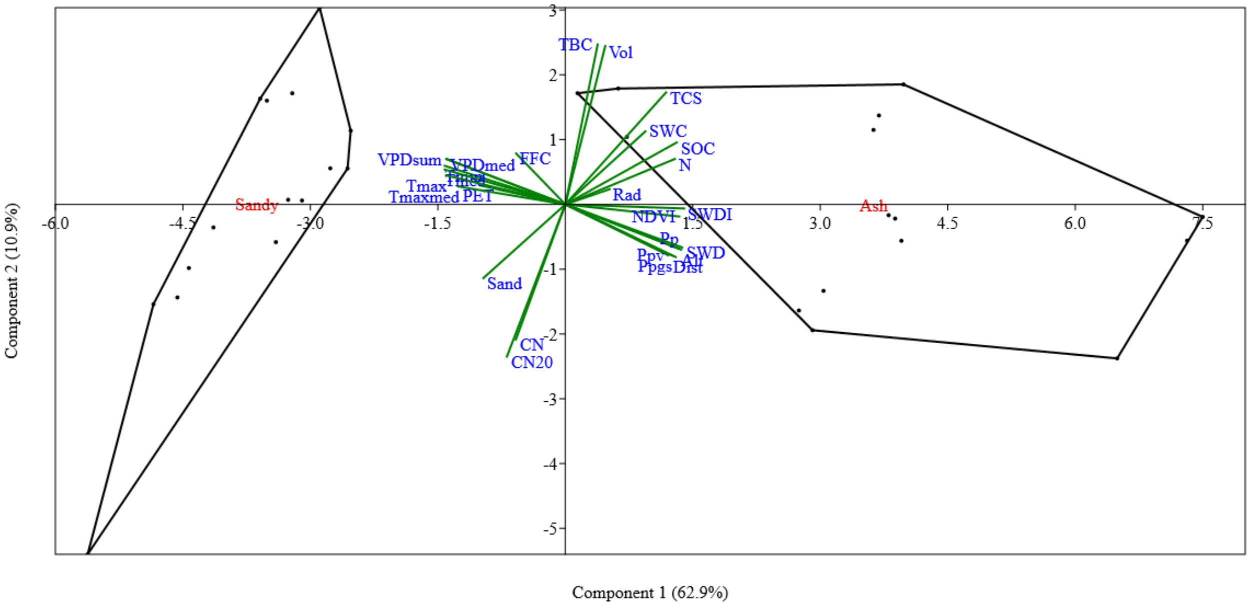


Figure 10. Biplot (principal components 1 and 2) from principal component analysis (PCA) for all evaluated sites. Areas denote groups defined of analysis of similarities (ANOSIM) ($p < 0.05$).

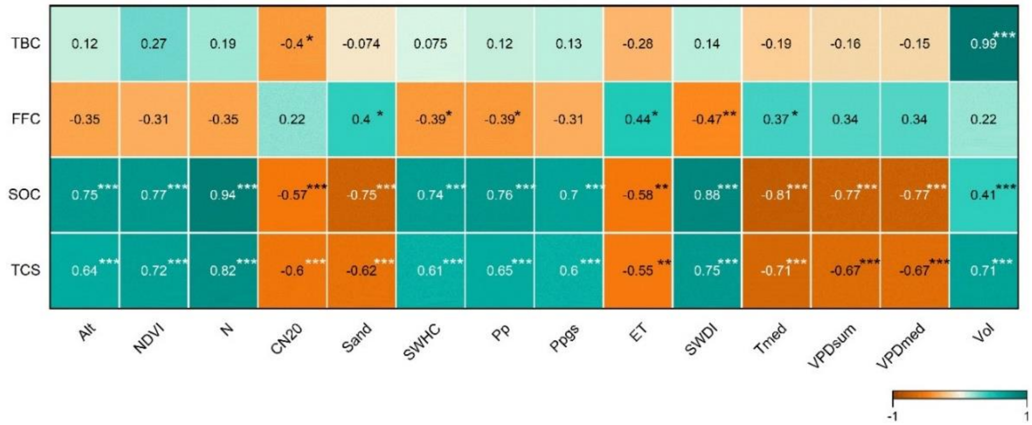
The environmental, soil and site variables obtained from the PCA analysis indicate that all those related to nutritional and water limitations (such as temperature, VPD, evapotranspiration, sand and C:N ratio) were higher in sandy soil type; while those related to growth and productivity of the stand (such as NDVI, precipitation and soil water holding capacity) were higher in recent ash than sandy soil types (Table 3).

Table 10. Mean values and range (minimum and maximum) of environmental, soil and site variables according to soil type (sandy and recent ash soil sites) obtained after Principal Component Analysis (PCA).

