Economic Tools to Improve Forest Practices' Outcomes

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ABSTRACT

This PhD dissertation work delves into critical issues within the forestry business related to carbon sequestration, land value maximization and climate change vulnerability. The study proposes different tools to enhance the efficiency and outcomes of forest practices. Chapter two involves an enhanced forest rotation deferral methodology for carbon dioxide sequestration, focusing on the forest's final product destination passed the Faustmann optimal rotation age. Instead of giving the same value for pulp wood and saw timber, the research acknowledges the benefit of increased carbon dioxide stored in saw timber materials. To drive landowners to the socially optimum rotation age, where the marginal benefits of extended carbon storage equal the private marginal cost of postponing forest rotation, an incentive based mechanism is proposed, using subsidies. Through sensitivity analysis on the underlying assumptions, the socially optimal rotation is consistently greater than the currently applied one-year harvesting deferral, and smaller than longer extensions, such as 20 years deferred rotations. In chapter three, a novel approach to design Streamside Management Zones widths that vary according to different landscape characteristics is presented, as opposed to the constant command and control width currently used in Virginia. This adaptive approach allows landowners to maximize land value, while ensuring water quality protection. To determine the sediment retention equation as a function of SMZ slope, width, and soil texture, we use data derived from the Watershed Erosion Prediction Project. By simulating different regulatory constraints concerning accepted sediment delivery, the study shows the tradeoff between water quality and land expectation value through the changes in the opportunity cost of Streamside Management Zones. Lastly, chapter four centers on a dataset collected in India about tree planting species choice followed by a second model that incorporates socio-economic, as well as revealed preference management choices, and tree planting species as explanatory variables in a binary crop loss model. The findings reveal that tree planting, except for fruit trees, compared to agricultural crops, diminishes the household’s probability of facing losses due to climate change, extreme weather events and pest attacks. Specifically, there is a 14.4% reduction in the probability of facing a loss when planting Eucalypt and Casuarina trees, a 7.6% reduction when planting palm trees, and 13.5% reduction when planting multiple trees, which evidences how trees are less vulnerable. Throughout this dissertation, the interdisciplinary research uses rigorous methodologies, comprehensive data analysis, and environmental economics theoretical foundation, culminating in valuable insights and potential policy recommendations to enhance forest practices in environmental challenging times.

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GENERAL AUDIENCE ABSTRACT

Climate change is a reality and forest practices can help us mitigate some of its consequences. However, forest practices are driven by private decisions that prioritize individual net benefits, often neglecting the broader ecosystem services forests provide. To enhance the collective benefits that forests provide to society, while maximizing the private economic return, it is crucial to employ tools to drive landowners to a socially optimal outcome. This dissertation aims to improve forest practices in three key environmental areas: carbon dioxide sequestration, land value optimization with water quality conservation, and crop vulnerability. The second chapter introduces a novel harvesting deferral methodology for carbon dioxide sequestration, which assigns greater value for saw timber production due to its longer product lifespan, thereby enhancing carbon dioxide sequestration away from the atmosphere. We align private landowner and social planner’s interests and propose a subsidy scheme to incentivize landowners to postpone their forest rotation age until the marginal cost of doing so equals the societal marginal benefit of the deferred rotation. The outcomes are contingent on the underlying assumptions, and in this study, all rotation deferrals were greater than the current one-year rotation deferral contract, and smaller than 20 years. In the third chapter, an alternative approach to defining Streamside Management Zones (SMZ) width is proposed. Rather than employing a fixed width value across various conditions, a varied SMZ width is suggested, according to specific landscape characteristics. The study formulates the landowner’s maximization problem, which is constrained to a fixed sediment delivery value. By simulating sediment retention delivery data using the Watershed Erosion Prediction Project, the research shows the opportunity cost of water quality through forgone timber revenue. Lastly, considering the direct link between climate change and food security, the dissertation utilizes data collected in India on household characteristics and revealed management choices. The first objective is to model the factors influencing the tree species planting decision, followed by a second model that focuses on how tree planting may reduce the probability of facing losses. The findings indicate that tree planting, except for fruits, reduces the probability of losses compared to planting agricultural crops. Throughout the dissertation, different methodologies, data analysis, and interdisciplinary research with potential policy implications are presented.

DEDICATION

To my wife Isabella, my mum and dad, my sister and my grandmas.

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1. INTRODUCTION

Land and forests are natural resources assets that require prudent utilization to maximize both their economic and environmental returns. Since resources are scarce, every time they are used, there is an implicit opportunity cost to it. In natural resources economics, we study how optimal decisions can be made to maximize private, social, or a combination of both benefits. Forestry, as a financially attractive private investment has the potential to offer significant social benefits by mitigating the adverse consequences of climate change (Bonan, 2008). However, improving the efficiency of forest practices by improving current approaches or proposing novel methodologies to apply optimal decisions in the forestry business is challenging due to the high performance already being practiced. This dissertation presents a multidisciplinary example on how environmental economics theory can be used to obtain forest resources optimal decisions.

Chapter two presents a proposed improvement to forest harvesting deferral programs (Parisa et al., 2022, Nepal et al., 2013). By extending the analysis and considering the benefits of postponing the forest rotation age through additional sawtimber production, which stores carbon dioxide away from the atmosphere for a longer time, the methodology effectively proposes an optimal reduction in the Social Cost of Carbon (SCC) associated with harvesting planted forests (Rennert et al., 2022), and find the socially optimal harvesting deferral time, which varies according to market values and the used assumptions. To find the socially optimal extension time, environmental economics theory is used to determine the optimal rotation deferral, which lies where the social marginal benefit of deferring the forest rotation equals the private marginal cost (Phaneuf & Requate, 2017) of not harvesting the forest at the private optimal time. Section two shows the landowner's optimal decision and using a subsidy paid for each deferred year, the proposed methodology drives landowner's optimal harvesting decision to the socially optimum rotation age, yielding greater social benefits from private investments in temporary planted forests. Results show that the socially optimal rotation is directly dependent on the assumptions used in terms of the Social Cost of Carbon, Social Discount Rates, sawtimber lifespan, stumpage prices and interest rates. Key findings show that for the provided examples, all socially optimum rotations are greater than one year, which reduces the probability of having non-additional deferral projects, and are smaller than extensive longer rotation contracts, such as 40 and 100 years extensions, which makes it more efficient in maximizing social net benefits from planted forests deferred rotation programs. This research contributes to the literature by reconciling private landowners with social planner's preferences, making temporary forests an important tool to mitigate climate change impacts.

In chapter three we determine Streamside Management Zones (SMZ) opportunity costs and discuss the decision made by a landowner under a proposed variable width SMZ that sets a different buffer width according to the landscape characteristics and the generated erosion post and during forest harvesting. SMZs main objectives are to provide water protection and wildlife habitat (Lakel et al., 2010), but they also represent an opportunity cost to landowners since forests are left unharvested (Aust et al., 1996). By doing varied width according to the land necessities, a landowner that does not generate excessive erosion due to land soil type and slope, or because the loggers apply high-quality forest harvesting Best Management Practices, for example, will be able to reduce the SMZ width, therefore reducing its opportunity cost and increase the land value through a higher production area. In defining the buffer width, we maximize the landowner's profits, constrained to a limited sediment delivery value. To determine the SMZ sediment retention capacity, we use data generated from the Watershed Erosion Prediction Project (Laflen et al.,1997), which allows us to simulate the sediment delivery and retention for different SMZ slopes, widths, and soil textures. With the estimated model and the assumptions on stumpage price, land dimensions, and slope, we show how the total value generated can be improved if we allow for varied SMZ widths. We contribute to the literature by providing a novel idea, to the best of our knowledge, that shows SMZ opportunity costs, maximizes private benefits, protects water quality, and provides benefits to wildlife that benefits from SMZ width variation (Larsen-Gray & Loehle, 2022). Our proposed methodology should be implemented on a case-by-case scenario and the generated information can be used by policy makers in cases where water protection standards need to be modified, as we provide trade off values in terms of SMZ opportunity costs and water protection quality.

Lastly, climate change and food production and safety are correlated (Tonnang et al., 2022), and as extreme weather events, fires, and pest attacks increase, it is important to understand how food security will be impacted, as well as how we can reduce household's vulnerability through alternative land investments. We collect data in India on more than 2,000 households containing information about socio-economic, revealed management and planting choices, as well as if the household faced any type of crop loss in the previous year. We contribute to the literature by showing how tree planting reduces the household's probability of facing a crop loss (where trees are also considered as a crop) by dividing our analysis into two steps. We start by applying a multinomial logistic regression where we model which household characteristics are important in determining the choice of planted tree species compared to planting agricultural crops, only. Secondly, we apply a probit model to estimate the household's probability of facing crop losses, and estimate how planted trees, an exogenous variable since the planting decision was done in the past, reduce the probability of facing crop losses. The provided information can be used by vulnerable households and for government policy makers by organizing better crop planting patterns and distribution according to loss event frequency, by setting more resistant crops, such as trees, where the causes for crop loss are more common.

This PhD dissertation presents several multidisciplinary challenges that demand innovative solutions to achieve a delicate balance between private benefits maximization and positive environmental outcomes to society. For the proposed CO_2 sequestration methodology through deferred forest rotation contracts, combining specificities of Social Cost of Carbon methodologies, sawtimber lifespan, interest rates, Social Discount Rates, and stumpage prices to produce marginal benefit and marginal abatement costs demands the combination of different definitions and literatures. For the Streamside Management Zone proposed varied width, finding data for a reasonable hypothetical example also represents a challenge. Finally, addressing the complexity relationship between climate change, food production, and household vulnerability in India required complex data collection and determination of statistical modeling approach. Analyzing household characteristics, revealed management choice, and crop loss probability demands an integrated approach with the combination of multinomial logit, and probit models.

By addressing these topics and overcoming their specific multidisciplinary challenges, this dissertation contributes to a deeper understanding on how we can manipulate forest practices, as private investments, to provide and enhance their societal benefits. The results hold significant implications for policymakers who aim to maximize the efficiency of forest practices while promoting and enhancing environmental welfare.

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2. A PROPOSED METHODOLOGY OF CARBON SEQUESTRATION THAT ACCOUNTS FOR ADDITIONALITY AND TEMPORARY CARBON STORAGE

Abstract

We present an innovative incentive-based methodology to determine an optimal harvesting deferral rotation time aimed at inducing landowners to extend their forest rotation from the private to the socially optimal time for temporary planted forests, which have the potential to help in climate change through forest's extended carbon dioxide sequestration. We analytically derive the landowner's optimal decision under a subsidy payment by the social planner for each deferred rotation year and then simulate how the socially optimal time changes for different site indices and methodology assumptions. The socially optimal rotation lies where the marginal cost of deferring the forest rotation (paid by the landowner) equals the societal marginal benefits of rotation deferral. Societal benefits of deferring the forest rotation come through the increase in the sawtimber production, which stores carbon dioxide away from the atmosphere for a longer time, therefore, effectively reducing Social Cost of Carbon associated with forest harvesting. We show the critical role of the assumptions in determining the socially optimal rotation time. Elevated Social Discount rates increase the marginal benefits, consequently postponing the socially optimal rotation age. Conversely, reduced sawtimber lifespan diminishes the marginal benefits, and, therefore, the socially optimal rotation time. Moreover, the higher the site index, the smaller the deferral time tends to be due to higher land and capital opportunity costs. All our examples suggest deferrals greater than one year, which reduces the probability of having non-additional harvesting deferral projects, and shorter than 20 years, which highlights the possibility to have more efficient contracts. Our incentive-based approach reconciles private landowners and social planners, by aligning private and social interests from deferred rotations of planted forests. Understanding the influence and adapting the assumptions as science evolves will enable stakeholders to implement tailored strategies to maximize forest environmental benefits while ensuring economic viability.

Keywords: Carbon dioxide sequestration; environmental policy instrument; harvesting deferral; sawtimber; additionality; temporary storage

2.1. Introduction

Forests are a natural and cost-effective carbon dioxide (CO_2) sequestration strategy that is fundamental for climate change mitigation (IPCC 2022). Moreover, forests provide a myriad of other ecosystem goods and services (Malmsheimer et al., 2011) boosting interest in their potential as a source of nature-based solutions to climate change mitigation and adaptation in addition to other social and environmental challenges we face as a society. In the U.S., non-industrial private forest landowners (NIPFs) must be part of strategies targeting carbon storage increase given that they represent over 40% of the land ownership in the country and more than 70% of forest ownership in the eastern U.S. (USDA, 2022). These lands represent a large CO_2 sink potential, which may be achieved through improved forest management, the establishment of additional forests (through reforestation and afforestation) and deferring (extending the planned) timber harvesting age (Lewis et al., 2019; Sohngen & Mendelsohn, 2003). Only recently, however, have these projects and programs started to become a reality to NIPFs owning less than five thousand acres of land due to the high costs associated with carbon contracts, especially with respect to monitoring and verification of carbon emissions and stocks.

