Empowering landowners to combat climate change: the economic case for forest carbon supply at the stand level

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Abstract

The objective of this study was to analyze the effect of extending rotation at the stand level in private landowner of *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata* established in contrasting productivity zones. The analysis also evaluates the impact of uncertainty in financial risk considering variations in the price per Mg of CO_2 stored, costs of silvicultural activities, wood products yield using the ad-hoc simulator growth model and the discount rate. Deterministic results show that lower productivity environment the rotation age can be extended 7 or more years in EUGL and 6 or more in EUNI, with respect to the 12-year baseline. Extending PIRA rotation age resulted in a negative CO_2 NPV, implying that a decision made at establishment to extend the harvest age beyond 22-years baseline will not increase financial returns, when aiming at potential payments for environmental services based on carbon storage. Sensitivity analysis shows that the uncertainties of the stored CO_2 price, pulpable product and discount rate are the main contributors to the total variance in the 13-year NPV of both *Eucalyptus* species. The uncertainty in price of captured CO_2 contributes more than 50% in either species, with pulpable product and discount rate contributing more than 16 and 4%, respectively.

Highlights

- Non-industrial forest landowners established in low-productivity environments can take advantage of payments for ecosystem services to increase their income.
- Payments for services are based on the additional carbon during the deferred rotation age.
- Payments for environmental services can change the choice of which tree species to produce.
- Consolidating a market for payments for ecosystem services will promote the entry of Owners of non-industrial forest lands into this market.

Introduction

Atmospheric CO_2 increase is the main cause of climate change, likely to have a great impact on the environment and economic development in many parts of the world. Forests have a primal role in absorbing CO_2 and storing it as wood or in the soil, reducing its concentration, helping to slow down the greenhouse. Therefore, increasing the number and size of forests through afforestation or reforestation is an alternative to reduce or counteract the amount of CO_2 in the atmosphere (Law et al., 2018). Thus, reforestation and afforestation are among the most promising natural climate solutions in terms of carbon sequestration (Bastin et al., 2019), and associated co-benefits (Schulte et al., 2021). Forests, including forest plantations, cover approximately 3,997 Gha worldwide and store large amounts of atmospheric CO_2, which according to Harris et al. (2021) were a net carbon sink of -7.6 ± 49 $GtCO_2$ yr^{-1}.

Although planted forests are primarily intended to produce timber for commercial purposes, they are increasingly recognized for their environmental benefits like mitigation of land degradation, their potential to ameliorate climate change and their ability to enhancement biodiversity (Nambiar, 1999). Thus, fast-growing planted forests represent an interesting alternative for developing carbon sequestration projects, because young forests (in full growth stages) store carbon at very high rates (Wright et al., 2000).

In Chile, the potential of forests planted with fast-growing species in relation to carbon sequestration is interesting. Although the country has a competitive timber market and a Climate Exchange that supports the design and development of greenhouse gas emission reduction projects, there is only an incipient carbon market, which impedes the supply of forest carbon from large private landowners as a climate mitigation tool. At the same time, using fast-growing species is a key component of Chile's Nationally Determined Contributions (NDC) to limit global warming to well below 2, compared to pre-industrial levels (Gobierno de Chile, 2020).

Currently, forest plantations exceed 2.3 million ha, out of them, *Pinus radiata* D. Don (PIRA) holds the largest area, with 55.98% coverage, followed by eucalyptus plantations with 36.82%, where *Eucalyptus globulus* Labill (EUGL) and *Eucalyptus nitens* (Deane and Maiden) Maiden (EUNI) stand out with 25.02% and 11.79% of the total INFOR (2021). Only 34.4% of plantations area -around 697,579 ha, is managed by small and medium landowners, where 69.3% is maintained by the segment of small owners with 483,831 ha.

Pan et al. (2011) argue that decisions in forest management practices can influence C uptake and storage in woody biomass and soils. Thus, in recent decades, interest has developed in reducing the frequency of forest harvesting (also referred to as "extended rotations"), with the purpose of favoring the maintenance and development of high levels of *in situ* forest C storage (West et al., 2019; Law et al., 2018; Balboa-Murias et al., 2006).

Most of the existing literature studies are species with longer rotation periods (Kärenlampi, 2021; Harmon and Marks, 2002; Foley et al., 2009; Roberge et al., 2016) and case studies and comparative analyses of fast-growing tree species with short rotation periods are scarcely reported. Examples of the latter are findings by West et al. (2019) on *Eucalyptus* sp., *Acacia* sp., *Pinus* sp. and *Tecton*a sp. showing decreasing carbon sequestration yields with increasing carbon payments and, as well as the study in radiata pine and maritime pine by Balboa-Murias et al. (2006) that showed how increasing rotation age and site quality and decreasing in thinning intensity, resulted in increases in total C stocks of aboveground and aboveground biomass.

In Chile, *Eucalyptus* spp and PIRA have enormous carbon sink potential, occupying an important position in the forest carbon sink, becoming the main forest carbon sink (Olmedo et al., 2020). The species are planted forests in the center-south of the country, with important timber production and benefits, ecological and social, and play an important role in the national economy (Tricallotis et al., 2018).

Carbon trading realizes the ecological benefits of forests through carbon subsidies and monetizes the ecological functions of forests (Streck, 2020). The comprehensive benefit based on carbon sink benefit has become the main body of carbon sink wood composite management. Analyzing the impact of changes in economic factors on comprehensive benefit, timber benefit and carbon sink benefit has important practical significance for realizing multiple benefit management and optimal forest management.

However, afforestation rates have declined considerably and the willingness of forest producers to afforest has weakened due to the loss of government incentives, which has affected to some extent the sustainable development of existing plantations. Then, the possibility of incorporating new and existing forest owners into carbon trading makes the ecological benefits of forests a reality through carbon stream payment, which monetizes the ecological functions of forests. One way to achieve this is by converting the forest's benefits into carbon credits under existing standards such as the Verified Carbon Standard (VCS). In the VM0003 methodology, VCS quantifies the greenhouse gas emission reductions and removals generated from improving forest management practices to increase the carbon stock on land by extending the rotation age before harvesting. And in this way, increasing the average carbon stock on the land and removing more emissions from the atmosphere (Ecotrust, 2012).