Variable	Sandy		Recent ash	
	Mean	Range	Mean	Range
Alt (m.s.a.l)	132.13	106.0 – 172.0	490.33	336.0 – 849.0
NDVI	0.74	0.71 - 0.76	0.79	0.75 - 0.85
N (%)	0.06	0.02 - 0.12	0.260	0.19 - 0.33
C:N20	24.80	16.75 - 58.42	17.36	14.45 - 20.33
Sand (%)	83.09	62.73 - 93.64	55.50	36.05 - 68.43
SWHC (mm)	70.20	19.80 - 175.40	250.04	179.00 - 375.10
Pp (mm)	1115.51	1055.12 - 1182.44	1453.31	1207.76 - 1585.04
Ppgs (mm)	191.70	174.84 - 232.68	292.97	206.20 - 344.04
PET (mm)	1812.89	1794.12 - 1851.76	1779.70	1705.07 - 1835.85
SWDI (mm)	-627.17	-696.34 - -487.04	-76.35	-252.99 - -14.97
Tmed (°C)	13.56	13.35 - 13.65	11.46	9.80 - 12.53
VPDsum (°C)	1.37	1.34 - 1.38	1.20	1.05 - 1.29
VPDmed (°C)	1.15	1.11 - 1.16	0.98	0.85 - 1.07

Alt: altitude; NDVI: normalized difference vegetation index; N: total soil nitrogen; CN20: C:N ratio at 20 cm depth; Sand: soil sand content; SWHC: soil water holding capacity at 1 m depth; Pp: cumulative annual precipitation; Ppgs: cumulative precipitation on the growing season; ET: evapotranspiration; SWDI: soil water deficit index; Tmed: mean annual temperature; VDPsum: mean vapor deficit pressure on the summer season; VDPmed: mean annual vapor deficit pressure; Vol: stand volume

Then, a correlation analysis was carried out between all continuous variables, both predictor (climatic, soil and site characteristics) and dependent (all carbon pools) variables (Figure 3). The carbon stock in total biomass (TBC) presented an evident direct and very high relationship with the stand volume (Vol) (r=0.99, $p < 0.05$), due to the use of allometric equations for both estimates, so the Vol variable was not included in the following multiple regression analyzes for this carbon pool. Another significant variable inversely related to TBC was CN20 ($p < 0.05$). No other predictive variable was significantly related to TBC for correlation analysis. The carbon stock in forest floor (FFC) presented significant and positive correlation with Sand, ET and Tmed, and negative correlation with WCHC, Pp, and SWDI (showing partial relationship with variables related with water stress) ($p < 0.05$). The carbon stock in the mineral soil (SOC) presented significant correlation with all predictive variables ($p < 0.05$), with positive relationships with those variables related to direct water conditions to stand growth (SWHC, Pp, Ppgs, SWDI), soil fertility (N) and stand characteristics (NDVI, Vol) and Alt; while negative relationships were found between SOC with those variables related to drought (VPDsum, VPDmed, Tmed, ET) and most limiting soils (CN20, Sand). Total carbon stock of the stands (TCS) presented significant correlations with all the predictor variables ($p < 0.05$), with correlations like those found for the SOC, showing a great effect of the variables related to water and soil conditions on the carbon stocks of the stands.



	Alt	NDVI	N	CN20	Sand	SWHC	Pp	Ppgs	ET	SWDI	Tmed	VPDsum	VPDmed	Vol
TBC	0.12	0.27	0.19	-0.4*	-0.074	0.075	0.12	0.13	-0.28	0.14	-0.19	-0.16	-0.15	0.99***
FFC	-0.35	-0.31	-0.35	0.22	0.4 *	-0.39*	-0.39*	-0.31	0.44*	-0.47**	0.37 *	0.34	0.34	0.22
SOC	0.75***	0.77***	0.94***	-0.57***	-0.75***	0.74***	0.76***	0.7 ***	-0.58**	0.88***	-0.81***	-0.77***	-0.77***	0.41***
TCS	0.64***	0.72***	0.82***	-0.6***	-0.62***	0.61***	0.65***	0.6***	-0.55 **	0.75***	-0.71***	-0.67***	-0.67***	0.71***

Figure 11. Pearson correlation coefficient (r) between all carbon stocks (TBC: total biomass carbon; FFC: forest floor carbon; SOC: soil organic carbon; and TCS: total stock carbon) and predictor variables (Alt: altitude; NDVI: normalized difference vegetation index; N: total soil nitrogen; CN20: C:N ratio at 20 cm depth; Sand: soil sand content; SWHC: soil water holding capacity at 1 m depth; Pp: cumulative annual precipitation; Ppgs: cumulative precipitation on the growing season; ET: evapotranspiration; SWDI: soil water deficit index; Tmed: mean annual temperature; VDPsum: mean vapor deficit pressure on the summer season; VDPmed: mean annual vapor deficit pressure; Vol: stand volume) derived from PCA test. Non-

significant variables (p > 0.05) are not shown in the correlation matrix. *ns* denoted no significance differences, * denoted significance at $p < 0.05$, and ** at $p < 0.01$.