In this study, we focus on costs and benefits associated with planted forest deferred rotation contracts for carbon dioxide sequestration. Currently in the US, different deferred rotations contracts propose various extension periods depending on the used protocols (American Carbon Registry (ACR), Verra, or Climate Action Reserve (CAR) though improved forest management projects, for example) and their target market type (be it voluntary or compliance). These deferral periods can range from as short as one year (Parisa et al., 2022) to as long as 20 (Stokland, 2021) or even 100 years commitments (Nepal et al., 2013). This broad time horizon may pose a challenge for landowners to include carbon in their forest management decisions. At the same time, the long time horizon is not necessarily compatible with forest-based climate mitigation societal goals and may be inefficient from the perspective of a social planner, as we will show in this article.

Although one-year deferrals are more attractive for landowners due to their shorter commitment, social planners might benefit from contracts that defer the rotation longer as each extended year's benefits might be greater than their marginal costs, since the forest is still growing and sequestering carbon dioxide at the financially optimal rotation age (Sohngen and Brown, 2008). On the other hand, deferring forest rotation for too long, such as 100 years, although offering greater certainty to carbon offset buyers or investors, they represent a greater opportunity cost to private landowners, and were shown to be the least preferred option by landowners in a study in Florida (Soto et al., 2016). Longer deferrals will demand a higher payment, and the deferred rotation might extrapolate a socially optimal rotation time (the rotation that society benefits the most from extending the private optimal rotation age), making the contract less efficient from a social planner's perspective. Additionally, deferring the forest for too long can increase the reversal risk, which is the risk of having carbon dioxide released as a consequence of more common pest attacks and forest fires, for example (Galik and Jackson, 2009).

Despite the discussion in the literature concerning the climate mitigation benefits of carbon storage through delays in timber harvest, there is no work we are aware of that has studied this type of forest carbon contracts reconciling the social planner and forest landowner's perspectives to determine a socially optimal deferred rotation time using a methodology that considers the reduction in the social cost of carbon associated with additional CO_2 stored in sawtimber products. In this article, we examine a harvest delay forest carbon contract in which a subsidy is offered by the social planner (i.e. government) in exchange for the social benefit created when additional carbon is stored in the form of increased sawtimber production generated through the forest rotation deferral. Instead of fixed deferred rotation time, we propose a comprehensive and systematic methodology that considers a flexible deferred harvesting time according to market and site indices (i.e., productivity) parameters to maximize social net benefits from planted forests. We solve the landowner's land maximization problem and examine the size of the subsidy necessary to drive the landowner from the private to the socially optimum harvesting time found by the social planner. The subsidy paid to the landowner is drawn from the social planner's net benefit maximization problem, which recognizes the rotation deferral as a carbon emission abatement effort realized by the private landowner. Based on simulated data for a hypothetical even-aged loblolly pine plantation in the US South, we then explore analytically how site characteristics and offset contract assumptions impact the resulting efficient abatement effort and the optimal deferral recommendation.

An example of forest carbon program that has become popular recently is the one-year deferred rotation age program (Parisa et al., 2022), in which forest landowners receive a payment for delaying their timber harvesting for one year. The current argument that defends the use of temporary one year rotation age deferrals is that multiple tons of short-term carbon storage (additional to optimal rotation age) are equivalent to a permanent carbon removal (Fearnside et al., 2000; Moura Costa et al., 2000; Parisa et al., 2022). On the other hand, there are also longer deferrals, such as 100 years deferred rotation programs which provide longer carbon dioxide sequestration and enhance the amenities generated by planted forests, providing longer wildlife benefits, ecosystem stability, recreation and aesthetic values, and longer water and soil protection, for example, but that demand a longer commitment from landowners. The main challenge to the success of these and other types of forest carbon programs is the potential for asymmetry of information between landowners and carbon buyers (Mason & Plantinga, 2013), with respect to the landowner's planned harvesting time. From a landowner's perspective, benefits of deferring the forest rotation age include the price premium they may receive for the sequestered carbon, the gains in timber volume resulting from forest growth, and the increased sawtimber volume that might be sold at higher value (Regmi et al., 2022), in addition to the maintenance or increase of other forest amenities. Postponing any forest rotation, however, implies serious opportunity costs of capital and land, which are well known and the reason for a needed fair carbon price premium (Amacher et al., 2009).

There has been discussion in the general carbon storage literature that is supportive of the benefits of extended rotation ages through the delayed release of carbon dioxide emissions (Marshall & Kelly, 2010; B. W. Nordhaus, 1982; Rennert et al., 2022; Tol, 2008; van Kooten, 2013; West et al., 2019). On the other hand, Mackey et al. (2013) argue that offsetting emissions from fossil fuels through the use of land-based strategies is flawed, because any current storage comes at a cost of past carbon emissions through historical land use change. Another common concern of using temporary carbon storage is that this carbon is reversible and that the benefits may come in the short, but not in the long run (Kirschbaum, 2006; Levasseur et al., 2012). Kirschbaum (2006), even states that the use of temporary carbon storage could increase greenhouse gas emissions compared to not using temporary biological sinks. Further, the chosen time horizon for rotation age delays, which has a direct impact on forest climate change mitigation benefits, is subjective and sensitive to the used discounting rates (Levasseur et al., 2012), highlighting the importance of transparency and the necessity to define methodologies to account for the benefits from deferred forest rotation age.

The rest of the chapter is structured as follows. In section 2, we present how a deferred rotation carbon contract with an annual subsidy is factored into the forest landowner's land value maximization problem along with a comparative statics analysis, followed by the social planner's problem that aims to drive landowners to the socially optimal forest rotation time through an environmental policy subsidy. In section 3 we present an empirical example of such contract into play for lands with different site indices and under different methodology assumptions. Finally, in section 4 we discuss contract improvement opportunities in terms of leakage and reiterate the importance of the assumptions of our methodology for policy implications, optimal harvesting deferral time, and private landowners' decisions.

2.2. Carbon offset program

In the deferred rotation-based forest carbon contract we study, we assume that we are working with an even-aged forest stand and that carbon dioxide (CO_2) is slowly released back to the atmosphere once the forest is harvested (as with other contracts). We account and give a higher value to the extended carbon storage benefits from the additional sawtimber that is a produced as the forest grows in the deferred contract period.[1] In other words, we consider the additional CO_2 sequestered during the increased rotation, when not only total forest biomass continues to grow but more sawtimber is produced; the additional sawtimber grown will, in turn, be transformed into consumer products with a longer lifespan (such as in houses, tables and doors) as compared to pulpwood products, bringing additional benefits to society both through their use and through longer CO_2 storage. The benefits from transitioning between merchantable classes and from timber growth

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[1] Methods to account for carbon from forests has been debated over the past two decades. The most common approach is ton years accounting, which takes into consideration the total tons of CO_2 temporarily sequestered, multiplied by the time it is stored (Moura Costa and Wilson, 2000; Fearnside et al. (2000). The Lashof method assumes that carbon stored in the temporary project is completely re-emitted, and the benefit is the residual carbon passed during the chosen timeframe (Fearnside et al., 2000).

depend on tree species, site quality (measured by site index), and the optimal rotation age (Sohngen & Brown, 2008). In our proposed forest carbon contract, the landowner agrees to postpone their loblolly pine planted forest rotation in exchange for a subsidy that varies according to the total deferral time, and the reduction in the harvesting Social Cost of Carbon (which is defined as the present value of costs to society associated with emitting one extra ton of CO_2 to the atmosphere (Rennert, et al., 2022a)) associate with the direct conversion from pulpwood (encompassing biomass) to longer lifespan sawtimber merchantable class. In the following subsections, we analytically derive the landowners' optimal deferral time decision for a given subsidy, and we determine the socially optimal rotation age extension time from a social planner's perspective that values CO_2 storage.

2.2.1. The landowner's optimal decision in the face of a deferred forest rotation contract – Deriving the Marginal Abatement Cost function

Hartman (1976) established that private landowners will not increase their forest rotation age (and consequently increase CO_2 sequestration storage time through increased sawtimber production, in our case), unless they receive a premium for that change in behavior.[2] On the other hand, a social planner values a longer rotation because this behavior increases the time of temporary CO_2 storage, which reduces the Social Cost of Carbon (SCC) of an extra ton of CO_2 in the atmosphere associated

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[2] This argument has been used before in forest rotation-based carbon modeling. For example, van Kooten et al. (2015) extrapolated the amenities idea and focused on optimal rotations that value CO_2 sequestration passed optimal forest harvesting time. In their model, they considered the time of carbon sinks through ecosystem absorption and present in the products generated, apart from the avoided carbon emission by not using cement and steel in constructions that use wood material, and the emission from harvesting, hauling, and processing, and carbon stored in the system. Pingoud et al. (2010) used boreal forest data and found that longer forest rotations provided higher carbon sequestration benefits through a higher carbon stock in the forests and final wood products with higher substitution credit (substituting materials that demand high energy or fossil fuels to be produced). They also pointed out that wood that is only used for biomass has smaller benefits in emission reduction, while management activities that generate greater sawtimber production could be the most beneficial due to its substitution effects in Finland and Sweden.

with forest harvesting practices. We propose a subsidy provided by the social planner (or any private contracting firm) designed as a payment to a representative forest landowner as an incentive to increase sawtimber production by choosing a longer private optimal forest rotation age.

Suppose the landowner starting with bare land only adopts a one-time increase forest rotation, and then subsequent rotations are those in which the landowner receives no subsidy (it is a one-time contract).[3] The landowner problem may be written as:

$$\max_{N} pf(T+N)e^{-r(T+N)} + \int_{T}^{T+N} Se^{-rx}dx - C + \frac{pf(T)\ e^{-rT} - C}{1-\ e^{-rT}} e^{-r(T+N)} \qquad 2.1$$

where p is the market stumpage price and *f(.)* is the forest growth function, which is a function of time t such that $f''(t) > 0$ until an inflection point $(t = \bar{x})$, and then $f''(t) < 0, when\ t > \ \bar{x}$. The variable *r* represents the market interest rate. The variable T is the private optimal rotation age, *N* is the deferred rotation period to achieve the socially optimal extension time (in years), and S is the subsidy paid to the landowner. The first term in equation 2.1, $Pf(T+N)e^{-r(T+N)}$, is the discounted revenue from selling the trees expressed as the stumpage price multiplied by the total forest volume at the end of the deferred rotation time. The harvesting revenue is summed to the present value of an annual subsidy benefit paid from time T to time T+N ($\int_{T}^{T+N} Se^{-rx}dx$) (we could easily adapt the model for lump-sum payments at the beginning, or at the end of the contract, without loss of generality, but with the necessity to change the subsidy time value). Forest establishment cost is a constant equal to C and is represented in present value terms. The last term in equation 2.1 represents the value of the land under the assumption of equal infinite future forest

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[3] Without loss but with increased notation, we could easily allow the landowner to have an existing forest that is harvested to begin a subsidy-based rotation followed by subsequent rotations without the subsidy.

rotations, but without the subsidy payment proposed in our methodology (Faustmann land expectation value). It comes from the derivation of the optimal rotation age condition and has been presented in multiple papers in the literature (e.g., see Samuelson 1976 and Amacher et al., 2009).

Our model is different from the Hartman model of combined timber and amenity production (Hartman, 1976), in the sense that the amenity benefit is only considered post the private optimal rotation age (additional sequestered CO_2), and different from the model suggested by West et al. (2019), where they assume the additional environmental service post Faustmann optimal rotation age is present in all future infinite equal rotations. In our case, we assume the contract is signed only once, since we have no information on the landowner's land future investments, followed by infinite equal traditional forest rotations without further payments for carbon dioxide sequestration as our land vaalue post contract. The landowner's problem in 2.1 is to obtain the optimal one-time rotation deferral period, N, for a fixed offer subsidy S. Differentiating equation 2.1 with respect to the deferral time N, yields the following first-order condition (FOC):

$$FOC: pf'(T+N)e^{-r(T+N)} - rpf(T+N)e^{-r(T+N)} + Se^{-r(T+N)} - \left(\frac{r\left[\left(Pf(T)\right).e^{-r(T)} - C\ \right]e^{-r(T+N)}}{\left(1-e^{-r(T)}\right)}\right) = 0 \qquad 2.2$$

To simplify, we divide all terms by $e^{-r(T+N)}$ (see Appendix A.1 for steps), which leaves us with the following equation:

$$pf'(T+N)\ +\ S\ =\ rpf(T+N) + \mathrm{r} * LEV \qquad 2.3$$

In equation 2.3, $pf'(T+N)$ represents the marginal forest growth value from deferring the rotation by N years, S is the subsidy value, LEV is the land expectation value $\left(\frac{[(Pf(T))\, e^{-rT}-C\,]}{(1-e^{-rT})}\right)$, and the other terms are as previously described. Equation 2.3 shows that the optimal deferral period will be chosen so that the marginal forest growth value $(pf'(T+N))$, combined with the subsidy term are equal to the opportunity cost of the capital invested in the forest $(rpf(T+N))$ and the opportunity cost of the forest land $(\mathrm{r} * LEV)$. By further manipulating equation 2.3, we can isolate the subsidy S as follows:

$$S = rpf(T+N) + \mathrm{r} * LEV - pf'(T+N) \qquad 2.4$$

Equation 2.4 implies that the landowner will increase the harvesting time by N years until the value of the subsidy is equal to the net opportunity cost of the deferred rotation (opportunity costs minus the revenues of the deferred rotation). If we assume that the subsidy is a constant value defined by the social planner, it then represents a constant marginal benefit of deferring rotation age from the perspective of the landowner. The right-hand side of Equation 2.4 herein after is referred as the marginal abatement cost (MAC) associated with the deferred rotation (or harvest deferral), since it is a practice that reduces or abates the Social Cost of Carbon associated with forest harvesting. The Marginal Abatement Cost function is composed of the marginal forest growth value (obtained from the extra forest volume as the landowner defers the forest rotation), minus the opportunity cost of the capital from not harvesting the forest and investing the money on a bank, for example, minus the opportunity cost of the land, which represents the cost of postponing the establishment of future forests.