Estimating the monetary value of carbon stored or fixed can have an impact on the way forests are evaluated for fiscal policies, in order to calculate optimal environmental taxes or subsidies (Ovando et al., 2010). Thus, it is important to analyze the impact of changes in economic factors on integrated benefits, i.e., timber benefits and carbon sink benefits, to achieve optimal forest management with multiple benefits. Thus, the objective of this study was to analyze the effect of extending rotation at the stand level in private landowner of *Eucalyptus globulus*, *Eucalyptus nitens* and *Pinus radiata* established in different productivity zones. The analysis also considers variations in the price per ton of carbon stored and in the discount rate.

Material and methods

Description of the study area

The study considers information on the area of industrial forest plantations established in the country. The area occupied by plantations presents a great variability in climate, topography, and soils, and located in the central zone of Chile, from the administrative regions of Libertador Bernardo O'Higgins (latitude 33°55) to Los Lagos (latitude 41°30). Concentrated in the regions of Maule, Ñuble, Biobío and La Araucanía, where 77.9% of the national area of all species, 86.9% of *P. radiata* plantations (PIRA), 77.4% of *E. globulus* plantations (EUGL) and 66.4% of *E. nitens* plantations (EUNI) are located.

Simulation and projection of growth in volume (wiz)

The Chilean growth and yield initiative divides plantation areas into 12 growing zones. Each one of these zones has different growth and yield systems (Universidad de Concepción, 2013). For EUGL and EUNI, growth data from three growth zones (i.e., zones 1, 2 and 3) were used. The volume yield of only one potential product (i.e., pulpwood) between 1 and 20 years for 3 contrasting productivity soil-site environments (i.e., 20, 25 and 30) was generated with the *Eucasim Simulator Version* 2020.11.26.

Management was not considered for any of the species. Total and component biomass for individual trees was obtained using the biomass allometric functions developed by (Sandoval et al., 2022a).

For PIRA, growth data from growth zone 10 was used. This area has a wide latitudinal range including narrow variation in climatic conditions, but somewhat common soil properties over the plantation range. The volume yield of six potential products between 1 and 30 years for four contrasting productivity soil-site environments (i.e., site index 23, 23, 29 and 32) were generated with the *Insigne Simulator Version* 2020.11.26 (Table 1), considering variations of management schemes according to the site (Table 2). Total and component biomass for individual trees was obtained using the biomass allometric functions developed by Sandoval et al. (2022b)

Table 1
Description of the potential products to be obtained from the *P. radiata* stands.

Product	Minor diameter (cm)	Length (m)
Pruned	32	5,10
Pruned	32	4,10
Pruned	32	2,60
Without pruning	28	4,10
Without pruning	16	3,30
Pulp	8	2,44

Table 2
Description of management regimes.

Treatment	Management		
	Intensive (26-29-32)	Multipurpose (26-29-32)	Pulp (23-26-29-32)
First pruning	5 year / 700 trees / 1.9 m	6 year / 700 trees / 2.1 m	
Second pruning	6 year / 700 trees / 2.8, 4.0, 4.6 m by SI	8 year / 400 trees / 4.5 m	
Tirth pruning	7 year / 700 trees / 3.9, 5.3, 5.5 m by SI		
Precommercial thinning	5 year / 700 trees	6 year / 700 trees	8 year / 700 trees
Commercial thinning	11 year / 450 trees	12 year / 450 trees	

* Site index in parentheses.

Quantification of atmospheric carbon stored

The optimal rotation age depends on forest growth and economic variables, such as the price of forest products, inputs and the discount rate (Faustmann, 1849). To estimate the convenience of extending the optimal rotation age in the cultivation of the three species under study, the theoretical framework proposed by West et al. (2019) was followed. For this work, the model of Faustmann (1849) was adapted to include the effects of payments for environmental services based on stored carbon on the optimal rotation age of forest plantations, assuming that payments occur at the end of the harvesting cycle and are based on the additional stock of carbon stored during the extension of the rotation relative to an optimal management scenario without carbon incentives.

Calculations of the maximum NPV incorporated the discount rate, the type, volume and price of the products, the price per Mg CO_2 stored, the carbon stored in the tree biomass, and the administrative, silvicultural treatment and monitoring costs. In this way, first a baseline carbon stored through the optimal rotation in the absence of payments for ecosystem services (PES) was established for each species productivity environment (Eq. 1).

$$\max \mathrm{NPV}_z\,[T] = \left(\sum_{i=1}^{n}\left(p_{w_i} \times w_{iz}(T) - R\right)\right)\frac{1}{e^{rT}-1}$$

1

where max NPV $_z[T]$ is the maximum net present value of the *i*-th productivity zone at time *T* ($ ha^{-1}), *T* is the optimal rotation age (years), p_{wi} is the timber price of the *i*-th product ($), $w_{iz}(T)$ is the commercial volume of the *i*-th product in the *i*-th productivity zone at time *T* (m^3 ha^{-1}), *R* represents reforestation and management costs ($ ha^{-1}) (under the simplified assumption of pre-existing plantations, i.e., no initial planting costs occur without immediate harvest revenues) and *r* is the discount rate (%).

In this study, we worked with rotation age considering only the best utilization of the fiber for industrial purposes is achieved. Thus, the rotation age for *E. globulus* and *E. nitens* was assumed to be 12 years old and for *P. radiata* 22 years old.