2.4.3. L*inear models between carbon stocks with climate, soil, stand and site variable*.

To model the total biomass carbon stock (TBC), we performed a first full multiple linear regression with all potentially predictive variables (without considering Vol, due to the use of allometric equations for tree volume and biomass estimates). Despite having an Adj-r^2=0.64, the full model was not significant (p=0.07). Then, following a stepwise process for the potential predictive variables, five variables were included in the reduced model (p < 0.05) (Table 5 and Figure 4a). The model used to predict TBC was (eq. 11):

$$TBC_i = a + b(Alt_i) + c(Sand_i) + d(Pp_i) + e(SWDI_i) + f(Tmed_i) \qquad (11)$$

Where a, b, c, d, e and f are the determined parameters of each predictor variable; i=1, 2, … site.

Table 11. Adjusted coefficients and statistical criteria values for total biomass carbon stock (TBC, Mg ha^{-1}) considering reduced model (by Stepwise approach).

Variable	Parameter	Estimate	Std Error	p value	Adj-R2	RMSE	AIC
	a	5404.64	743.37	0.001	0.71	21.58	184.6
Alt	b	-1.79	0.26	0.001			
Sand	c	-4.3	1.06	0.001			
Pp	d	0.38	0.15	0.027			
SWDI	e	-0.85	0.19	0.001			
Tmed	f	-412.51	58.94	0.001			

Alt= altitude (m.a.s.l.), Sand=sand content in the soil profile (%), Pp=mean annual precipitation (mm $year^{-1}$), SWDI=soil water deficit index (mm); Tmed=mean annual temperature (°C); *S.E.*: standard error; *p*: p-values of regression coefficients; Adj-r^2: adjusted coefficient of determination; RMSE: root mean square error; *AIC*: Akaike information criterion values.

These variables with negative coefficients are associated with limitations to plant growth due to drought conditions or high temperatures (Table 5). Through an analysis of the importance of the model predictor variables on the variability explained, it was possible to observe for TBC, Tmed (mean annual temperature) was the most important variable.

To model the forest floor carbon stock (FFC), we performed a first full multiple linear regression with all potentially predictive variables. This model, as in TBC, despite having an Adj-r^2=0.54, the model was not significant (p=0.15).

Then, following a backward process to model FFC, six predictor variables were included in the reduced model (p < 0.05) (Table 6 and Figure 4b). The model used to predict FFC was (eq. 12):

$$FFC_i = a + b(Alt_i) + c(Sand_i) + d(Pp_i) + e(SWDI_i) + f(Tmed_i) + g(Soil_i) \quad (12)$$

Where a, b, c, d, e, f and g are the determined parameters of each predictor variable; i=1, 2... site.

Table 12. Adjusted coefficients and statistical criteria values for forest floor carbon stock (FFC, Mg ha^{-1}) considering reduced model (by Backward approach).

Variable	Parameter	Estimate	Std Error	p value	Adj-R2	RMSE	AIC
	a	381.83	105.08	0.002			
Alt	b	-0.14	0.04	0.001			
Sand	c	-0.38	0.15	0.002			
Pp	d	0.51	0.02	0.03	0.60	3.38	129.15
SWDI	e	-0.13	0.03	0.001			
Tmed	f	-32.52	8.44	0.001			
Soil(Ash)	g	9.75	2.35	0.001			

Alt= altitude (m.a.s.l.), Sand=sand content in the soil profile (%), Pp=mean annual precipitation (mm year^{-1}), SWDI=soil water deficit index (mm); Tmed=mean annual temperature (°C); Soil(Ash)=dummy variable, that is 1when Soil=Ash or 0 when Soil=Sandy; *S.E.*: standard error; p: p-values of regression coefficients; Adj-r^2: adjusted coefficient of determination; RMSE: root mean square error; *AIC*: Akaike information criterion values.

For FFC model, Alt, Sand, SWDI and Tmed had negative estimated parameters; and Pp with the factor Soil type (with positive value for ash soil) had positive estimated parameters (Table 6). Through an analysis of the importance of the models predictor variables on the variability explained, it was possible to observe for forest floor carbon stock (FFC) the SWDI (soil water deficit index) and Pp (mean annual precipitation) were the most important variables.