With the second order condition of equation 2.1 holding (see the Appendix A.2 for proof), we proceed to a comparative statics analysis to understand how the optimal rotation age deferral would change as we change exogenous factor values (i.e., stumpage price, interest rate, establishment cost, and the subsidy value).

$$\frac{dN}{dp} = -\frac{\frac{dFOC}{dp}}{\frac{dFOC}{d(N)}} = -\frac{f'(T+N) - rf(T+N) + r^2 f(T)e^{-rT}(1-e^{-rT})e^{-r(T+N)}}{pf''(T+N) - prf'\,(T+N) + S'(T+N)} < 0 \qquad 2.5$$

$$\frac{dN}{dr} = -\frac{\frac{dFOC}{dr}}{\frac{dFOC}{d(N)}} = -\frac{-\left(pf(T+N) - S + LEV + r\frac{dLEV}{dr}\right)}{pf''(T+N) - prf'\,(T+N) + S'(T+N)} < 0 \qquad 2.6$$

$$\frac{dN}{dC} = -\frac{\frac{dFOC}{dC}}{\frac{dFOC}{d(N)}} = -\frac{r(1-e^{-rT})}{pf''(T+N) - prf'\,(T+N) + S'(T+N)} > 0 \qquad 2.7$$

$$\frac{dN}{dS} = -\frac{\frac{dFOC}{dS}}{\frac{dFOC}{d(N)}} = -\frac{1-r}{pf''(T+N) - prf'\,(T+N) + S'(T+N)} > 0 \qquad 2.8$$

From the comparative statics, we can see that an increase in the stumpage price (Equation 2.5) decreases the rotation deferral time for a landowner who wants to maximize the value of the land. Similarly, an increase in the market interest rate decreases the rotation deferral period (Equation 2.6) because that increases the opportunity cost of not harvesting the forest. On the other hand, an increase in the forest establishment cost (Equation 2.7) will cause an increase in the rotation deferral period. These comparative statics have similar results as found in the traditional Faustmann rotation problem (i.e., under no subsidies). In terms of subsidy comparative statics analysis (Equation 2.8), if the social planner increases the subsidy rate, the landowner has a higher incentive to defer the harvesting rotation age.

2.2.2. The Social Planner’s perspective and the optimal deferral time - Deriving the Marginal Benefit function

If Equation 2.4 represents the landowner’s optimal forest rotation length decision when offered a given subsidy to do so, it also implies that the social planner can drive the landowner to a desired forest rotation length deferral by manipulating the subsidy value. More specifically, the social planner can improve total efficiency of forest carbon programs from society’s perspective by choosing a subsidy where the social marginal benefit function of deferring the rotation age equals the rotation extension marginal abatement cost born by the forest landowner. By doing so, we finally obtain an abatement effort (deferral time) where the socially marginal benefits from delayed forest harvesting are equal to the private marginal abatement cost of deferring the forest rotation age.

We now turn our analysis to the marginal benefits to society of postponed emissions of a ton of CO_2 stored in sawtimber products. The longer the landowner decides to defer the forest rotation, the smaller the forest harvesting Social Cost of Carbon because more sawtimber is produced, and the carbon is stored longer in wood products, and, consequently, there is a smaller marginal CO_2 damage to society (a benefit). This marginal benefit of postponed emissions is obtained by calculating the marginal decrease in the SCC for each deferred year passed the private optimal rotation age. For that reason, the chosen SCC methodology and its assumptions are crucial in determining the damages of present and future emissions (Rennert et al., 2022). Estimating the SCC demands inputs from different fields of knowledge, such as economics (expected economic growth), demography (population changes through space and time), and climate sciences (global changes in climate patterns and estimates of damages caused by increased CO_2 emissions) (W. D.

Nordhaus, 2017). Its estimation is done through integrated assessment models (IAMs) (Rennert et al., 2022). In our analysis, we consider one of the current SCC estimated by Rennert et al. (2022) of U$61 and assume constant future SCC values.

Together with the choice of a SCC methodology, Social Discount Rates (SDR) have historically been a point of discussion among economists since its choice can generate completely different outcomes (Drupp et al., 2018). Ramsey (1928) argued that discounting future benefits is an unethical practice, so the choice of a discount rate should be zero. Arguments for a higher interest rate indicate that the generation of benefits to future society will only happen if projects contain higher rates of return (Birdsall and Andrew, 1993). The choice of discount rate is still an active debate concerning SCC calculations, with no clear consensus. For this reason, we adopt a recommendation by Drupp et al. (2018), who interviewed more than 200 experts on discounting rates; over three-quarters of them chose a 2% social discount rate. A higher Social Discount Rate assumption would imply that storing CO_2 in sawtimber products today gives a higher benefit in present value terms than under a smaller Social Discount Rate assumption. So, together with the 2% Social Discount Rate assumption, we also provide the MB curves under 1% and 5% Social Discount Rates for sensitivity analysis and analyze how marginal benefits and optimal deferral times change under different assumptions.

Before determining the marginal benefit function, we first calculate the total CO_2 present in the tree biomass by using the factors found in Thomas and Martin (2012). The carbon content is multiplied by 3.67, which is the molecular ratio of CO_2 to C. Figure 2.1 shows how the sawtimber and pulpwood green weight in tons/acre dynamically change through time for an example where 500 trees were planted per acre, followed by a row thinning treatment at age 15 that left a basal area of 80, on a land with a 75 site index (simulated using Tauyield 2.0 (Amateis et al., 2016)).

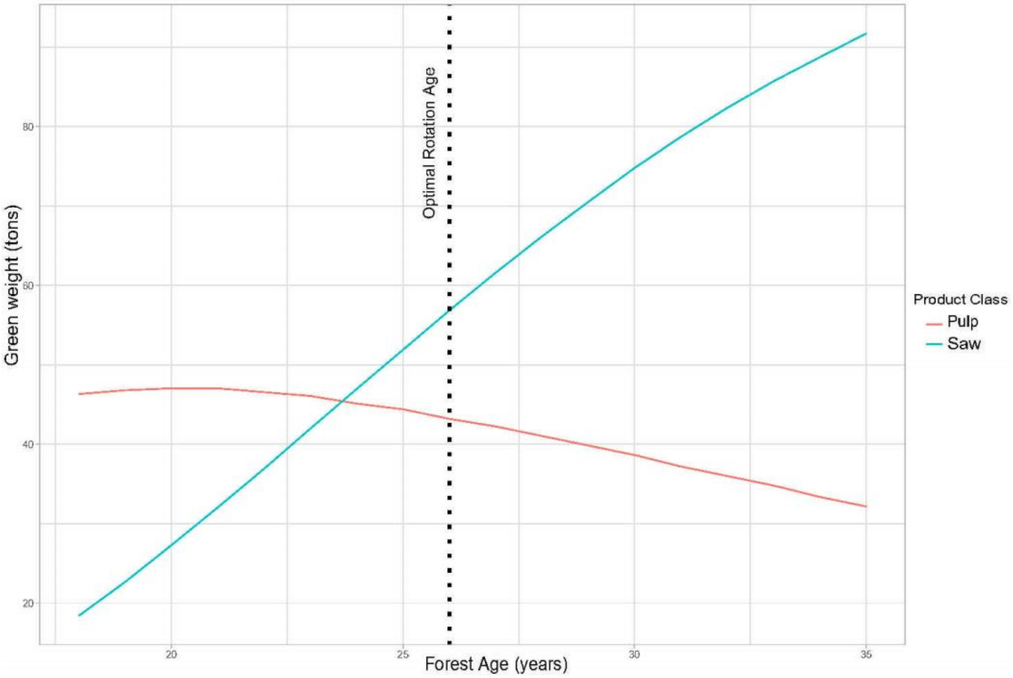

Figure 2. 1: Merchantable class distribution over time.

In order to be more conservative in terms of CO_2 sequestration, and aware of the decrease in number of pulpwood companies in the southeastern U.S. (primary.forestproductslocator.org), combined with the increase in biomass facilities (Brandeis & Abt, 2019), we only credit the conversion of pulpwood to sawtimber categories in our contract scheme. That way, we guarantee the benefit of longer storage independently of pulpwood merchantable trees being used as pulp or biomass. As presented in figure 2.1, for our specific example, sawtimber production increases as the forest gets older, which reduces the Social Cost of Carbon (providing the benefit) as presented in the following equations:

$$SCC_t = \frac{tons\ of\ CO_2\ Pulp_{t+1} * SCC_{pulp} + tons\ of\ CO_2\ Saw_{t+1} * SCC\_sawtimber}{(1+SDR)^t} \qquad 2.9$$

and

$$SCC_{t+1} = \frac{tons\ of\ CO_2\ Pulp_{t+1} * SCC_{pulp} + tons\ of\ CO_2\ Saw_{t+1} * SCC\_sawtimber}{(1+SDR)^{t+1}} \quad 2.10$$

Which finally drives us to the marginal benefit curve:

$$MB_{(t)} = SCC_t - SCC_{t+1} \quad 2.11$$

where both SCC are in present value terms (discounted to the private optimum rotation age using the Social Discount Rate), and it represents the marginal benefit of increasing sawtimber production and decreasing the SCC as the forest ages and CO_2 is stored longer in sawtimber products. We then calculate equation 2.12 year by year to obtain the marginal benefit curve.

2.3. Empirical examples

Simulated data for woody biomass per product merchantable class was obtained from Tauyield (Amateis et al., 2016).[4] Our example of how the methodology works is for an "average landowner", who starts a loblolly pine plantation with 500 trees/acre on a 75 Site Index (SI) (base age 25) and that thins the forest to an 80 residual basal area once the forest is 15 years old. Land Expectation Value is calculated based on the assumptions presented in table 2.1 which are based on Timber Mart South 2022 last quarter values.

Table 2. 1: Assumptions made for the economic analysis.

Financial factors	Assumptions
Saw timber stumpage price	25 U$/ton

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[4] Tauyield is a stand-level growth model that estimates loblolly pine pulp and saw timber volume under different scenarios of site index, age, thinning intensity, and fertilization (Amateis et al., 2016).

Pulp wood stumpage price	10 U$/ton
Interest Rate	5%

For this specific scenario, table 2.2 shows how pulpwood to sawtimber conversion happens as the forest gets older, as well as how the forest economic returns (NPV, and LEV) vary for different forest ages.

Table 2. 2: Green weight through time for medium site index treatment.[5]

Age	Pulp (tons)	Saw (tons)	NPV	LEV
18	49.7	19.7	356.8	610.4
19	50.2	24.3	384.4	636.2
20	50.5	29.3	411.3	660.1
21	50.5	34.4	434.9	678.5
22	50.0	39.6	454.4	690.5
23	49.4	45.0	472.7	700.9
24	48.4	50.4	485.9	704.3
25	**47.6**	**55.7**	**497.0**	**705.2**
26	46.4	61.0	504.4	701.8
27	45.3	66.1	509.2	695.5
28	44.0	71.0	510.3	685.1
29	42.7	75.7	508.6	671.9
30	41.5	80.2	505.3	657.5
31	39.9	84.4	498.4	639.3
32	38.6	88.4	489.9	620.0
33	37.3	92.0	479.3	599.1
34	35.8	95.2	466.5	576.1
35	34.5	98.4	453.8	554.3
36	33.2	101.1	439.1	530.7
37	31.9	103.5	423.2	506.5
38	30.4	105.6	406.2	481.6
39	29.4	107.3	389.2	457.4
40	28.1	109.0	372.4	434.0
41	26.8	110.31	354.6	410.0
42	25.7	111.1	337.0	386.8
43	24.5	112.0	319.0	363.67
44	23.4	112.6	301.5	341.4

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[5] The appendix presents values for similar treatments at different site indices (60 and 90 ft).

45	22.4	112.9	284.2	319.8

For this specific forest, maximum LEV is achieved when the forest is 25 years old. That means that for this proposed carbon contract methodology, any age past 25 years can receive a premium (subsidy) for the saw timber conversion. The numerical values for site indices 60 and 90 are shown in Appendix tables A.3.1 and A.3.2, respectively.

From the simulated values, we obtained the marginal abatement cost for the three different site indices (60, 75, and 90 feet) under a private interest rate assumption of 5%, and the corresponding marginal benefit through SCC reduction from deferred rotation periods under a social discount rate assumption of 2%, although we also considered 1% and 5% Social Discount Rates for sensitivity analysis. For the final product lifespan, we assume sawtimber carbon dioxide stays 60 years longer than in pulpwood products, which are guiding values obtained from Smith et al. (2006), although this value could be different under different conditions. The resulting MAC and MB curves are shown in Figure 2.2 for the proposed silvicultural example under 60, 75 and 90 site index forests.