Then, PES was included in Eq. 1 to reward landowners based on the additional carbon stock (Mg CO_2) resulting from extended rotations, under the assumption that PES occurs at the end of the extended rotation (i.e., ex post). The adapted Faustmann model based on our PES framework is given by:

$$\max \mathrm{NPV}_z[T_\tau] = \left(\begin{array}{c}\sum_{i=1}^{n}\left(p_{w_i} \times w_{iz}(T_\tau) - R - M + p_c\theta\left(AGB_{T_\tau} - AGB_T\right)\right. \\ -c_c\theta(AGB_{T_\tau} - AGB_T)\end{array}\right)\frac{1}{e^{rT_\tau}-1}$$

2

where max $NPV_z[T_\tau]$ is the maximum net present value of the *i*-th productivity zone at the new rotation age T_t, *M* is the cost for monitoring and verification associated with carbon offset projects ($ ha^{-1}), applied according to the voluntary carbon market standards (Ecotrust, 2012); p_c is the payment received per Mg of additional CO_2 stored by extending the rotation length to T_τ ($), *cc* are the stock exchange commission fees for placing carbon credits on the market and, θ expresses the conversion of total biomass to Mg CO_2. It is assumed that verification and monitoring costs are disbursed one year before the contract and climate exchange commission fees are disbursed from the first year of the extended rotation.

$$\theta = \varphi \frac{44}{12}$$

3

where φ is the carbon fraction of wood and, 44/12 is the carbon to CO_2 conversion factor based on molecular weights.

Using all biomass accumulation (Mg ha^{-1}) and CO_2 stored information calculated from each productivity environment, a deterministic and stochastic assessment analysis was carry out. The economic model spanned from plantation establishment to the sale of biomass at farm gate. Field operational costs corresponding to each silvicultural activity and their timing of application are presented in Table 3.

Table 3
Investment and production costs.

Item	Year	Value			Unit
		EUGL	EUNI	PIRA	
Clearing land	0	463.00	96.00	100.00	$ ha^{-1}
Site preparation	0	292.00	257.00	186.00	$ ha^{-1}
Residues management	0	346.00	113.00	160.00	$ ha^{-1}
Seedlings acquisition and planting	0	501.00	264.00	377.00	$ ha^{-1}
Chemical weed control	0	104.00	201.00	190.00	$ ha^{-1}
Fertilization	0	83.00	79.00	26.00	$ ha^{-1}
Moisture control	0	53.00	11.00	3.00	$ ha^{-1}
Lagomorph control	0	361.00	11.00	20.00	$ ha^{-1}
First pruning	see Table 2			298.70	$ ha^{-1}
Second pruning	see Table 2			198.40	$ ha^{-1}
Third pruning	see Table 2			200.30	$ ha^{-1}
Precommercial thinning	see Table 2			149.40	$ ha^{-1}
Commercial thinning	see Table 2			12.70	$ m^{-3}
Administration	each year	10.00	10.00	10.00	$ ha^{-1}
Harvesting cost	at rotation age	7.05	7.05	7.05	$ m^{-3}
Transport	at rotation age	10.55	10.55	10.55	$ m^{-3}
Stored CO_2 price	at rotation age	10.00	10.00	10.00	$ Mg^{-3}
Exchange commission fees*	extended rotation	0.50	0.50	0.50	$ Mg CO_2^{-1}
Verification and monitoring	each contract year	10.00	10.00	10.00	$ ha^{-1}
Poduct_pr5.0	at rotation age			108.00	$ m^{-3}
Poduct_pr4.10	at rotation age			98.00	$ m^{-3}

Item	Year	Value			Unit
		EUGL	EUNI	PIRA	
Poduct_pr2.60	at rotation age			87.00	$ m^{-3}
Poduct_wp4.10	at rotation age			52.00	$ m^{-3}
Poduct_wp3.30	at rotation age			44.00	$ m^{-3}
Poduct_pu2.44	at rotation age	48.16	40.52	33.79	$ m^{-3}

Source: Local contractors, forest companies and Santiago Climate Exchange* (SCX, 2022).

The deterministic assessment allowed calculations of a profitability indicator for the maximum net present value (NPV) associated with each of the species established in each environment. For all estimates a 0% annual inflation was considered for the NPV. To represent the results of the stochastic evaluation, we used the simulation of silvicultural management without environmental payments that obtained the lowest and highest deterministic NPV for each species under study at the optimal rotation age. The deterministic evaluation with environmental payments was performed for each year of rotation age extension. Only the uncertainties of extending the rotation by one year with environmental payments are shown in the results. Oracle's *Crystal Ball* Release 11.1.0.3.0.000 software was used to run Monte Carlo simulation. The value drivers identified from the project's sensitivity analysis were selected as the input variables. To account for uncertainty in these value drivers, suitable probability distribution functions (PDF) were assigned. Variables subject to uncertainty treated in the Monte Carlo simulation are presented in Table 4. Parameters ranges were established using local contractors' costs. Monte Carlo simulation was carried out for the most profitable species-productivity environment management. To calculate the probability distribution for NPV, 1500 iterations were run following the methodology proposed by Gottfried (1984).

The assumptions on the data in the simulation sets were modeled as: Weibull distribution function for the variation in crop productivity (growing stock Mg ha^{-1}) (Sandoval et al. (2012), lognormal distribution for prices and silvicultural costs ($ ha^{-1}) and uniform distribution for discount rate was considered (dimensionless) (Woolf et al., 2016). We also include a reduction of the discount rate from the point of view of intergenerational equity, given the length of the forest project (Hepburn and Koundouri, 2007).

Results

Aerial carbon increment

To represent the results of stored CO_2 increment, the simulations that obtained the lowest and highest biomass yield were used (Fig. 1). Cumulative biomass yield varied among soil-sites environment and species. As expected, both *Eucalypts* species accumulated higher total biomass per hectare in all sites.

The lowest growth was recorded at the poorest fertility and low water holding capacity site (northernmost).

Simulations show that the current annual increment (CAI) increases after stand establishment, peaks shortly after canopy closure, and then decreases. The mean annual increment (MAI) is derived from the CAI curve and shows the mean annual increment since stand establishment. MAI culminates when the CAI curve crosses and falls below the MAI curve, defining MAImax (considered the optimal age to harvest a stand when the objective is to maximize production volume over multiple rotations, in our case the maximum yield in total biomass).

Figure 1 shows how the either species established in the lowest productivity environment reaches the optimal financial rotation age before the MAImax, which could extend the rotation age in the case of *Eucalyptus* spp. (Fig. 1A and 1C) and PIRA (Fig. 1E). As a contrast, in the most productive environments EUGL and EUNI could extend rotation ages only a few years (Fig. 1B and 1D), but in PIRA optimal financial rotation corresponds with MAImax (Fig. 1F).