For carbon stock in the mineral soil (SOC), the full model was significant in SOC estimates ($p < 0.05$). The variables related with soil properties (SWHC and Sand) revealed the highest importance in the model (with positive and negative effects respectively), followed by the variables related with water stress (SWDI, Tmed and VPDmed, with negative coefficients), and NDVI (relate to stand productivity, with positive coefficient).

For SOC, we fitted two reduced models. Then, a first multiple linear model considered only soil and environmental variables to SOC estimates, the one that considered soil water holding capacity (SWHC) and mean annual temperature (Tmed) was significant and had a good fit (eq. 13) (Table 7).

$$SOC_i = a + b(SWHC_i) + c(Tmed_i) \tag{13}$$

Where *a*, *b* and *c* are the determined parameters of each predictor variable; *i*=1, 2, … site.

And we fitted a second reduced model for SOC, but that included volume plus some significant environmental variable as a predictor. Given that the SWDI is an index that relates precipitation, potential evapotranspiration, and soil water holding capacity, we fitted a multiple linear model considering stand volume (Vol) and SWDI as predictor variables (Table 7 and Figure 4c). The model used to predict SOC was (eq. 14):

$$SOC_i = a + b(Vol_i) + c(SWDI_i) \tag{14}$$

Where *a*, *b* and *c* are the determined parameters of each predictor variable; *i*=1, 2, … site.

Table 13. Adjusted coefficients and statistical criteria values for soil organic carbon stock (SOC, Mg ha^{-1}) considering reduced model.

Variable	Parameter	Estimate	Std Error	p value	Adj-R2	RMSE	AIC
	a	646.63	97.63	0.001			
SWHC	b	0.33	0.08	0.001	0.77	41.23	314.7
Tmed	c	-39.03	7.19	0.001			
	a	204.44	34.59	0.001			
Vol	b	0.19	0.06	0.001	0.81	36.57	306.1
SWDI	c	0.24	0.02	0.001			

SWHC=soil water holding capacity (mm); Tmed=mean annual temperature; Vol=stand volume (m^3 ha^{-1}), SWDI=soil water deficit index (mm); *S.E.*: standard error; *p*: p-values of regression coefficients; Adj-r^2: adjusted coefficient of determination; RMSE: root mean square error; *AIC*: Akaike information criterion values.

Between both models, the reduced model for SOC predictions with Vol and SWDI predictor variables, had the strongest and significant estimate of SOC (Adj-r^2=0.81, $p < 0.05$) (Table 7). It was observed that the WSDI variable was twice as important as the Vol variable with respect to the importance value for this model. However, the model for SOC predictions with SWHC and Tmed had a slightly lower coefficient of determination, and higher error and BIC. However, it is interesting model to consider due to its quick and easy implementation to estimate soil carbon stock.

Similar to SOC model, for total carbon stock of stands (TCS) the full model was significant in estimating TCS ($p < 0.05$). Among all predictive variables, Vol had the highest importance in the full model, followed by SWHC and SDWI. As in the SOC modeling, we fitted two reduced models. A first multiple linear model considered only soil and environmental variables to TCS estimates, the one that considered soil water holding capacity (SWHC) and evapotranspiration (ET) was significant and had a good fit (eq. 15) (Table 8).

$$SOC_i \ = a + b(SWHC_i) + \ c(ET_i) \tag{15}$$

Where *a*, *b* and *c* are the determined parameters of each predictor variable; *i*=1, 2, … site.

Then, we fitted a second reduced model for TCS, considering VOL and SWDI as predictor variables for TCS estimates (eq. 16) (Table 8 and Figure 4d):

$$TCS_i \ = a + b(Vol_i) + \ c(SWDI_i) \tag{16}$$

Where *a*, *b* and *c* are the determined parameters of each predictor variable; *i*=1, 2, … site.

Table 14. Adjusted coefficients and statistical criteria values for total carbon stock of stand (TCS, Mg ha^{-1}) considering reduced model.

Variable	Parameter	Estimate	Std Error	p value	Adj-R2	RMSE	AIC
	a	2445.96	602.61	0.001			
SWHC	b	0.48	0.17	0.001	0.54	69.57	346.2
ET	c	-1.18	0.33	0.001			
	a	211.88	34.26	0.001			
Vol	b	0.55	0.06	0.001	0.88	36.23	307.2
SWDI	c	0.22	0.02	0.001			

SWHC=soil water holding capacity (mm); ET=evapotranspiration; Vol=stand volume (m^3 ha^{-1}), SWDI=soil water deficit index (mm); *S.E.*: standard error; *p*: p-values of regression coefficients; Adj-r^2: adjusted coefficient of determination; RMSE: root mean square error; *AIC*: Akaike information criterion values.