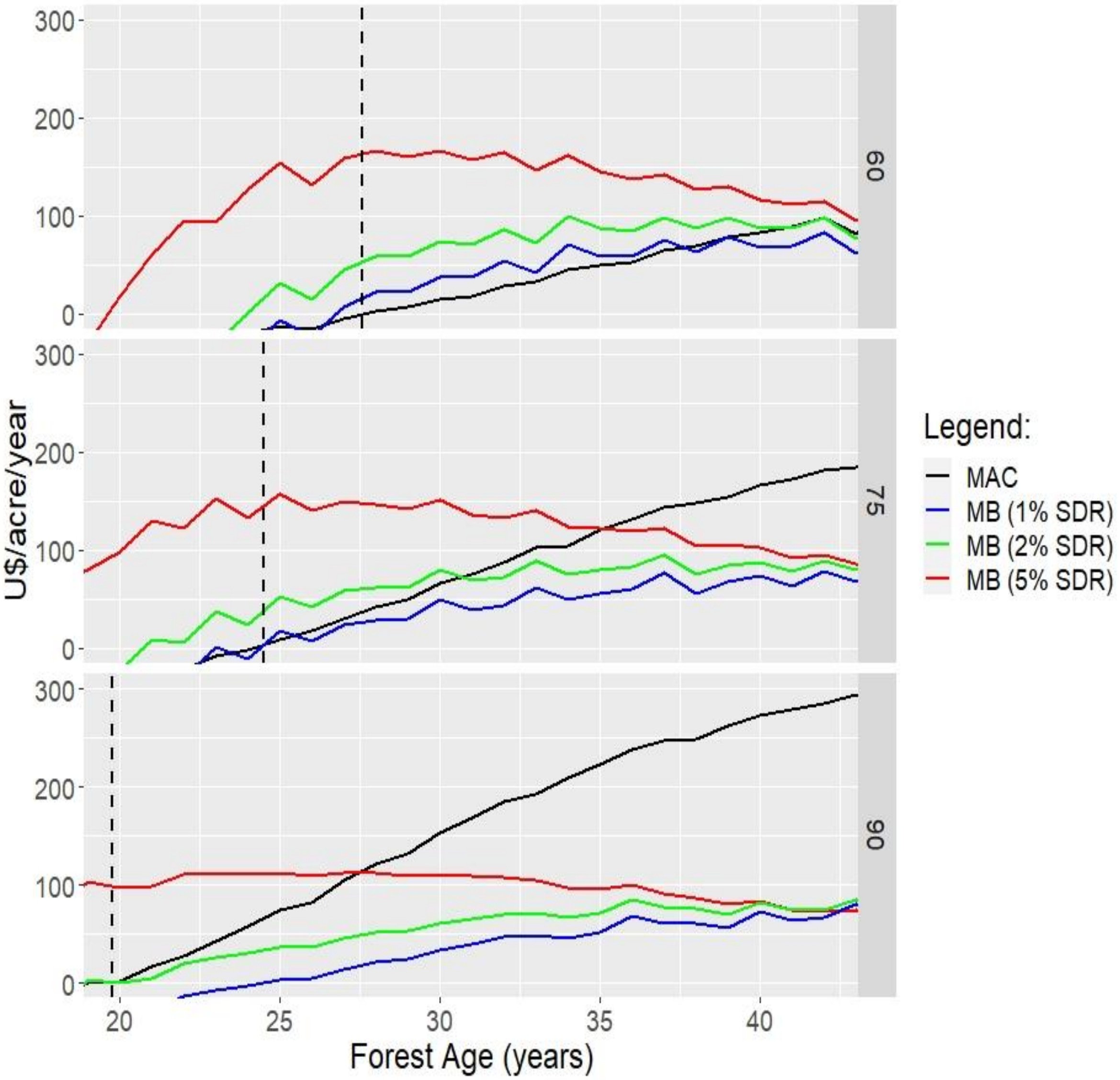

Figure 2. 2: Optimal deferred rotation graphical representation for different site indices under different SDR assumptions - 60 years sawtimber lifespan assumption

The dotted vertical lines in Figure 2.2 represent the private optimal rotation age that maximizes the value of the land under no contract offers for each of the three site index values (60, 75, and 90 feet). For the lower SI (60 ft. - first graph), this optimal rotation age is longer compared to higher SI (90 ft. – last graph). We also see that the slope of the MAC curve on a higher SI forest is steeper than under lower SI (first and second graphs). This occurs because both the opportunity cost of capital and the opportunity cost of the land on higher sites are greater than on lower site qualities, because they produce more green weight at a faster rate. The graphical representation in Figure 2.2 also shows where marginal abatement cost and marginal benefit curves meet, which indicates the optimal deferral time and the necessary subsidy value to achieve the socially optimum rotation age.

From the graphical representation in Figure 2.2, we can see that the avoided damage is directly related to the assumed SCC and the SDR used. The higher the Social Discount Rate, the higher the initial marginal benefit of deferring rotation age, while for smaller Social Discount Rate, deferring the rotation age has positive marginal benefits, but they are smaller in magnitude, because the benefit is discounted less compared to a higher Social Discount Rate. This highlights how higher Social Discount Rates imply higher benefits from postponed rotations. As a consequence, the rotation deferral time under a higher Social Discount Rate is longer than under smaller Social Discount Rate.

Referring to the 60 feet SI curve in Figure 2.2, the MAC curve meets the MB curve when the forest is around 41 years old (under the assumption of 2% SDR), which means an optimal deferral period of approximately 13 years. Under the assumption of 1% SDR, the optimal deferral time reduces to around 10 years, which means that the socially optimum harvesting time is when the forest is 37 years old. Note that the smaller marginal abatement cost pushes the deferral time longer than under better sites because it has smaller opportunity costs.

For the 75 site index class, under 2% Social Discount rate assumption, the social planner could offer a subsidy to defer the forest rotation age by approximately seven years (from BAU between 24 and 25 until 31), while under a 5% SDR assumption, this optimal deferral time could be of approximately 10 years. We also see that both under the 60 and the 75 feet SI, and under the lower

Social Discount Rate assumption, the MB curve is initially upward sloping. This happens because the increase in sawtimber production weight combined with the reduction in the SCC make benefits of future years greater than current and past years' benefits.

The last part of Figure 2.2 contains the 90 feet SI curves. Under 2% Social Discount Rate assumption, the socially optimal rotation age is basically equal to the private optimal rotation, and the social planner would not be interested in offering a subsidy to defer the forest rotation for this specific landowner, unless the used assumption is of a higher Social Discount Rate, such as 5%. The MAC curve does not meet the MB curve under a smaller Social Discount Rate because of the slope of the MAC, which highlights how much more expensive it is for a landowner to defer their forest rotation when the forest is located on a higher site index[6]. Under higher SDR assumption (5%), each deferred year brings higher benefits than the private cost of not harvesting the forest, until the curves meet at the socially optimal time, when the forest is around 27.5 years old. This would imply a rotation deferral of approximately seven years, for a subsidy near 110 U$/acre/year.

Finally, for the lifespan sensitivity analysis, Figure 2.3 provides the graphical representation of MB and MAC under a 100 year saw timber lifetime assumption. When sawtimber production lasts longer, all marginal benefit curves move upwards because the benefits of storing CO_2 are now greater than under the 60 years lifespan presented in Figure 2.2. See that for the 90 feet site index forest, besides a 5% Social Discount Rate, an optimal deferral is also found under the assumption of smaller Social Discount Rate (2%), as opposed to a lifespan of 60 years assumption, because now all marginal benefit curves go up under a higher lifespan assumption.

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[6] An alternative to reduce the social planner's subsidy payment cost could be the creation of a public-private partnership.

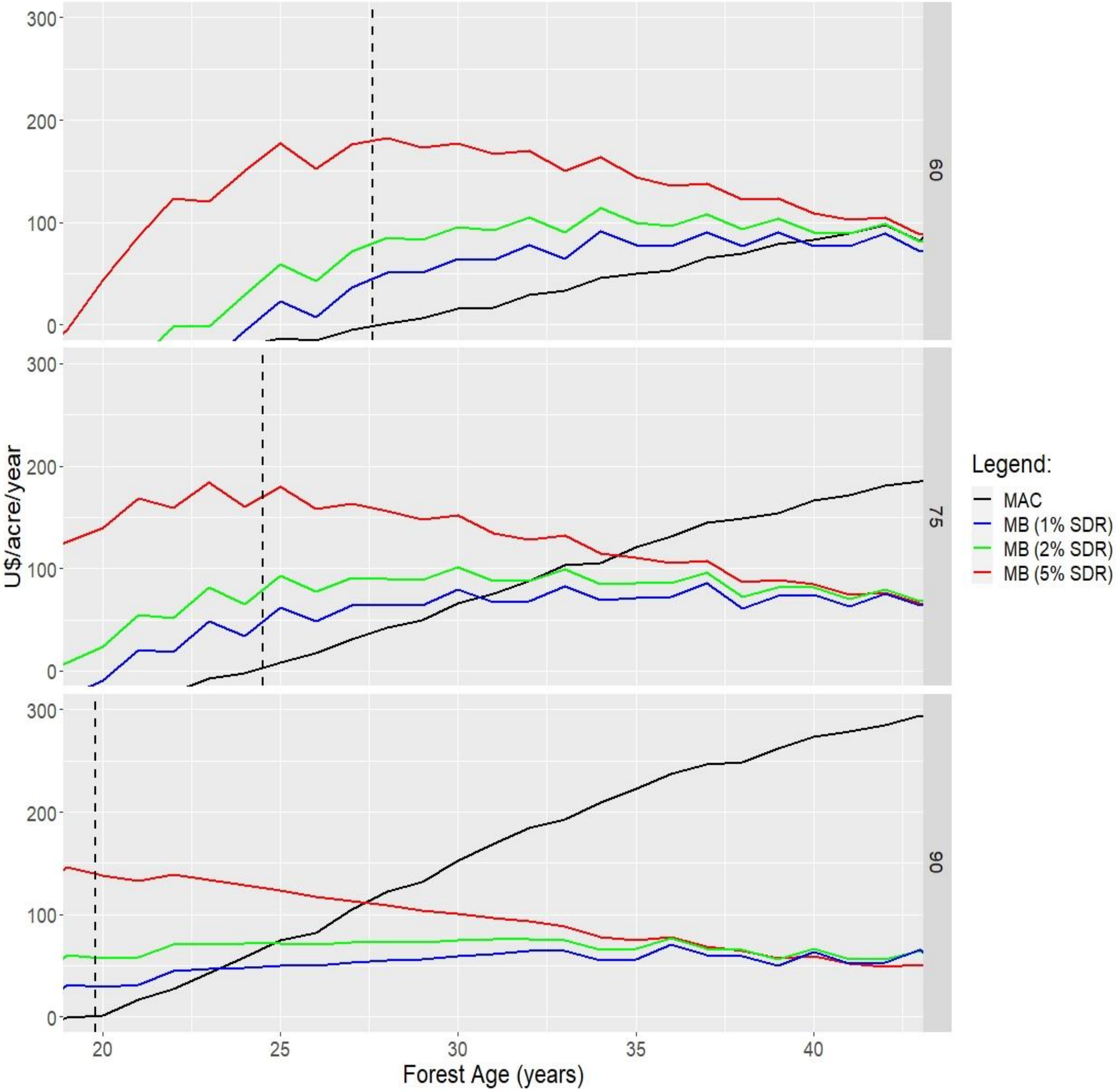

Figure 2. 3: Optimal deferred rotation graphical representation for different site indices under different SDR assumptions, and sawtimber lifespan assumption of 100 years before natural decomposition

The methodology is flexible and we could also change the Social Cost of Carbon assumption, and use U$185/ton (Rennert, Errickson, et al., 2022), for example, which would also increase the benefit of postponing the forest rotation and deferring the socially optimum rotation age.

2.4. Conclusion

Our research proposes a novel methodology to achieve a socially optimal forest harvesting deferral age that maximizes the social net benefits from planted forests. We study the problem of deferred rotation projects and highlight the environmental benefits obtained from additional sawtimber products that store CO_2 for longer periods, effectively providing benefits through a reduction in the Social Cost of Carbon and “buying time” to avoid tipping points while we develop technologies and cleaner energy sources (van Kooten, 2013). Additionally, we are the first to our knowledge to create a deferred rotation method that reconciles policy makers and private landowners’ preferences.

Although our methodology still does not directly cover for leakage, we anticipate that once the offset is stablished in different lands, there will be a reduction in timber supply, which will cause an increase in forest products prices and, therefore, make forest plantations more profitable and attractive for new land uses. This, in turn, is expected to increase the total area of forests, and more timber land means more carbon can be sequestered in the long run, especially if the land conversion happens from non-forested lands. We apply a fixed stumpage price for our hypothetical example, but in practice this value would change according to the market condition and distance to the mills. In terms of monitoring the sawtimber final destination, it is negligible, as the market directs sawtimber to sawmills due to their higher stumpage prices, which supports the viability of our novel methodology.

Any CO_2 sequestration contract must be transparent, and we adhere to our proposed methodology incorporating the Social Cost of Carbon by Rennert et al. (2022), combined with a discount rate recommended by Drupp et al. (2018). We show through sensitivity analysis that results are a direct response of all assumptions used, and that is why transparency is key. Although not addressed, the risks of deferring the forest rotation age could be embedded in the social marginal benefit function associated with the deferred rotation. As research is developed and provides a better understanding of the social value of carbon offsets, we will be able to obtain more accurate deferral recommendations.