Deterministic economic assessment

The results of NPV increases for timber and payments for environmental services are shown in Fig. 2. In EUGL and EUNI most simulations show positive NPV values for both assets. There are exceptions in the negative NPV of CO_2 in zone 1 of higher productivity if the rotation is extended 7 or more years in EUGL and 6 or more in EUNI. After that, in either species, the alternative of extending the rotation age is more profitable in lower productivity environments, which goes beyond the simulation horizon (Fig. 2A and 2B).

With respect to the 12-year baseline, the highest increase in average profitability is 18.9 and 20.9% for EUGL and EUNI (342.5 and 300.3 $ ha^{-1}), respectively, and the lowest is reached in zone 1 with 12.5 and 5.7% (155.2 and 49.4 $ ha^{-1}) for the same species, respectively.

Extending PIRA rotation age resulted in a negative CO_2 NPV, implying that a decision made at establishment to extend the harvest age beyond 22 years will not increase financial returns, when aiming at potential payments for environmental services based on carbon storage. (Fig. 2C).

Stochastic assessment and sensitivity analysis

Considering the variability of inputs used in the Monte Carlo simulation, there was a 0% probability that NPV achieved a negative result for all environments (Fig. 3). The expected mean NPV value for the lowest performance ranged from 2,576 for EUGL, 2,565 and 2,572 $ ha^{-1} for PIRA plantations. For the same results, cut-off values corresponding to a range of NPV index from the 5 to 95 percentiles, showed similar distances. As a contrast, highest performance doesn't have the same behavior. For eucalyptus, mean NPVs are higher than those achieved in PIRA. Thus, EUGL achieves an NPV of 11,618 $ ha^{-1} (8,235 to 15,317 $ ha^{-1}) and EUNI of 10,565 $ ha^{-1} (7,737 to 13,806 $ ha^{-1}). PIRA shows the lowest values of the three species, with average NPV values of 6,330 $ ha^{-1} (4,571 to 8,310 $ ha^{-1}).

The sensitivity analysis reveals that the uncertainties of the stored CO_2 price, pulpable product and discount rate are the main contributors to the total variance in the 13-year NPV of both *Eucalyptus* species. The uncertainty in price of captured CO_2 contributes more than 50% in either species, with pulpable product and discount rate contributing more than 16 and 4%, respectively (Fig. 4A to 4D). In particular, the price of captured CO_2 contributes more to low productivity environments and particularly in EUNI with 76%, compared to higher productivity environments where the price of CO_2 contributes - on average – 55% of the variation.

The uncertainties in pulp volume, harvesting cost, planting and transport contribute most of the remaining variance. All other variables combined contribute less than 3.4% to the overall variance of the results, regardless of the species and environment where they were established.

Model uncertainty was tested to determine the parameter values where Price of captured CO_2 would no longer be the largest contributor to variance by running analyses with lower values for the standard deviation. The price of captured CO_2 would have to reduce the standard deviation on average by 72% and price of product for pulp by 33.2% so that the uncertainty does not contribute more significantly to the variance of the model.

Discussion

In this study, the economic analysis was based on based on growth models developed from a large base of plots from EUGL, EUNI and PIRA plantations established throughout a large environmental gradient in the country. This database included a large range in site productivity, plantation ages and management regimes. However, for both eucalyptus species studied, more research is needed to understand the biomass development for harvest ages beyond 20 years. The economic analysis was also based on a series of assumptions with regards to costs of activities associated with the plantations, with inputs from forest landowners and forest contractors that provided years of experience making this analysis grounded in actual prices and activities in the field. The placement costs of carbon assets were incorporated into the analysis thanks to the collaboration of the Climate Exchange of Santiago de Chile.

Our results support the notion that harvesting of EUGL, EUNI and PIRA at the optimal financial rotation age is still a profitable activity for non-industrial private landowners in Chile. Profitability indicators showed that roundwood production produced significantly higher yields than pulpwood regimes, even without any additional payment for carbon storage, results consistent with those reported by Acuña et al. (2020).

Including hypothetical carbon additionality payments within the economic objective leads to longer rotations and higher total profits in most cases. Similar results have been recorded by Fischer et al. (2017) in a forest dominated by Douglas-fir and Western hemlock, and by Mei and Clutter (2022) based on a hypothetical southern pine plantation in the state of Georgia. In our analysis for eucalyptus, delaying the harvest is more profitable if these payments are made. Therefore, if owners delay harvest age by 8 years in eucalypts in low and medium productivity environments or by 4 years in high productivity environments, they will benefit from additional cash flows from carbon credits as maintained by West et al. (2019).

For PIRA, it was observed that the species has reached its economic maturity at the harvest age of 22 years of age. This means that by contracting to store additional carbon, they will only pay for marginal carbon over a given period, but at the expense of the landowners. In this case, government incentives are needed to stimulate forest carbon provision (Jensen et al., 2022). Mei and Clutter (2022) argue that extending the harvest age has a lower opportunity cost in low-productivity environments, and therefore the cost of conserving the stand as well as the amount of carbon stored are lower, discouraging landowners to enter the voluntary carbon market when faced with a fixed payment for forest carbon.

For landowners who have mature forests and seek a contract paying for marginal carbon sequestration over the next few years, only those who established eucalyptus will be able to benefit and, again, those who cultivate PIRA will not benefit if there are no government incentives.

When analysing stochastic valuation, the decision to opt for carbon payment is more sensitive to the price of carbon captured, roundwood and the discount rate. Similar results were found by Fischer et al. (2017), Simões et al. (2018) and Mei and Clutter (2022) in investigations analogous to ours using Monte Carlo simulation. Similar to them, it was found that the optimum rotation age does not deviate much from that defined by the Faustmann model when roundwood prices are above the price of the hypothetical carbon contracts.

In conclusion, considering that planted forests are a nature-based solution to contain the climate change we are experiencing, additional forest carbon from eucalyptus-planted forests becomes an effective option if we extend their harvest age. In *Pinus radiata*, this alternative may be economically viable only if there are government incentives. The existence of these incentives will encourage small forest landowners to cultivate this species or others with economic interest to the country. Therefore, the results of our study can help landowners better understand the voluntary forest carbon market and stimulate their entry into it. Increasing domestic roundwood production requires the design of mechanisms to reduce or eliminate the factors that currently prevent small landowners from establishing forest species and thus help mitigate global change.