This reduced model for TCS predictions, with Vol and SWDI predictor variables, had a high coefficient of determination and significant estimates (Adj-r^2=88, $p < 0.05$) (Table 8). WSDI variable was slightly more important than Vol variable with respect to the importance value to the TCS model. However, the model that considers SWHC and ET, despite having lower Adj-R^2 (0.54) and higher error and AIC, is interesting for its simple implementation. This model also indicated that total C stock of the stand is positively related to the soil capacity to store water, with a negative coefficient for evapotranspiration. In this way, both reduced models show how total C stock of the stands is directly related to both stand productivity and site water conditions, and negatively to water stress.

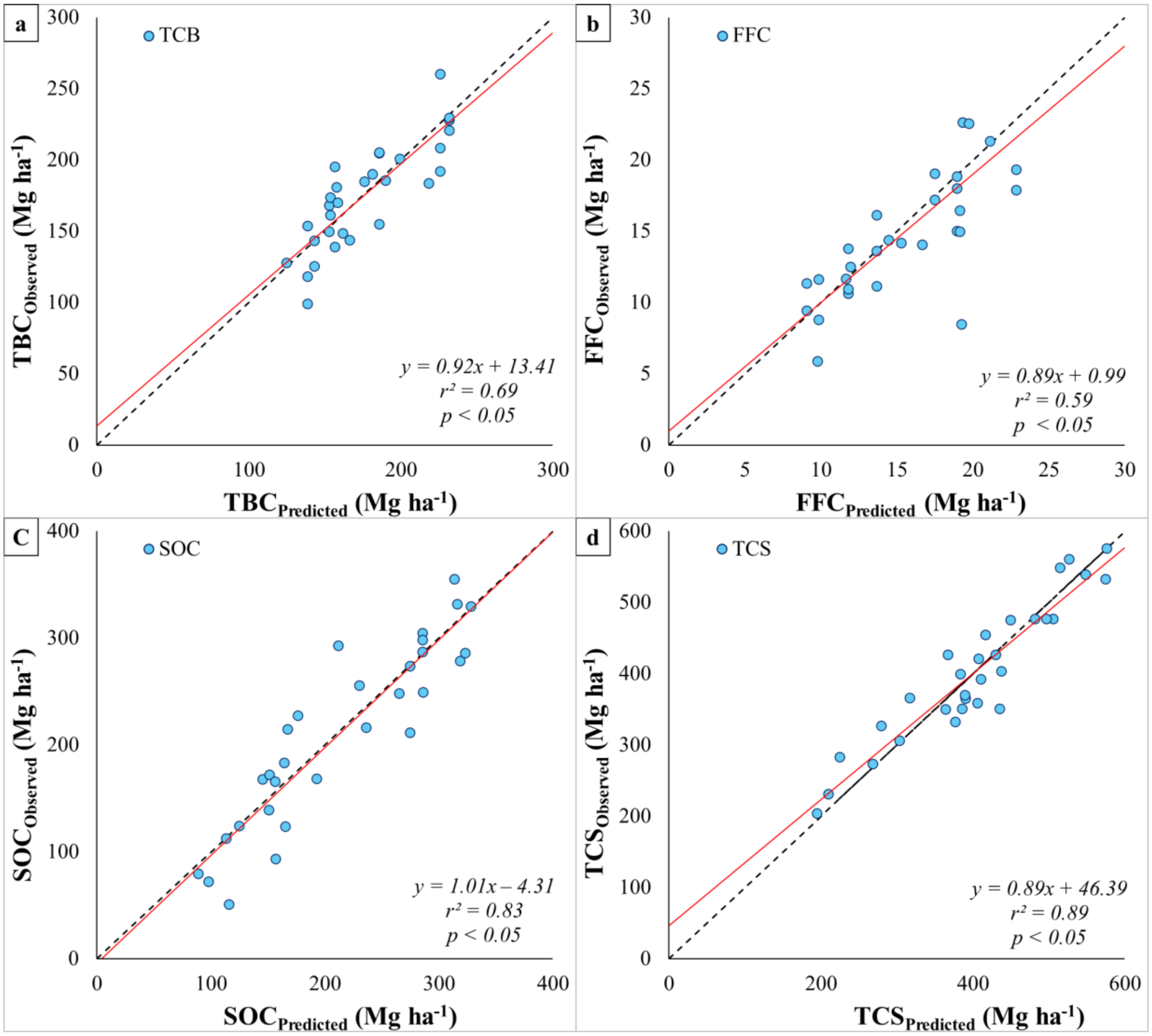


Figure 12. Relationship between observed and predicted carbon stocks using adjusted models for: total biomass carbon stock (TBC) (a); forest floor carbon stock (FFC) (b); soil organic carbon stock (SOC) with Vol+SWDI variables (c); and total stand carbon stock (TCS) with Vol+SWDI variables (d). In each panel, the dashed line denotes a 1:1 relationship.