In our results, we show the socially optimal rotation age varies according to market values, site indices and the methodology underlying assumptions. We show that the socially optimal rotation lies where the private landowner's marginal abatement cost curve equals the social marginal benefit associated with deferring the private optimal rotation age. To achieve the desired deferral time, we suggest a fixed subsidy, but the landowner could accept a smaller yearly deferral payment, as long as the annual payment is greater than the landowner's marginal abatement cost for that year, or even a smaller value for landowners who value being nice to society. For a social planner, we recommend the prioritization of lands that will provide the highest social net benefits (higher area below the marginal benefit curve minus the area below the marginal abatement cost curve (from time T to T+N), which is directly related to the used assumptions. The choice of the Social Discount Rate also plays a crucial role in the total benefits generated in our proposed contract and it influences the project's feasibility and profitability. For all our provided examples, the deferrals are greater than one year, which reduces the probability of non-additional contracts, and smaller than 20 years, which increases the efficiency of our contracts from society and social planner's perspectives.

Finally, our proposed methodology could adopt a lifecycle perspective by examining what happens to the timber once it is about to decompose, as well as from more accurate lifespan values for the different merchantable classes. We have assumed that the CO_2 sequestered in sawtimber products is naturally released back into the atmosphere after 60 years. For future research, the benefits of increasing saw timber production today could be even greater if we develop a circular use of the forest products through recycling, or through energy or pulp production, instead of allowing it to naturally decompose.

Overall, we propose a promising path for optimizing deferred rotation age contracts for temporary forest practices that contribute to climate change mitigation. As novel research is developed, we expect to keep improving the accuracy of the socially optimal deferral time recommendation, which will enable more effective and transparent initiatives.

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3. STREAMSIDE MANAGEMENT ZONES OPTIMAL DESIGN TO MAXIMIZE LAND VALUE AND PROTECT WATER QUALITY

Abstract

We propose a novel approach that designs Streamside Management Zones (SMZs) and calculates their opportunity cost according to specific landscape characteristics and environmental protection standards. By doing so, we maximize land investment returns and guarantee water protection from erosion generated in forest harvesting operations. Our optimal widths recommendation is dependent on the SMZ slope, soil type, the erosion generated in the harvested area arriving at the border of the SMZ, and total acceptable sediment delivery. To evaluate the SMZ soil retention capacity, we simulated data using the Watershed Erosion Prediction Project (WEPP). We set our optimization objective function, which is composed of the revenue obtained from harvesting the excessive SMZ, combined with the productive area, the use of the riparian buffer tax credit, and the selective harvesting within the SMZ. Our problem is constrained by the sediment delivery value, which sets a lower bound for the SMZ width. We derive the landowner's optimal choice and do comparative static analysis for the exogenous factors. For our empirical example, we provide a hypothetical scenario to compare water protection methods and show the costs of increasing water protection under stricter environmental regulations by providing the private net benefits of different protection schemes. Our tool provides policymakers with the tradeoff between the opportunity cost of SMZs and water protection, which could be used to find optimal policy designs by simultaneously improving land investment returns and promoting sustainable water resource management.

Keywords: Water protection; SMZ opportunity cost; Forestry Best Management Practices; Optimization

3.1. Introduction

To eliminate or alleviate unintended forest harvesting environmental damage consequences, Best Management Practices (BMPs) are implemented in forestry to protect water quality from sediment delivery before, during, and after forest harvesting (Cristan et al., 2016; Shaffer et al., 1998). One of the most common BMP activities present in harvesting sites near water streams are the Stream Side Management Zones (SMZs) forests[7]. From an environmental perspective, apart from protecting streams from soil particles and pollutants generated in forest harvesting (T.A. Dillaha et al., 1989), SMZs provide wildlife habitat (Larsen-Gray & Loehle, 2022), environmental benefits such as carbon sequestration (Matzek et al., 2018), improvement of riparian forest health (Sanders & McBroom, 2013), and maintenance of aquatic communities (LeDoux & Wilkerson, 2008).

Although SMZs provide different benefits to wildlife and society, they constitute a significant opportunity cost to forest landowners through forgone timber revenue (Shaffer et al., 1998; LeDoux, 2006), and to loggers and timber buyers (Shaffer et al., 1998; Kluender et al., 2000; Cubbage, 2004; Lakel et al., 2006) that must be better understood. Currently, many states in the US opt for a fixed SMZ width, such as 15.2 meters (50 ft), due to its ease of implementation and regulation. To reduce this opportunity cost and maximize the value of a planted loblolly pine land, while meeting water protection standards, in this manuscript we propose a novel SMZ width method tailored to the specific demands of each landscape. Instead of a one SMZ-size-fits-all approach, our methodology considers local characteristics such as expected erosion value, SMZ slope and soil type to determine the optimal width for each specific location. We analyze how each

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[7] Other examples of BMPs include stream crossings, culverts, road graveling, mulching, seeding, and turn outs (Kelly et al., 2017; Loehle et al., 2014)

of these factors impact the decision of a landowner who chooses the optimal SMZ width to maximize the value of a land constrained to a lower bound environmental quality standard that exists for water quality protection, as well as provide an example on how SMZ opportunity cost is calculated as water protection standards are modified.

SMZs opportunity cost varies according to distribution of the tree species, its total area, and the harvesting technology used in the forest tract (LeDoux, 2006). LeDoux et al. (2006) estimated cost to landowners for not harvesting SMZs to be between $252/ha to $1,659/ha. Lakel et al. (2015), found average SMZ value for the Virginia Piedmont region to be of $1,064.78/ha. Although these opportunity costs can be reduced through selective harvesting by leaving evenly spaced individuals (Cubbage, 2004; Phillips et al., 2000), or by applying to the riparian buffer tax credit, which is a financial incentive or tax credit for landowner who establish and maintain riparian buffers (VDOF, 2011), this practice increases the probability of growth of shade-tolerant to intermediate shade-tolerant species, such as red maple and American beech, which may be of lower value for future rotations (Lakel et al., 2015).

The literature on the trade-offs associated with SMZs widths and water quality is extensive. Lakel et al. (2010) analyzed four different SMZ treatments (7.6-m SMZs with no thinning, 15.2-m SMZs with no thinning, 15.2-m SMZs with thinning, and 30.2-m SMZs without thinning) in 16 harvested watersheds in the Virginia piedmont region. They found no significant differences in sediment trapping among treatments and recommended a 15.2m SMZ width with selective harvesting to protect water quality. Aust et al. (2012) found that selective harvesting created conditions for herbaceous vegetation, which improved sediment retention. Secoges et al. (2013) analyzed stream characteristics for different SMZ widths and found that greater than or equal to 15.2m buffers protected water quality. Clinton (2011) analyzed water chemistry, total suspended soil and water temperature for a no buffer, 10 meters buffer, 30 meters buffer and a reference site followed forest harvesting, and found that 10m width SMZs were effective in protecting the stream for the analyzed indicators. Ward & Jackson (2004) had three main objectives on their research: an effectiveness value of SMZs in sediment trapping for the Georgia piedmont region, a model capable to predict that efficiency as the SMZ width vary, and finally a relationship between estimated erosion from the RUSLE model versus the measured data. Effectiveness values were between 71% to 99%, but no predictive model was found, and RUSLE values were not good predictors compared to the measured sediment.

Similar works related to what we propose in terms of varied SMZ widths include the one by Miettinen et al. (2020), which found optimal buffer area (as a percentage of the total land) and estimated a marginal abatement cost function of implementing riparian buffers as a function of lost timber revenue, which was dependent on a maximum nutrient load delivery accepted by society, the price of timber, and the interest rate. Besides the optimal SMZ width, they also derived the optimal rotation age for a single cycle and found the cost of water protection through forest buffer zones is the highest when compared to sedimentation ponds, and overland flow fields. Laurén et al. (2007) used the Forestry Environmental Management (FEMMA) ecohydrological model to simulate nitrogen stream load values for different SMZ width and thinning intensities. They found the unit cost of reducing nitrogen and stated that water cost effective protection can be achieved through optimizing SMZ width and SMZ thinning.

It is essential to emphasize that with our proposed methodology, we can calculate SMZ opportunity costs and by following the recommended width, we expect to increase social net benefits from forest lands and enhance water protection if necessary. Although we do not directly consider a monetary value for wildlife in the presented maximization problem, the variability we suggest in SMZ widths are beneficial as recently suggested in terms of wildlife (Larsen-Gray & Loehle, 2022) and also in terms of increasing water protection when scenarios are for steeper slopes and more erodible soils that demand more protection efforts (Sanders & McBroom, 2013), guaranteeing that SMZs two main objectives are achieved, while private benefits are maximized.

The rest of the chapter is organized as follows: In section two, we present the theoretical framework with the private landowner's optimal decision, followed by a comparative statics analysis. Section 3 is composed of an empirical example where we first develop a SMZ sediment retention model as a function of SMZ slope, SMZ soil texture, and SMZ width, followed by an empirical example for a hypothetical forest land, which exemplifies how the opportunity cost of water protection through forgone timber SMZ timber revenue can be estimated for different water protection standards. Finally, in section 4 we conclude with the methodology limitations and policy implications.

3.2. Theoretical model

The maximization problem is represented as a function of the optimal SMZ width (w). The landowner's decision is static, in the sense that the optimal width is defined once and kept the same for all future rotations (keeping exogenous variables constant), and partial because the analysis is considered for a single market. The property dimensions and characteristics are represented in Figure 3.1.

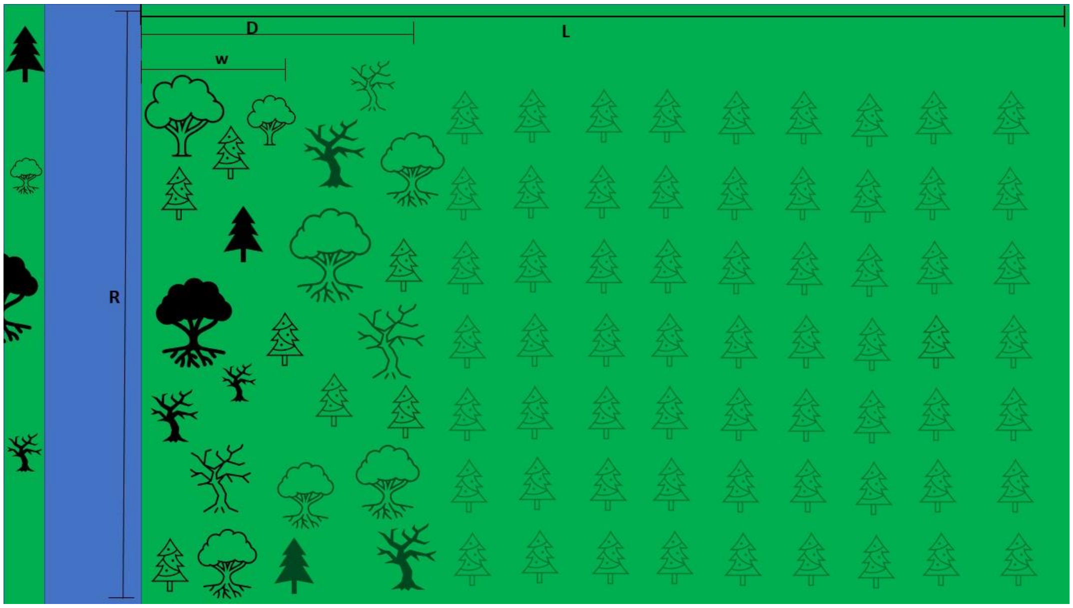

Figure 3. 1: The land characteristics and dimensions for a hypothetical scenario

From figure 3.1, we can see the property area is assumed to have a river (R meters long) passing on one side through its whole dimension. The initial productive area ((L-w)*R) has recently been harvested and the residual SMZ forest area (w*R) is composed of many different species. In figure 3.1, w represents the optimal SMZ width (the control variable in the problem), which will be determined at the productive area clearcut time. The decision of an optimal SMZ has two different implications. First, by reducing (or increasing) the current SMZ width, a landowner could sell the harvested trees (or pay to increase it), and secondly, increase (decrease, when landowners need to increase the SMZ width) the productive area for future rotations. Consider P_P as the stumpage price in U$ dollars/acre for selling the productive area and (paid when leaving unharvested wood) the decreased (or increased) SMZ forest buffer area, $\tau(h)$ as the price received assuming the landowner applies for the riparian buffer tax credit, and it is a function of the landowner's decision of harvesting inside the SMZ, or not (where $\tau(h) = \frac{P_P}{4}$ if the landowner does not harvest inside the SMZ $(h = 0)$, or $\tau(h) = \frac{P_P}{8}$ if the landowner implement SMZ selective harvesting $(h = 1)$ –

both values assuming the payment methodology currently used by the Virginia Department of Forestry (VDOF, 2011) also in U$ dollars/acre, aware that another possibility could be through SMZ forest inventory, but that is more expensive alternative. P_h is the value obtained from selective harvesting SMZs (here assumed to be 50% of the total SMZ value ($P_h = P_P/2$) for infinite rotations (we know this value would go down with time as the landowner keep harvesting selectively in future cycles, but initially this value could be greater than 50% since the landowner is allowed to harvest 50% of the SMZ basal area and through selective harvesting could select only the most valuable trees). The problem faced by a forest landowner who wants to maximize private land profits subject to an ethical and regulatory law for water protection, is presented as follows:

$$\max_{w} U(w, \tau(h), P_h, P_P) \qquad 3.1$$

Which can be represented as:

$$\underset{w}{max} \; R * (L - w) * P_P + R * \frac{(w * \tau(h))}{1 - e^{-rt}} + R * \frac{(w * P_h) * h}{1 - e^{-rt}} + R * \frac{(L - w) * P_P - C}{1 - e^{-rt}} \qquad 3.2$$

$$s.t.: \quad E * \left(1 - SR\left(w,\ soil\ texture,\ SMZ_{slope}\right)\right) \leq a$$