Declarations

Conflict of interest statement

None declared.

References

1. Acuña, E, Pinto, A, Cancino, J, Sandova, S (2020). Fair value of standing timber in the context of ias 41 implementation: A case study with *Pinus radiata*. *Ciencia Florestal*, 30(4), 1217-1229. doi:10.5902/1980509824460.
2. Balboa-Murias, MÁ, Rodríguez-Soalleiro, R, Merino, A, Álvarez-González, JG (2006). Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. *For Ecol Manage*, 237(1-3), 29-38. doi:10.1016/j.foreco.2006.09.024.
3. Bastin, JF, Finegold, Y, Garcia, C, Mollicone, D, Rezende, M, Routh, D, et al. (2019). The global tree restoration potential. *Science*, 365(6448), 76-79. doi:10.1126/science.aax0848.
4. Ecotrust. (2012). Methodology for improved forest management through extension of rotation age (IFM ERA). VM0003, Version 1.2. Washington, DC: Verified Carbon Standard (VCS).
5. Faustmann, M (1849). Reprinted in translation as: Calculation of the value which forest land and immature stands possess for forestry. *J. For. Econ.*, 1(1), 7-44.
6. Fischer, PW, Cullen, AC, Ettl, GJ (2017). The effect of forest management strategy on carbon storage and revenue in Western Washington: A probabilistic simulation of tradeoffs. *Risk Anal.*, 37(1), 173-192. doi:10.1111/risa.12611.
7. Foley, TG, Richter, Dd, Galik, CS (2009). Extending rotation age for carbon sequestration: A cross-protocol comparison of North American forest offsets. *For Ecol Manage*, 259(2), 201-209.
8. Gobierno de Chile. (2020). Chile's nationally determined contribution. Santiago, Chile: Consejo de Ministros para la Sustentabilidad.
9. Gottfried, BS. (1984). Elements of stochastic process simulation. Englewood Cliffs, N.J.: Prentice-Hall.
10. Harmon, ME, Marks, B (2002). Effects of silvicultural practices on carbon stores in Douglas-fir - Western hemlock forests in the Pacific Northwest, U.S.A.: Results from a simulation model. *Can J For Res*, 32(5), 863-877. doi:10.1139/x01-216.
11. Harris, NL, Gibbs, DA, Baccini, A, Birdsey, RA, de Bruin, S, Farina, M, et al. (2021). Global maps of twenty-first century forest carbon fluxes. *Nat. Clim. Change*, 11(3), 234-240. doi:10.1038/s41558-020-00976-6.
12. Hepburn, CJ, Koundouri, P (2007). Recent advances in discounting: Implications for forest economics. *J. For. Econ.*, 13(2-3), 169-189. doi:10.1016/j.jfe.2007.02.008.
13. INFOR. (2021). Anuario forestal 2021. Boletín Estadístico N° 180. Santiago, Chile: Instituto Forestal (INFOR).
14. Jensen, F, Thorsen, BJ, Abildtrup, J, Jacobsen, JB, Stenger, A (2022). Designing voluntary subsidies for forest owners under imperfect information. *J. For. Econ.*, 37(1), 73-101. doi:10.1561/112.00000541.
15. Kärenlampi, PP (2021). Capital return rate and carbon storage on forest estates of three boreal tree species. *Sustainability*, 13(12), 6675. https://www.mdpi.com/2071-1050/13/12/6675.

16. Law, BE, Hudiburg, TW, Berner, LT, Kent, JJ, Buotte, PC, Harmon, ME (2018). Land use strategies to mitigate climate change in carbon dense temperate forests. *PNAS*, 115(14), 3663-3668. doi:10.1073/pnas.1720064115.
17. Mei, B, Clutter, ML (2022). Benefit-cost analysis of forest carbon for landowners: An illustration based on a southern pine plantation. *Front. For. Glob. Change*, 5(931504). doi:10.3389/ffgc.2022.931504.
18. Nambiar, S (1999). Productivity and sustainability of plantation forests. *Bosque*, 20(1), 9-21.
19. Olmedo, GF, Guevara, M, Gilabert, H, Montes, CR, Arellano, EC, Barría-Knopf, B, et al. (2020). Baseline of carbon stocks in *Pinus radiata* and *Eucalyptus* spp. plantations of Chile. *Forests*, 11(10), 1-28. doi:10.3390/f11101063.
20. Ovando, P, Campos, P, Calama, R, Montero, G (2010). Landowner net benefit from Stone pine (*Pinus pinea* L.) afforestation of dry-land cereal fields in Valladolid, Spain. *J. For. Econ.*, 16(2), 83-100. doi:10.1016/j.jfe.2009.07.001.
21. Pan, Y, Birdsey, RA, Fang, J, Houghton, R, Kauppi, PE, Kurz, WA, et al. (2011). A large and persistent carbon sink in the world's forests. *Science*, 333(6045), 988-93. doi:10.1126/science.1201609.
22. Roberge, JM, Laudon, H, Bjorkman, C, Ranius, T, Sandstrom, C, Felton, A, et al. (2016). Socio-ecological implications of modifying rotation lengths in forestry. *Ambio*, 45 Suppl 2(2), 109-23. doi:10.1007/s13280-015-0747-4.
23. Sandoval, S, Cancino, J, Rubilar, R, Esquivel, E, Acuña, E, Muñoz, F, et al. (2012). Probability distributions in high-density dendroenergy plantations. *For. Sci.*, 58(6), 663-672. doi:10.5849/forsci.11-028.
24. Sandoval, S, Montes, CR, Olmedo, GF, Acuña, E (2022a). Modelling above-ground biomass of *Eucalyptus globulus* and *Eucalyptus nitens* trees in a latitudinal gradient. *Forestry: An International Journal of Forest Research*, Submitted. doi:10.1093/forestry/cpab048.
25. Sandoval, S, Montes, CR, Olmedo, GF, Acuña, E, Mena-Quijada, P (2022b). Modelling above-ground biomass of *Pinus radiata* trees with explicit multivariate uncertainty. *Forestry: An International Journal of Forest Research*, 95(3), 380-390. doi:10.1093/forestry/cpab048.
26. Schulte, I, Eggers, J, Nielsen, JØ, Fuss, S (2021). What influences the implementation of natural climate solutions? A systematic map and review of the evidence (Review). *Environmental Research Letters*, 17(1). doi:10.1088/1748-9326/ac4071.
27. SCX. (2022). Resumen ejecutivo situación actual y proyecciones de largo plazo del mercado de los offsets de carbono. Santiago, Chile: Bolsa del Clima de Santiago (SCX).
28. Simões, D, Dinardi, AJ, Da Silva, MR (2018). Investment uncertainty analysis in eucalyptus bole biomass production in Brazil. *Forests*, 9(7), 384. https://www.mdpi.com/1999-4907/9/7/384.
29. Streck, C (2020). Who Owns REDD+? Carbon Markets, Carbon Rights and Entitlements to REDD+ Finance. *Forests*, 11(9), 959. https://www.mdpi.com/1999-4907/11/9/959.
30. Tricallotis, M, Gunningham, N, Kanowski, P (2018). The impacts of forest certification for Chilean forestry businesses. *For. Policy Econ.*, 92, 82-91. doi:https://doi.org/10.1016/j.forpol.2018.03.007.