2.5.DISCUSSION

High carbon stocks were found in radiata pine plantations at pre-harvesting age evaluated in sandy and recent ash soil sites, with a tendency for sites with lower water and nutritional limitations to reach the largest total carbon stock (Kranabetter, 2009; Olmedo *et al.*, 2020) (Table 3). Our results showed that stand carbon stock of radiata pine plantations is strongly related with climatic variables (Tables 5, 6, 7, and 8 and Figure 2 and 3). Temperature affects tree growth and decomposition and respiration rates, impacting on the forest productivity and carbon capture into biomass, mineral soil, and forest floor (Cooper *et al.*, 2017; Sun *et al.*, 2023; Zhao *et al.*, 2024). While, precipitation and water availability showed high positive correlation with stand growth, biomass and SOC (Becknell *et al.*, 2012; Alvarez *et al.*, 2013; Ojeda *et al.*, 2018), with water stress being a clear limiting factor in the accumulation of carbon accumulation in the evaluated radiata pine stands.

Respect to total biomass carbon stock (TBC), there was no effect of soil type on the total biomass carbon stock nor in the cumulative volume; but the diameters (DBH) and heights (total and dominant heights) were higher in the recent ash soils compared to the sandy soil sites. Although there were no differences in the C stock in the biomass at the stand level (Table 3), there were differences in cumulative carbon at the individual tree level, with 25.5 % more C in tree biomass on recent ash soils (0.74 Mg tree^{-1}) than in sands (0.59 Mg tree^{-1}) sites. Other studies that have evaluated productivity in radiata pine stands at rotation age in Chile have also shown higher growth in diameters, heights and stand volume in recent ash and red clay soils sites compared to sandy soils sites (Rubilar *et al.*, 2023). Our results on TBC were similar (but slightly lower) to those reports by Olmedo *et al.* (2020) for radiata pine stand in Chile of similar age and management schemes for sandy soils (181.2 Mg ha^{-1}) and ash soil (214.0 Mg ha^{-1}). However, the type of soil, specifically related to texture, has been described as a key factor in the growth of stands (Flores and Allen, 2004), and therefore, in the accumulation of carbon in both aboveground and belowground biomass (Olmedo *et al.*, 2020). And this could be observed in the adjusted linear model (Table 5), in which the sand content has a negative coefficient, indicating that soils with a lower percentage of silt and clay will present lower carbon accumulation in the total biomass of the stand. In studies that have evaluated the productivity and growth of *Pinus radiata* stand in Chile, they have shown that environmental variables such as precipitation have a direct effect on growth and leaf area index (LAI) in a gradient of sites, while the soil water deficit has a direct inverse effect on both variables (Alvarez *et al.*, 2013; Ojeda *et al.*, 2018). This is related to the predictor variables of the linear model fitted for TBC (Table 5), in which precipitation was the only variable with a positive coefficient, indicating than an increase in water availability increases stand growth and biomass. And on the contrary, the variables related to water stress, such as temperature, sand percentage and soil water deficit, presented negative coefficients, indicating that, as was observed on other studies, minor water availability reduce LAI and therefore growth and biomass (Flores and Allen, 2004; Alvarez *et al.*, 2013). These results are related to what was found by Olmedo *et al.* (2020), in that when evaluating the biomass carbon stock by climatic zone, the most restrictive sites in terms of water availability presented lowest C stock in both in above and belowground biomass.