Where L is the land width (an exogenous parameter), and C is the planted forest establishment cost/acre followed forest clearcut. For our constraint, E is the erosion rate post forest harvesting measured in tons arriving at the border of the SMZ, a is the accepted sediment delivery value, also measured in tons of sediment per river section passed the SMZ buffer and going inside the water stream (the higher the used section, the higher the erosion and accepted values), and SR is the SMZ sediment retention capacity, which is a function of the SMZ width, soil texture, and SMZ slope. w has a concave relationship with sediment retention, which means that as we increase the SMZ width, soil retention increases, but at a decreasing rate ($SR'(w) > 0, SR''(w) < 0$). For the SMZ slope, we also assume a concave relationship with SMZ soil retention. Equation 3.2 can be simplified as follows:

$$\max_{w} R*(L-w^{*}).P_P+\frac{R*(w^{*}.\tau(h))+R*(w^{*}.P_h)+R*[(L-w^{*}).P_P-C]}{1-e^{-rt}} \qquad 3.3$$

$$s.t. E.(1-SR(w, soil\ texture, SMZ_{Slope}))\leq a$$

The first term of the maximization problem in equation 3.3 ($R*(L-w^{*}).P_P$) represents a single revenue at the clearcut time obtained from harvesting the productive area combined with the excessive SMZ ($(D-w)*R$) (in case methodology recommends a reduction in the SMZ width). The second term ($R*\frac{(w*\tau(h))}{1-e^{-rt}}$) represents the riparian buffer tax credit the landowner could apply for. See it is a function of the SMZ harvesting decision h, which means that if the landowner opts to selectively harvest inside the SMZ ($h=1$), the tax value is only 12.5% of the total value found in the productive area (in U$/acre), while if not selectively harvesting ($h=0$), this value grows to 25% of the value/acre found in the productive area, considering the current payment methodology used in Virginia (VDOF, 2011). This tax credit is assumed to be applied at the end of every future forest rotation). The third term in equation 3.3 ($R*\frac{(w*P_h)*h}{1-e^{-rt}}$) is devoted to the SMZ selective harvesting, which is also assumed to happen at every forest harvesting cycle. The last term ($R*\frac{(L-w)*P_P-C}{1-e^{-rt}}$) represents the present value of infinite amount of forest rotations in the new productive area ($(L-w)*R$) starting from bare land (recently harvested, with its value covered in the first term of equation 3.3). This problem could be easily adapted to account for carbon sequestration in the SMZ forest by manipulating the value of the riparian buffer tax credit benefit, for example, since this part of the model accounts for the forest left unharvested in the land. The maximization constraint establishes that the maximum sediment delivery value will be less than or equal to the maximum water pollution set by the social planner for forest operations. The constrained optimization problem can be solved analytically since all factors are a function of w. We solve it by setting the Lagrange equation represented below:

$$\mathcal{L} =(D - w) * R * P_P + \frac{w * R * \ \tau(h)) + (w * R * P_h) + [(L - w) * R * P_P - C]}{1 - e^{-rt}} \\ + \quad \lambda * (a - E * (1 - SR\big(w, soil\ texture, SMZ_{Slope}\big)) \tag{3. 4}$$

Where λ is the shadow value of the water protection, a is the maximum sediment delivery value, and the other terms are as previously described. Solving the Lagrange First Order Condition with respect to optimal SMZ width, and with respect to λ, we obtain:

$$FOC_w = \frac{\partial \mathcal{L}}{\partial w} = \frac{-P_P + \tau(h) + P_h - P_P}{1 - e^{-rt}} + \lambda.\mathrm{E}.\mathrm{SR}'(w) \tag{3. 5}$$

$$FOC_\lambda = \frac{\partial \mathcal{L}}{\partial \lambda} = -E.\Big(1 - SR\big(w, soil\ texture, SMZ_{Slope}\big)\Big) + a \geq 0 \tag{3. 6}$$

$$FOC_\lambda = \frac{\partial \mathcal{L}}{\partial \lambda}.\lambda = 0 \tag{3. 7}$$

Where equation 3.7 is the complementary slackness of the Kuhn-Tucker condition, a necessary condition for solving optimization problems with inequality constraints. The second order conditions hold and are presented in the Appendix C section. By isolating λ, we have:

$$\frac{P_P - \tau(h) - P_h + P_P}{E.SR'(w^*) * (1 - e^{-rt})} = \lambda \tag{3. 8}$$

Which is positive and increases as the width increases, because of the concave relationship between SMZ width and soil retention ($SR'(w)$ decreases as w increases). The numerator indicates that the shadow price of water protection increases as the stumpage price for the SMZ forest and the planted forest increase, but it reduces if the landowner applies for the riparian buffer tax credit and/or implement selective harvesting inside the SMZ. If, for example, we allow for carbon credits inside the SMZ through an increase in the riparian buffer tax credit, for example, the shadow value of water protection (also seen as the opportunity cost of the SMZ) would decrease.

From the previous equation, we see that the denominator of the shadow value of water quality protection increases in places with conditions that facilitate erosion (higher slope, higher soil erodibility and smaller SMZ width). In order to reduce its costs and sediment delivery, higher SMZ width would be necessary, or alternatively, better BMP implementation can be applied to reduce total erosion arriving at the boarder of the SMZ.

We now proceed with comparative statics, to analyze how the optimal width (w^*) changes, as we change exogenous factors, such as the stumpage prices (presented in equation 3.9), the riparian buffer tax credit (presented in equation 3.10), the interest rate (presented in equation 3.11), SMZ slope (presented in equation 3.12), and erosion values (presented in equation 3.13). We proceed the analysis assuming $h = 1$, and 50% of the SMZ value is harvested.

$$\frac{\partial w^*}{\partial P_P} = \frac{\frac{\partial FOC}{\partial P_P}}{\frac{\partial FOC}{\partial w^*}} - \frac{\frac{-1+\frac{1}{8}+\frac{1}{2}-1}{1-e^{-rt}}}{\lambda(\mathrm{E.SR}''(w^*))} < 0 \qquad 3.9$$

which means that if the value from harvesting the productive area (which also means the SMZ value would increase by our definition), we expect a decrease in the SMZ buffer size, because the opportunity cost of not harvesting the SMZ forest and planting pines in the productive area increases. This harvest has a lower bound limit, which exists to guarantee water protection. We now proceed with the comparative statics with respect to the tax credit benefit from having SMZs.

$$\frac{\partial w^*}{\partial \tau(h)} = \frac{\frac{\partial FOC}{\partial \tau(h)}}{\frac{\partial FOC}{\partial w^*}} - \frac{\frac{\frac{1}{8}+\frac{1}{2}}{1-e^{-rt}}}{\lambda(\mathrm{E.SR}''(w^*))} > 0 \qquad 3.10$$

Which means that, as the value of the riparian buffer tax credit increases, the buffer size is expected to increase. This would happen only if the revenue made from selling selective harvested forest and applying for the riparian buffer tax credit is greater than the discounted value of the planted forest combined with the revenue from selling the SMZ trees, which is not so realistic. This is because to maximize the value of the land, there are competitive options, and the one with the highest value/acre will be chosen. We can also see that if carbon sequestration is considered, which could be implemented through a higher riparian buffer tax benefit payment, if the price of carbon increase, we would expect the SMZ to increase too, as long as the SMZ value per area is greater than the value generated from planting pines. This would imply that the productive area would become a conservation area, which is not so realistic, but could happen under great conservation incentives. Next, we proceed to the comparative statics for the interest rate.

$$\frac{\partial w^*}{\partial r} = \frac{\frac{\partial FOC}{\partial r}}{\frac{\partial FOC}{\partial w^*}} - \frac{\frac{-t * e^{rt}[P_P - C]}{1 - e^{-rt}}}{\lambda(\mathrm{E.SR}''(w^*))} < 0 \qquad 3.\ 11$$

Which means that as the interest rate increases, the SMZ width decreases (if not at the environmental protection lower bound yet) because the opportunity cost of the money has increased, and the landowner is better off planting more pines. Next, we present the comparative statics for a change in the slope.

$$\frac{\partial w^*}{\partial S} = \frac{\frac{\partial FOC}{\partial S}}{\frac{\partial FOC}{\partial w^*}} - \frac{\lambda.\mathrm{E.SR}''(\mathrm{S})}{\lambda(\mathrm{E.SR}''(w^*))} = - \frac{\mathrm{SR}''(\mathrm{S})}{\mathrm{SR}''(w^*)} > 0 \qquad 3.\ 12$$

Equation 3.12 suggests that an increase in SMZ slope will demand a wider SMZ protection, ceteris paribus. Lastly, aware of the benefits from other BMPs apart from SMZs in reducing soil erosion levels from harvesting activities (Hawks et al., 2022), as well as the relationship between amount of soil erosion in a land with site characteristics and management choices (Renard, 1997; Ward & Jackson, 2004), we now proceed to the comparative statics analysis to understand how the optimal width should change as erosion values change, ceteris paribus.

$$\frac{\partial w^*}{\partial E} = \frac{\frac{\partial FOC}{\partial E}}{\frac{\partial FOC}{\partial w^*}} - \frac{\lambda.\mathrm{SR}'(\mathrm{w})}{\lambda(\mathrm{E}.\mathrm{SR}''(w^*))} > 0 \quad 3.13$$

The positive sign highlights that an increase in erosion levels demand an increase in the SMZ, ceteris paribus, the same way as a reduction in erosion (through better BMPs implementation, for example) would allow for a reduction in the optimal SMZ width, ceteris paribus.

3.3. Empirical examples

We use an empirical example to highlight how the methodology can be used to determine the tradeoff value between water quality standards and SMZ opportunity costs. In our hypothetical example, we assume a total loblolly pine forest volume for a 35 years old forest (hypothetical private optimal rotation age) of 99 tons/acre (245 tons/ha) (Thomas, 2018) and an average sawtimber stumpage price of USD25.87 (http://www.timbermart-south.com/prices.html). Considering everything is sawtimber at this forest age, we arrive at an average net income for the productive area of USD6,328/ha at the harvesting age[8]. For our analysis, we assume that the SMZ selective harvesting value/SMZ acre is 50% of the average value/acre harvested in the productive area. If the landowner/logger decides to harvest inside the SMZ, the riparian buffer tax credit value per SMZ acre is 12.5% of the per acre value found in the productive area (VDOF, 2011). If the landowner/logger does not harvest inside the SMZ, this value is 25% of the per acre value found at the productive area (VDOF, 2011). The net income for the SMZ riparian buffer tax credit, and the other assumptions such as private interest rate, SMZ value per hectare according to SMZ selective harvesting decisions, forest establishment cost, and land dimensions are presented in table 3.1.

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[8] Although these are high values, it does not impact on the SMZ optimal decisions and the opportunity cost of different policies, since both policy objective values would change by the same amount.

Table 3. 1: Objective function assumptions.

	Assumed values
River length (meters)	400
SMZ value/ha (U$/ha) through selective harvesting	3,164
Tax credit revenue/ha (U$/ha) – With selective harvesting	791
Tax credit revenue/ha (U$/ha) – Without selective harvesting	1582
Pine net income/ha (U$/ha)	6,328
Interest rate (%)	5
Forest Rotation age (years)	35
Land width (meters)	500
Initial SMZ width (meters)	15.2
Forest establishment cost (U$/ha)	250

As described in table 3.1, our hypothetical land is 400 meters by 550 meters, representing a total of 22 hectares. In this hypothetical example, we divide the river length into four sections to determine erosion arriving at the border of the SMZ, as well as the total sediment delivery accepted for each 100 meters section.

In terms of the problem constraint, to the best of our knowledge, no previous experiment has determined SMZ sediment retention as a function of SMZ width, slope, and soil texture. Part of it is because of the natural stochasticity present in the erosion process, and part because it is hard to control for all the variables that impact the soil retention capacity and create a causal relationship between the SMZ characteristics and its retention capacity. For these reasons, we use data simulated from the Water Erosion Prediction Project (WEPP) (Laflen et al., 1997), which allows us to estimate different erosion rates and calculate different sediment retention values, as we vary SMZ characteristics (slope, soil texture, and width).