31. Universidad de Concepción. (2013). Tablas auxiliares de producción. *Pinus radiata*, *Eucalyptus globulus* y *nitens*. Concepción, Chile: Modelo nacional de simulación, Universidad de Concepción. Facultad de Ciencias Forestales.
32. West, TAP, Wilson, C, Vrachioli, M, Grogan, KA (2019). Carbon payments for extended rotations in forest plantations: Conflicting insights from a theoretical model. *Ecol. Econ.*, 163, 70-76. doi:10.1016/j.ecolecon.2019.05.010.
33. Woolf, D, Lehmann, J, Lee, DR (2016). Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration. *Nat. Commun.*, 7(13160). doi:10.1038/ncomms13160.
34. Wright, JA, DiNicola, A, Gaitan, E (2000). Latin American forest plantations: Opportunities for carbon sequestration, economic development, and financial returns. *J. For.*, 98(9), 20-23.

Figures

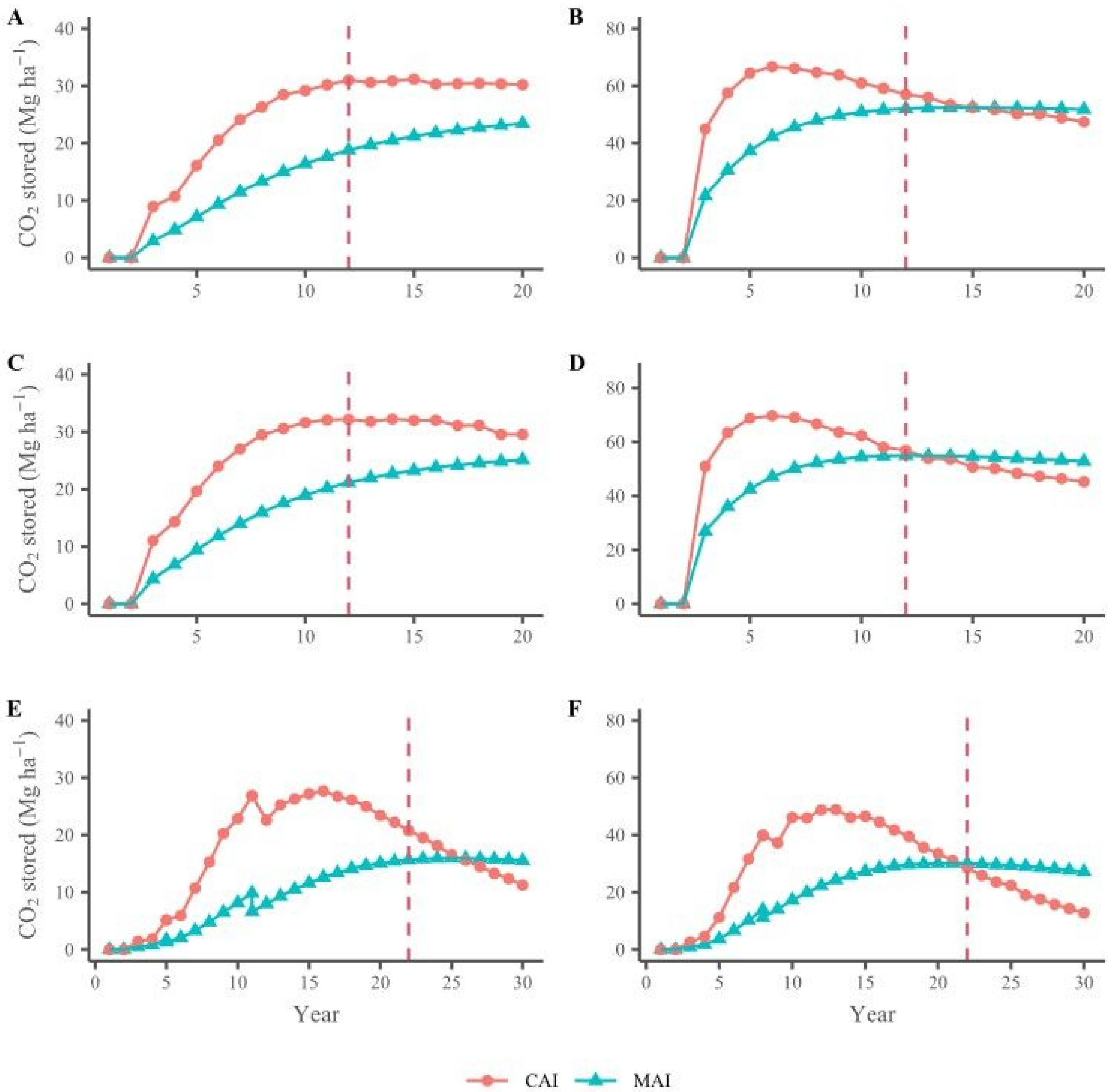

Figure 1

Mean annual increment and current annual increment in CO_2 for contrasting conditions of productivity of the species under study. In the right column sites with lower yielding and in the left column sites with higher yielding. A, B increments in EUGL; C, D increments in EUNI and D, E increments in PIRA. The red dashed vertical line represents the rotation age for industrial purposes.