Soil organic carbon stock (SOC) was higher on volcanic ash soils (281.4 Mg ha^{-1}) than in sandy soils (139.9 Mg ha^{-1}) sites (Table 3). Our results, both from the correlation analyzes and from the fitted linear model (Figure 3 and Table 6), clearly indicate that SOC is positively influenced by variables related to soil nutrients and water storage (total nitrogen and clay and silt content), precipitation, and stand productivity (by positive correlation with stand volume and LAI); while variables related to water stress such as VPD, evapotranspiration, temperature, high sand content, and high C:N ratio and stability of organic matter were related negatively with SOC. In radiata pine plantation, a direct relationship has been observed in the increase in soil respiration (CO_2 flux) with temperature (Bown and Watt, 2016), which could be related to the fact that SOC in our study presented a negative correlation with temperature ($r = -0.81$, $p < 0.05$), which could be related to the increase in organic matter decomposition due to this environmental variable (Prescott and Vesterdal, 2021). According to our analyses, soil texture affects soil attributes such as water storage capacity, soil carbon stock, and the stand growth (related to total carbon biomass of the stand). Some soil properties, such as the aggregation of its particles, the clay and silt content, and the mineralogy of the clays and their specific surface area are key characteristics than affect the soil carbon in the mineral soil (Wiesmeier *et al.*, 2019; Paula *et al.*, 2021; Georgiou *et al.*, 2022; Pinto *et al.*, 2023). Those factors display different capacities for accumulation, stabilization, and protection of soil organic matter (SOM) (Torn *et al.*, 1997; Denef and Six, 2005; Prescott and Vesterdal, 2021). Furthermore, clay content contributes to retention and availability of water and nutrients in the soil, aggregation, and formation of micropores, which promotes long-term organic matter accumulation in the soil, which improve stand productivity and soil carbon stock (Bronick and Lal, 2005; Pinto *et al.*, 2023). Our results, like the studies by Olmedo *et al.* (2020) and Crovo *et al.* (2021) who evaluated the SOC in radiata pine plantations in Chile, suggests that, due to the clay type and higher content of clay+silt in recent volcanic ash, a high organic matter content and available water is stored and maintained over time in those soils (Matus *et al.*, 2014; Soto *et al.*, 2019; Paula *et al.*, 2021; Georgiou *et al.*, 2022). Recent volcanic ash soils, as Andisols, present secondary minerals, including short-range-order (SRO) minerals (Wiesmeier *et al.*, 2019), as allophane and imogolite (Garrido and Matus, 2012). These clay type and soil aggregates, with high specific surface area and variable charge, provided a physical and chemical protection and stabilization for SOM (Torn *et al.*, 1997; Garrido and Matus, 2012; Wiesmeier *et al.*, 2019); evidencing that Andisols are among the most productive soils in the world (Shoji *et al.*, 1993). On the contrary, sandy soils have lower potential to storage high soil carbon stock because their coarse texture, larger pore size, and lower water and nutrient availability that affects stand productivity but also speed of decomposition and storage of organic matter (Rubilar *et al.*, 2013; Chendev *et al.*, 2014; Olmedo *et al.*, 2020; Ouimet *et al.*, 2023; Pinto *et al.*, 2023).

SOC presented a high estimate with the linear model fitted with volume and soil water deficit index as predictor variables (Adj-r^2=0.81, $p < 0.05$) (Table 7 and Figure 4c). Therefore, as mentioned previously, the soil water available is a factor of great importance in the storage of carbon in the soil, a variable that also presented greater importance value in the model. A good estimate of this C stock is of great importance, because in our study, it was the most important C pool for recent ash soil sites, and the second most important C stock for sandy soil sites (Table 3). Furthermore, in many studies it has been found that SOC is the component with the highest proportion of the C pool in forests (Houghton, 2007; Ola *et al.*, 2024). Therefore, having a model that considers both the stand volume and soil and site water characteristics will be of great help to quantify SOC up to one meter deep. In our fitted models to SOC estimates, which combine soil characteristics, climate and stand productivity, the predictor variables are easy and quick to obtain, which will allow good estimates of this carbon stock. And as Paula *et al.* (2021) indicated, climatic variables are of great importance for the estimation of C, but soil characteristics must also be considered improve SOC estimates.