For the WEPP simulation part, we used constant weather information for Blacksburg, VA. In terms of soil texture, we run the simulation for sandy, clay and silty textures. For SMZ forest width, we considered a range of values from two to 90 feet buffers. Lastly, we vary slopes from one degree to 15 degrees. After the simulation, we ended up with a total of 280 simulated erosion and sediment delivery values, which were used to create our model that determines SMZ soil retention capacity as a function of SMZ slope, soil type and width. It is important to re estate that our model has its intrinsic limitation because the data used for its creation comes from a simulation. The final model is described in table 3.2:

Table 3. 2: Regression result

	Model	
(Intercept)	-1.8658	***
	(0.0943)	
ln (SMZ width)	0.6607	***
	(0.0202)	
ln (SMZ slope)	-0.398	***
	(0.0300)	
Sandy soil	0.5518	***
	(0.0409)	
Silt loam soil	0.2149	***
	(0.0279)	

*** $p < 0.001$
Standard errors are reported in parentheses.

In table 3.2, standard errors are robust, and the dependent variable is ln (retention). The residual's graph with a lowess curve is presented in Figure D.1 in the Appendix D section. SMZ erosion retention increases at a decreasing rate as its width increases. In terms of SMZ slope, an increase in slope decreases the retention, but at an increasing rate.

We now proceed with a hypothetical scenario. To define total erosion and get a value for the SMZ slope, we divide the river into sections. Each section is 100 meters long, and we assume the only erosion arriving at the boarder of the SMZ section comes from the near 100 meters perpendicular to the SMZ boarder (making it an assumed total of one hectare of land bringing erosion to the boarder of the SMZ independently on the determined optimal SMZ width). To start with an erosion value that reaches the SMZ border, we consider similar values found by Fielding et al. (2022), but with the difference that we convert their values to tons arriving at the SMZ border. The erosion process stays for the following years post-harvest, but since the forest is being developed, this value decreases with time (Aust & Blinn, 2004), which means that if the buffer can protect the stream for the first year, it will protect it for the following ones as well. The value we use for the erosion arriving at the SMZ border, per 100 meters section is 6 tons (similar value converted from the 2.2 tons/acre/year and 2.7 tons/acre/year for the Coastal Plain and Piedmont regions, respectively by Fielding et al. (2022)). The accepted sediment delivery value assumed in this analysis is assumed to be of 1 ton/section, which means that each SMZ section needs to retain 5 tons of eroded soil. The considered SMZ slope for the sediment retention equation is the average value for that section width (inside the SMZ).

Next, figure 3.2 exemplifies a hypothetical example on how SMZ width allocation can be determined according to the assumed accepted sediment delivery values, erosion rates and SMZ slopes, using our proposed methodology, as opposed to a fixed SMZ width. To find the optimal width for the different scenarios, we used the nloptr function from R Studio.

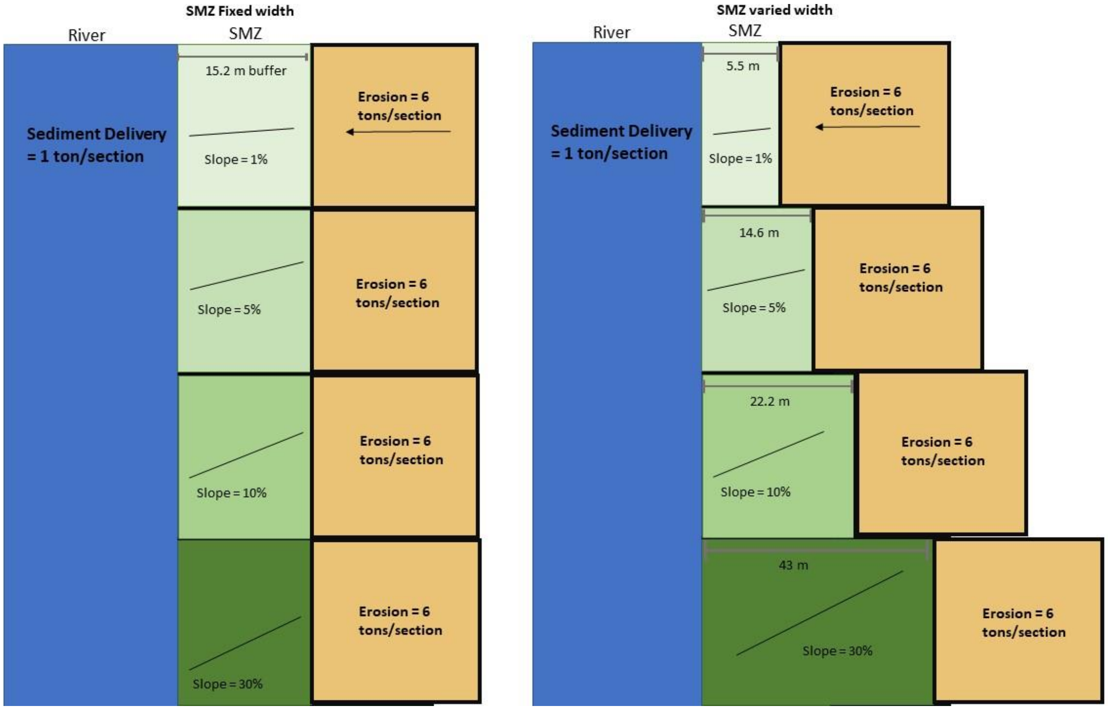

Figure 3. 2: Fixed and varied SMZ width hypothetical example for a sandy texture soil in Virginia

In this hypothetical example, SMZ slope is determined for every 100 meters section (four sections in total for the hypothetical land). An average slope value for that section is determined, and then this value becomes an input in the maximization problem. See that in the varied SMZ approach, as the SMZ slope increases, the control variable also increases to guarantee the minimum water protection standard.

For each section, the optimal width value is determined and plugged back in the maximization problem to obtain the objective function value, which tells us how much money could be generated in our hypothetical land. For the exact same hypothetical land, we now calculate how much it would cost to create a policy that, instead of allowing for 1 ton of sediment delivery, decreases the allowed value to 0.5 ton, which helps us visualize what the opportunity cost of water protection is through a reduction in the total objective function value. The new scenario is described in figure 3.3.

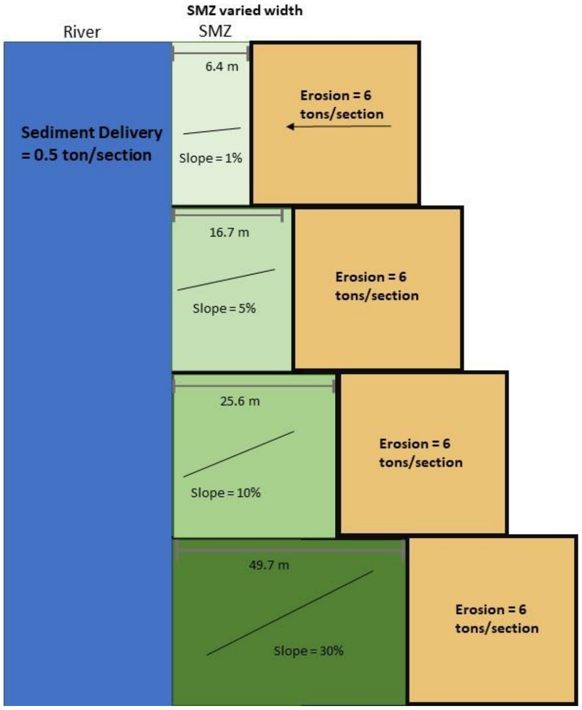

Figure 3. 3: Hypothetical application of variable width for a sandy texture soil with 0.5 tons of allowed sediment delivery.

Next, we present table 3.3, which shows how the objective function value changes for different sediment delivery policy scenarios (fixed SMZ width, 0.5 ton/section and 1 ton/section), assuming the values presented in table 3.2 for this hypothetical land.

Table 3. 3: Objective function values for different SMZ slopes under different policy regimes for the hypothetical analyzed land (using assumptions from table 3.2)

		Accepted sediment delivery (tons/section)	
	Fixed width (15.2 m)	**1**	**0.5**
Slope section (%)	**Objective function (U$/section)**	**Objective function (U$/section)**	**Objective function (U$/section)**
1	$ 68,699	$ 69,705.71	$ 69,626.30
5	$ 68,699	$ 68,868.60	$ 68,659.28
10	$ 68,699	$ 68,169.83	$ 67,852.11

30	$ 68,699	$ 66,249.38	$ 65,633.65
Total present value in USD for the hypothetical land	$ 274,797.25	$ 272,993.51	$ 271,771.33
Present value in USD/ha	$ 12,490	$ 12,408	$ 12,353

Different policies imply different SMZ widths. For our hypothetical land, table 3.4 presents the total SMZ area.

Table 3. 4: SMZ area under different water protection standards

	Accepted sediment delivery (tons)		
	Fixed width (15.2 m)	**1**	**0.5**
SMZ size (ha)	0.608	0.853	0.984

If land size, or stumpage prices increase, the objective function increases, but their difference keeps constant since they would increase in same amount for all scenarios. We now proceed to two different comparisons. First, we compare the fixed SMZ width with the proposed varied SMZ width under the assumption of one ton of sediment delivery acceptance. Second, we compare the varied width methodology under two different accepted sediment delivery values (0.5 ton and 1 ton).

For our first comparison in this hypothetical example, moving from a fixed SMZ width to a varied SMZ width where we accept one ton of sediment delivery per section in the stream means an increase in SMZ size from 0.608 ha for the fixed width, to 0.853 ha for the varied width. In this specific example, the objective function decreases by U$1,803 and although we see a reduction in the objective value, there is an increase in water protection. In this specific scenario, there is a USD7,359/SMZ ha (USD1803/.245SMZ ha), which means that the opportunity cost of increasing 1 ha of SMZ area in our hypothetical land is USD7,359 through a reduction in the objective function value. Implementing the proposed methodology is a question on how much the erosion negative externality in this hypothetical land would bring to the whole society. Referring to the total value presented in table 3.3, if the cost of cleaning the water is greater than the gain in the objective function obtained by staying with the fixed SMZ width (USD1,803), the policy maker should proceed with the varied width approach. Conversely, if the costs of water cleaning, combined with the possible fish and wildlife losses due to excessive sediment delivery are smaller than the gain in the objective function obtained by sticking to the fixed width buffer, the policy maker could stay with the fixed SMZ width approach.

For our second comparison on different allowed sediment delivery values for the varied SMZ width approach, we can see that moving from a more relaxed policy (allowing 1 ton of sediment delivery per section) to a stricter one (0.5 ton per section), increases the total SMZ area from 0.853 ha (sum of the SMZ total area) in 1 ton of sediment delivery per section scenario to 0.984 ha under a 0.5 ton of sediment delivery scenario. This represents the increase in SMZ opportunity cost through a USD1,222 reduction in the total objective function (USD 9,328/SMZ ha). By referring to table 3.3, this implies that if the reduction in cost of treating the water quality for this hypothetical land tract is greater than USD 1,222 (SMZ opportunity cost of the new policy in this example), then the stricter policy should be implemented, otherwise, it should not, because the costs of cleaning the water would be greater than the benefits the new policy brings.

Both mentioned scenarios are hypothetical examples, completely dependent on the assumptions made, and the same analysis could be done relaxing different parameters according to different landscape and policy scenarios. In defining if a policy should be implemented, each scenario must be analyzed individually to obtain a more accurate cost benefit analysis, as well as with more accurate data and information about erosion, sediment retention, as well as the costs of cleaning water from excessive soil erosion.

3.4. Discussion and Conclusion

We demonstrate a novel approach to enhance our current Streamside Management Zones width design and calculate their opportunity costs based on specific landscape characteristics and regulation scenarios, revealing that the conventional fixed SMZ widths design can be enhanced. By optimizing SMZ allocation according to landscape characteristics, environmental regulations, and total generated harvesting erosion, we can increase social net benefits. Our method is adaptable and can potentially be extended for specific land conditions, such as inundation and saturated areas as proposed by Creed et al. (2008), or presence of upland-originating groundwater as suggested by Kuglerová et al. (2014), for example.

Several factors influence the design, and consequently, the opportunity cost of SMZs. A higher SMZ slope, higher soil erosion rate reaching the boarder of the SMZ (due to land conditions, soil texture, such as clay as opposed to silty or sandy, or bad harvesting practices with poor BMP implementation quality), or stricter water quality policies imply a wider SMZ and therefore, elevate SMZ opportunity cost. Conversely, smaller SMZ slopes, a decrease in erosion values (possibly present when better BMPs are applied), or relaxed sediment delivery acceptance levels can reduce SMZ width, thereby increasing the planted pines productive area and reducing the SMZ opportunity cost.

Our approach sets a water quality environmental protection constraint that ensures a lower boundary for SMZ widths, which guarantees water quality, assuming our sediment delivery function assumptions hold. Whenever a reduction in SMZ width does not compromise water quality, landowners can increase their productive area by adjusting the initial fixed SMZ width and increase their land value. By a continuous improvement in BMPs such as in roads, decks, and skid trails, which generate the highest percentage of erosion in the piedmont region (63%), as found by Barrett et al. (2016), we can reduce the total generated erosion, therefore reduce SMZ width and its opportunity cost.

While our empirical example uses data of sediment retention generated from WEPP, our model could further benefit from the establishment of a controlled field experiment for refinement. Although the simulated data is for landscape values in Virginia, it could be easily adapted for other global scenarios. Looking forward, we could make use of remote sensing for mapping the suggested SMZs, and LIDAR to detect micro slopes, flow accumulation and flow directions to gain accuracy and information about local landscape characteristics, which are not considered in our current method. Although not considering specific scenarios, the policy could be implemented for shared landscape characteristics, such as physiographic regions, where each group could follow the same recommendation to facilitate its implementation. Lastly, our generic model is capable of defining different site index for different regions through different private optimal rotations and stumpage prices according to geographic location, which would be translated in different SMZ opportunity costs for different land characteristics and geographic locations.