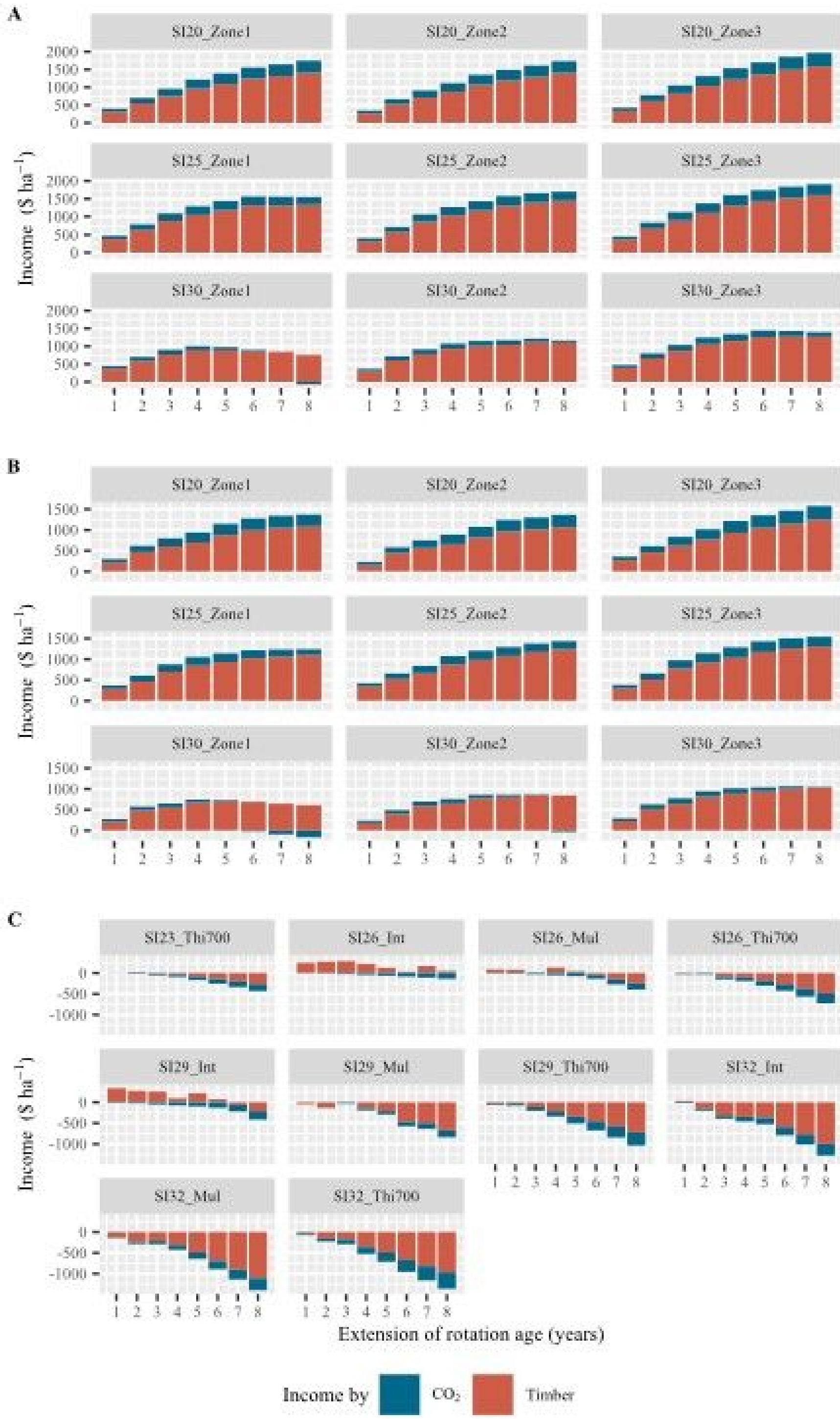

Figure 2

NPV increments. A) EUGL B) EUNI y C) PIRA. Orange color in timber, blue color in payments for environmental services.