The lowest carbon stock in our study was found in the forest floor, and significant differences were observed between soil types (Table 3). Interestingly, sandy soils sites showed higher estimates (18.6 Mg ha $^{-1}$) compared to recent volcanic ash soils (13.4 Mg ha^{-1}) sites. Furthermore, this carbon stock was the only one that did not correlate with the stand productivity ($p > 0.05$). The mean values of this carbon stock were similar to those recorded in other studies in radiate pine stands, with 12.4 to 16.7 Mg ha^{-1} in New Zealand (Oliver *et al.*, 2011); an average of 14.8 Mg ha^{-1} (on a range of 2.5 to 42.1 Mg ha^{-1}) in Spain (López-Senespleda *et al.*, 2021); but our mean values were higher than reported in Argentina with 8.3 Mg ha^{-1} (Ferrere and Lupi, 2023). Olmedo *et al.* (2020) estimated lower mean values for the forest floor carbon stock than those of our study, and inversely to our results, it presented a higher carbon stock in recent ash soil (9.1 Mg ha^{-1}) than in sands soil sites (7.1 Mg ha^{-1}). In all the studies, forest floor is the lowest proportion of carbon stock in adult stands, which has been reported about 5 % of total carbon stock in world forest (Pan *et al.*, 2011). However, forest floor is a key component in the site carbon and nutrient dynamic, but also in its contribution to soil mineral C and its role as a nutrient reservoir for successive rotations (Prescott and Vesterdal, 2021; Díaz Villa *et al.*, 2022). In our study, the adjusted model to estimate the FFC presented negative coefficients for variables related to water stress, soil water deficit index and mean annual temperature, in contrast to precipitation (Table 6). López-Senespleda *et al.* (2021) estimated forest floor carbon stocks in Spain, using linear and Random Forest models, and found some climatic and environmental significant variables similar to those recorded in our study, such as precipitation and temperature, which have been reported to have a significant impact on decomposition rates of the forest floor (Aerts, 1997; Parton *et al.*, 2007; Garcia-Palacios *et al.*, 2013). Many studies have reported an increase in litter decomposition with increasing temperature and precipitation (Aerts, 1997; Zhang *et al.*, 2008). Another significant variable found in our adjusted model and with negative coefficients was altitude, which could be due to the inverse relationship of this variable with temperature, decreasing decomposition rates in colder areas (higher altitude) and increasing forest floor decomposition in warmer areas (Simmons *et al.*, 1996). At higher altitudes, has been reported a higher forest floor in forest of United States (Woodall *et al.*, 2012), which was contrary to our results. In our study, a highest forest floor carbon stock was found in the sandy soil sites, in which although these sites have higher mean temperatures than recent ash soil sites, they are more limiting sites in available water (with a stronger soil water deficit index), which could be related to the fact that greater aridity decreases the litter decomposition rates (Bravo-Oviedo *et al.*, 2017). Therefore, in our evaluated sites, due to the higher soil water availability and precipitation in the recent ash sites, there could have been a effect on the decomposition rates of forest floor, resulting in a lower carbon stock than in sandy soil sites. Because lower humidity and higher temperature have been observed to decrease litter decomposition rates (Ostertag *et al.*, 2008) due reduced biological activity of soil organism (Prescott and Vesterdal, 2021), which could explain the results of higher biomass in our sandy soil sites. Therefore, in the ash soils sites, organic matter can be incorporated more quickly into mineral soil, being associated, and protected within aggregates or associated with mineral clay particles (Prescott and Vesterdal, 2021).

2.6. CONCLUSSIONS

Soil type was a key factor in carbon stocks in the adult radiata pine stands evaluated. We found significantly more total C in the recent ash soil than in the sandy soil sites. In both types of soil, a high C stock was found in the mineral soil up to 1 m deep. The forest floor represented the lowest carbon pool of the stands in both soil types. The climate, soil and stand productivity variables were highly related to all C stocks in our radiata pine stands, being good predictors in our adjusted models, with high significance estimating each carbon stock (biomass, forest floor, mineral soil, and total carbon stock). Those variables related to soil water availability (silt and clay content, and soil water holding capacity), annual precipitation and stand productivity (stand volume and NDVI) were strongly and directly related to all carbon stocks, while those variables related to drought and water stress, such as temperature, VPD, soil water deficit index, evapotranspiration and higher sand content decreased the C stock of stands. Those results indicate that increasing growth and stand productivity could increase the potential capacity of forests to capture and storage carbon. Our developed models to estimate C stocks presented good fits, with variables that were easy to acquire, measure and sample, which could help in the analysis of estimating the effects of different scenarios of climate change on forests.

3. CONCLUSIONES

El tipo de suelo fue un factor clave en el stock de C en los rodales de *Pinus radiata* evaluados, siendo en los sitios con suelo de trumao que en los sitios de arena. En ambos tipos de suelo se encontró un alto SOC, siendo el principal stock de C en los sitios de trumao, y el segundo en los sitios de suelo de arena; lo que enfatiza la importancia de incluir las evaluaciones del C en el suelo mineral hasta 1 m de profundidad. El piso forestal representó la menor proporción del stock de C en ambos tipos de suelo, aunque es importante por el aporte de nutrientes y materia orgánica al suelo. Se observó una débil relación entre la productividad del rodal con el SOC y TCS, la cual aumentó fuertemente al considerar el efecto del tipo de suelo como variable *dummy*. Las variables relacionadas con la disponibilidad de agua en el suelo, la precipitación y la productividad del rodal (volumen y NDVI) estuvieron fuerte y directamente relacionadas con todos stocks de C; mientras que aquellas variables relacionadas con la sequía y el estrés hídrico, como la temperatura, el índice de déficit hídrico del suelo, la evapotranspiración y el mayor contenido de arena disminuyeron el stock de C de los rodales. Nuestros modelos desarrollados para estimar stocks de C presentaron buenos ajustes, con variables fáciles de adquirir, medir y muestrear, lo que ayudará en el análisis de modelado y estimación de los efectos de diferentes escenarios de cambio climático en los bosques.

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