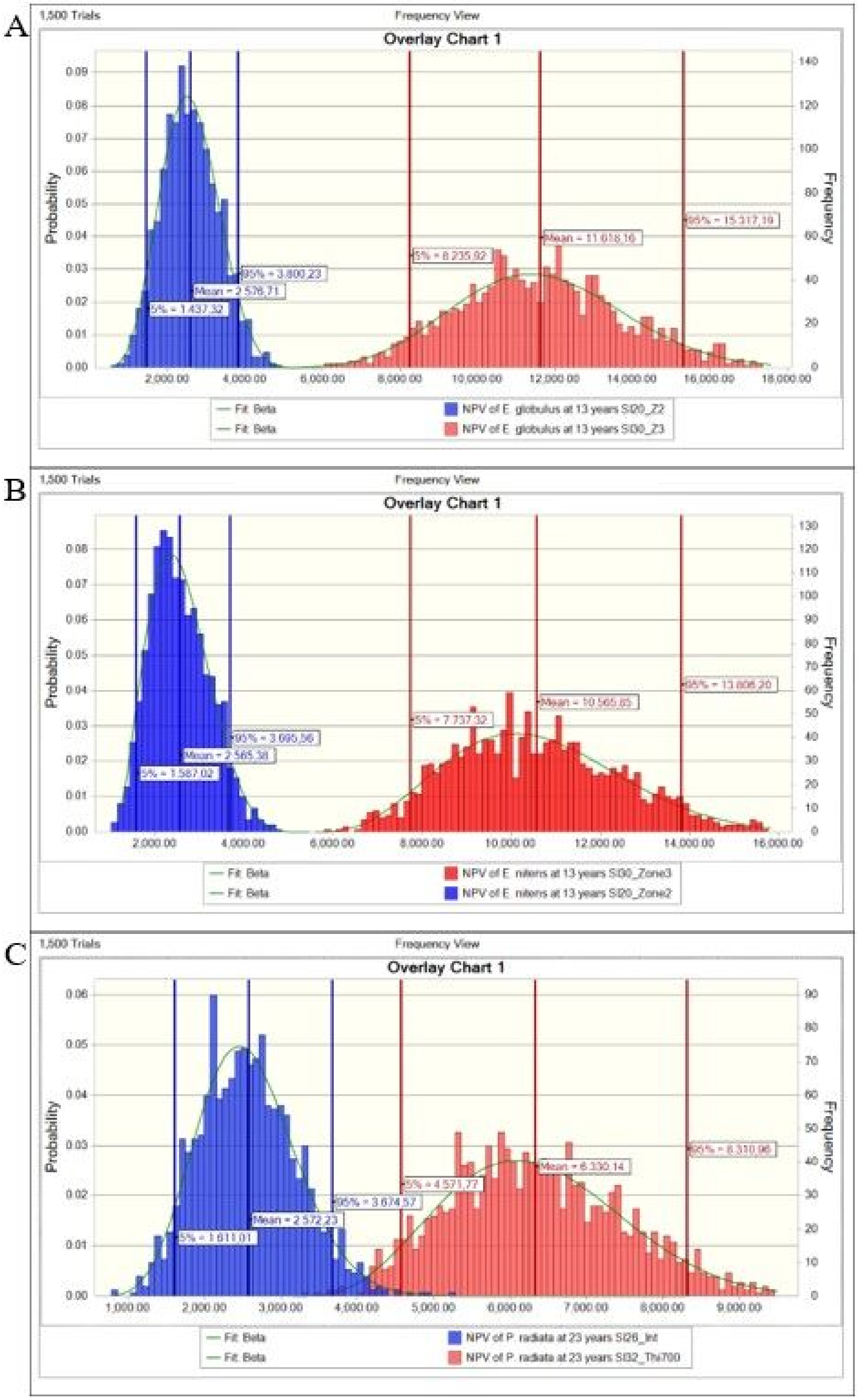

Figure 3

NPV probability distribution with PES for lowest and highest deterministic performance. A: denotes the sensitivity analysis for *E. globulus*, B for *E. nitens*, and C for *P. radiata*.

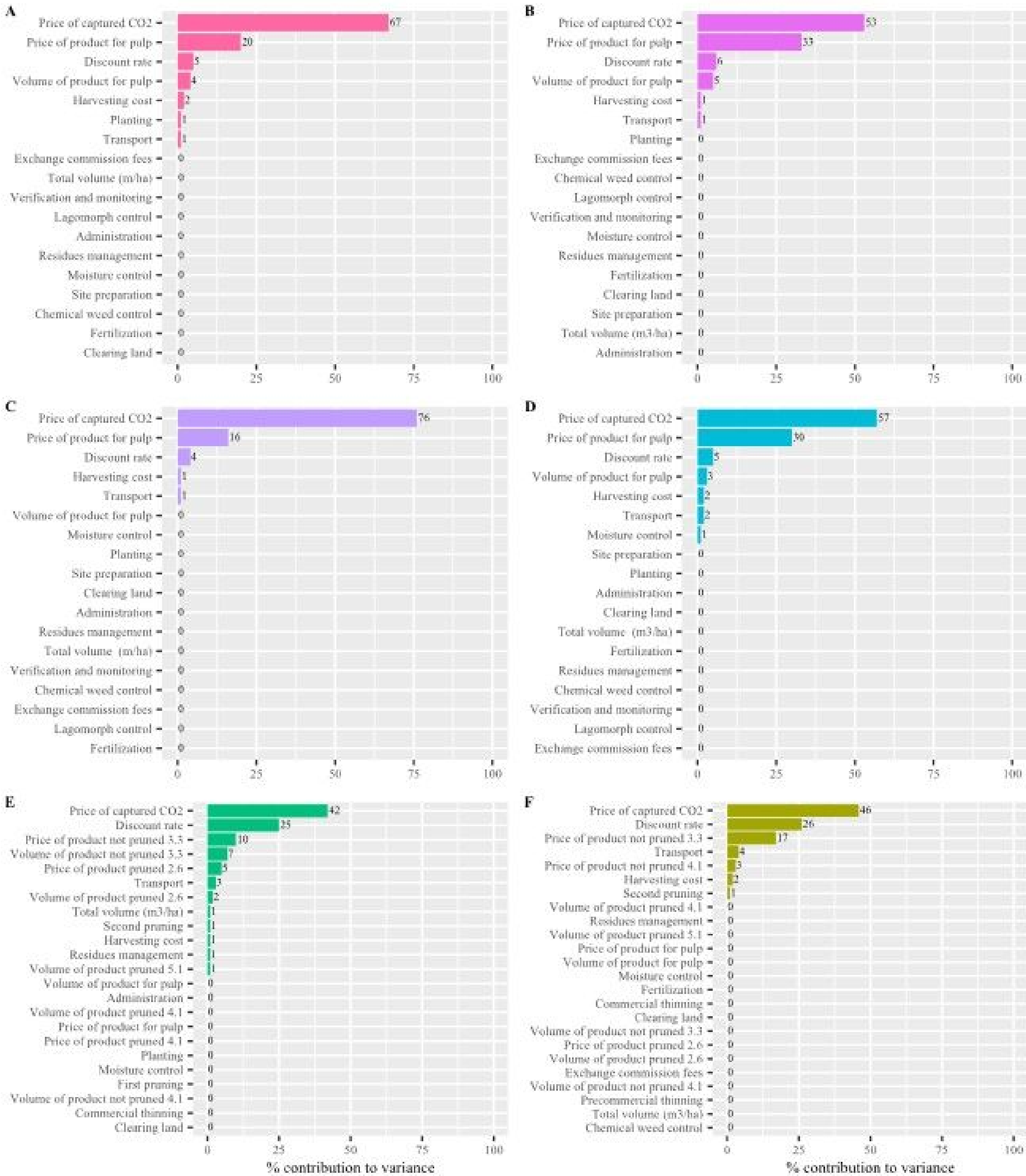

Figure 4

Sensitivity analysis showing percent contribution to variance for lowest (left column) and highest (right column) deterministic NPV.