In conclusion, our research introduces a method for designing and calculating SMZ opportunity costs that highlights the potential of improving fixed SMZ widths. By optimizing SMZ allocation according to landscape characteristics and water protection standards, we can maximize social net benefits while protecting and enhancing water protection from forest harvesting operations. As we continue to advance forestry Best Management Practices and explore additional sources like LIDAR, our approach has great potential to advance forest management strategies to enhance private investments in parallel with environmental protection efforts.

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4. TREE PLANTING CHOICE AND THE IMPACT IN CROP LOSSES IN INDIA

Abstract

Climate change and food security are highly related, demanding a comprehensive understanding of its impact on agricultural practices and in production alternatives, as extreme weather events become more common. We collect data among household farmers in India to investigate socio economic factors and revealed management choices characteristic influencing their tree planting decision when compared to planting agricultural crops. Our analysis is divided into two parts. In part one, we model which factors impact the decision of planting tree species, compared to planting agricultural crops through a multinomial logit model. We find that time working off-farm, elevation, plot average area, and number of managed plots are the most common statistically significant positive factors impacting households' decisions, while irrigation is the most common statistically significant factor negatively impacting the choice of planting tree species compared to agricultural crops. In part two, we employ a probit model and estimate the probability a household will face crop loss according to their socio-economic and revealed management choices. We find that tree planting, especially Eucalypt or Casuarina, palm trees, and mixed trees, significantly reduced the probability of facing losses when compared to planting solely agricultural crops. These results underscore the potential of tree planting in improving farmer's resilience by mitigating the adverse effects of climate change on food security. Through our results, we provide valuable insights for policymakers and farmers in creating a more secure and resilient future in food and income sources for a future of increased environmental uncertainties.

Keywords: food security, climate change, tree planting, binary choices

4.1. Introduction

Forests are being converted to crop production areas due to population growth that demands more food (Ashraf et al., 2015), and also due to an increase in temperature anomalies that cause crop damages (Zaveri et al., 2020). As a result of the decrease in forested area, climate change problems are increasing (Worku et al., 2018), and increasing environmental problems, such as soil erosion, decrease in soil fertility and biodiversity, and increase in poverty (Ndayambaje et al., 2012). With the intensification of climate change problems and its consequential extreme weather events, food security and food safety are threatened (Mirón et al., 2023) as crop damages become more common (Malhi et al., 2021). In this manuscript, we study how tree plantation may reduce the household's probability of facing a crop loss (where the planted trees are also considered as a crop). We start by modeling how Indian rural household demographics, socioeconomics, geographic, and revealed management choices impact their tree planting choices compared to planting solely agricultural crops, followed by how tree planting species may reduce the frequency of losses faced by households in India. We hypothesize that all planted trees reduce the probability of facing a loss when compared to crops, given trees' higher resilience to extreme weather events. With the predicted crop loss probability model, we suggest policy mechanisms to eliminate or mitigate future crop losses and enhance food production security and income diversification for households in India.

India is an agricultural country with 54.6% of its workforce connected to agriculture and related sector activities (Eliazer Nelson et al., 2019). With variable climatic conditions due to its geographic location, with most of it being in the tropics, India allows the cultivation of cereals, pulses, oil seeds, horticulture, and different vegetables (Pimentel & Peshin, 2014, Chapter 9). Before 1960, many Indian people were under famine conditions and an increase in crop production was achieved by increasing the crop area (Singh, 2000). Once the area availability became more scarce, the increase in crop production happened with the Green Revolution that improved technologies, implemented high yielding crops (HYC), as well as management practices such as the use of fertilizers, tractors and pesticides, which combined increased crop productivity from 72×10^6 Mg in 1965–1966 to 203×10^6 Mg in 1998–1999, through increasing the planted area and crop productivity (Parayil, 1992).

Together with the increase in crop productivity, the Green Revolution also brought costs, such as the increase in crop losses caused by pests because of the increase in monoculture systems, for example (Pimentel & Peshin, 2014, Chapter 9). There was an increase in the focus of planting subsidized high yielding crop monocultures, which caused a decrease in varieties and the genetic pool of crops that were cultivated before the Revolution (Eliazer Nelson et al., 2019). New varieties were created to generate higher crop yields when fertilized and irrigated (Parayil, 1992), and with the excessive use of fertilizers and irrigation, soils lost its main physical and chemical functional characteristics, and water bodies increased their amount of phosphate and nitrate (Singh, 2000). With the losses in soil quality, farmers started to use disproportional management practices to increase their yield production, as stated by Eliazer Nelson et al. (2019). With the excessive use of chemicals on crop monocultures, pests became more common, and although the use of pesticides increased, crop losses did not reduce due to pest resistance (Shetty, 2004), and also because of excessive use of chemicals killing pests' natural enemies (Shatty, 2000).

At the same time that natural resources are impacted by unplanned land use and management originated in the Green Revolution, issues of climate change from industrial development caused an increase in the occurrence of extreme weather events such as heat waves, floodings, droughts, and storms that impact crop production (Gomez-Zavaglia et al., 2020). It is important to mention that food production per se is a catalysator of climate change through the emission of greenhouse gases, and this highlights the importance of finding production alternatives that reduce crop production' footprints (Gomez-Zavaglia et al., 2020). Crop production and climate change are extremely corelated (Tonnang et al., 2022), and as climate change impacts increase, it is important to understand how crop security in India is going to be impacted, given its high reliance on agricultural production and how climate variables change impact crop production (Bhardwaj et al., 2022).

Tandzi (2020), in chapter 2, classified factors influenced by climate change that cause yield losses as technological, environmental, and biological (where losses by pest attacks are included, for example), with climate variables such as temperature, water availability and increase in CO_2 levels having direct impact on the amount of pests (Lehmann et al., 2020; Skendžić et al., 2021). Iizumi et al. (2018), for example, estimated a negative impact of climate change on crop production from 1981-2010 compared to preindustrial levels, and Tonnang et al. (2022), highlighted how the rise in temperature affects insect status and cause crop losses. As climate issues evolve and exacerbates the problems with pest attacks through the increase in pests geographic areas, weather survival, the number of pest generations, increase in the risks of having invasive species attack, and plant disease transmitted by insects, it is important to monitor and look for management alternatives (Skendžić et al., 2021).

With tree plantation, some of climate issues can be minimized through better soil stabilization and higher water infiltration (Ma et al., 2009), through the prevention of land degradation (Pandey et al., 2015), reduction of the impact of extreme weather events, increase in biodiversity and by providing improved food security systems (Wollenberg et al., 2009). Besides the vulnerability reduction, trees plantation diversifies households' income and increase food security, by reducing the dependency on monocultures, and provide an increase in organic matter, which can help increasing crop productivity with a more fertile soil (Wollenberg et al., 2009).

Research on household decisions to plant trees exist (Ashraf et al., 2015; Ndayambaje et al., 2012; Schons et al., 2022). Ashraf et al. (2015) developed a binary logistic regression and found household's cropping area, family income, the experience of tree planting faced by the head of the family, the access to irrigation, household head's education level, and seedling availability to have a significant impact on tree planting decision. They found that farmers with better land quality are producing for welfare, but also opting for new initiatives, such as planting trees (Ashraf et al., 2015). Ndayambaje et al. (2012) also developed a binary logistic regression and found that factors impacting tree planting decisions included the gender of household head, the amount of salaried household members, quantity of fuelwood in the farm, number of meals in a day, house location and if they sold any tree products. Schons et al. (2022) found that average travelling distance from home to the planting plot, land tenure time, land area, time spent working off-farm, and elevation to be statistically significant and positive in predicting the decision of planting trees. On the other hand, scheduled tribes compared to forward caste, irrigation, if they have taken loans in the past were statistically significant and negative in predicting the decision of planting trees. In terms of tree species, Ndayambaje et al. (2012) found that factors impacting its presence were mainly economical, such as food availability, poles, and firewood, and total household income.

To understand how tree plantation can help households reduce their losses risk and at the same time diversify their income sources, we now proceed to our analysis where we first determine what factors impact the tree species choice, followed by the crop loss modeling. The rest of the paper is organized as follows: In our methods section we present the theoretical model for the household's choice with the econometric specification. Next, we present the results of both models and then we conclude.

4.2. Methods

4.2.1. Household decision – Tree species choice

Our main interest is to understand which factors impact the tree species planting decision, followed by how tree planting may reduce the probability a household faces crop loss. We seek to understand which factors make households move from agriculture production to tree planting in any of the plots they manage. The decision we analyze is important for public goods production, as well as a risk diversification approach for a place where climate change extreme weather events become each time more common.

We now proceed to a simple decision making model by farm households to understand the choice between planting agricultural crops and planting trees. The specie choice is dependent on the rent from all decisions the household makes for the whole farm and land the household owns. Our theoretical model follows the same structure as the one presented by Schons et al. (2022):

$$T - d = L_C + L_F + L_O \tag{4. 1}$$

where T is the total time for a household, d is assumed to be exogenous and represents the time spent from the house to the market and/or to the managed plots, L_C is the time allocated for crop production, L_F is the time devoted for forest production, and L_O is the time devoted to work outside the farm (Schons et al., 2022). Now the household's decision is to maximize the utility $U(l, C_b, \theta) = U(T - d - L\ , C_b; \theta)$ which is dependent on the time allocated for income activities L, the household's own consumption C_b and other exogenous factors that provide utility to the household.

The household also faces an income constraint, where all the income must be equal to the expenses necessary to produce the crops and tree planting, summed to their own consumption. As in Schons et al. (2022), let income $I = I_{ex} + I_o + (Q - C_b)P_a + FP_{f_s}$ where I_{ex} is the exogenous income or assets, $I_o$is income from off-farm work, Q is crop production, P_a is the market price obtained from selling crops left after consumption, and P_{f_s} is the market price obtained from selling tree species s. By combining these definitions, we arrive at:

$$I = I_{ex} + \ I_o + (Q - C_b)P_a + FP_{f_s} = wL_H + rK \qquad 4.\ 2$$

Where Q and F are household's production relating outputs to all important inputs from labor and non-labor sources, and the other variables that impact the production of income.

$$Q = Q(L_c, K, L_H, \nabla) \qquad 4.\ 3$$

$$F = F(L_f, K, \nabla) \qquad 4.\ 4$$

Where ∇ is household accounts experience from the household and farm characteristics that are relevant in the production function. The household's problem, constrained to the income value can now be represented as follows:

$$\max_{L, C_b, L_H, K, C_P, S} U(T - d - L\ , C_b; \theta) \qquad 4.\ 5$$

$$s.t.: \ I_{ex} + \ I_o + (Q - C_b)P_a + FP_{f_s} = wL_H + rK$$

where S is the tree species choice, and the optimal decisions in terms of labor time, consumption level, use of hired labor, and for the other inputs can be found through deriving the first order conditions.

4.2.2. Econometric specification of the tree species choice

The household will choose the tree species that provides the highest indirect utility. The decision to plant trees is captured by a variable T_{ij} where i represent each household, and j is divided in the following categories:

0: If the household plants no trees across its plots – Our reference group.
1: If the only tree species the HH plants at least in one of the plots is for fiber production (Eucalyptus or Casuarina).
2: If the only tree species the HH plants in one of the plots is Palm
3: If the only type of tree species the HH plants in one of the plots is for fruit production
4: If the HH plants a combination of tree types (of 1-3) in one of the managed plots.

The household will choose $T_{i1}\ if\ V_{i1} > V_{ij}\ \forall\ j$.

The indirect utilities are not observed. For this reason, we determine the probability of a household i to choose tree species j (Y_{ij}) as a function of observable variables, as follows:

$$Y_{ij} = g_{ij}\beta + \epsilon_{ij}, \epsilon_{ij} \sim N(0, \sigma^2) \qquad 4.\ 6$$

In Equation 3.6, g_{ij} is a vector of h independent variables, β is a $hx1$ vector with the independent variables estimated parameters, and ϵ_{ij} is a random error term.

4.2.3. Econometric specification – Crop loss probability

The probability y_i a household i will face a crop loss is a function of observable variables, where:

$$y_i = g_i\beta + \ \epsilon_i, \epsilon_i \sim N(O, \sigma^2)$$

Where g_i is a vector of h independent variables, β is a $h\ x$ 1 vector of coefficients to be estimated, and ϵ_i is random error assumed to be Normally distributed with mean zero and σ^2 variance. An estimable model of loss has the following form:

$$\Pr(F_i = 1|g_i, \epsilon_i) = \Pr(y_i > 0|g_i, \epsilon_i) = \Psi(\mathrm{g_i}\beta + \epsilon_i) \qquad 4.7$$

The parameter β is estimated using the maximum likelihood procedure. To obtain the impact of a one unit increase of any independent variable on the probability a household faces a loss, we can develop the marginal effect, $\frac{\partial\Psi(\mathrm{g_i}\beta+\epsilon_i)}{\partial\mathrm{g_i}}$, which provides us important information to understand how losses can be changed as the household chooses different inputs.

4.2.4. Data collection

The data was collected across four villages in the districts of East Godavari and 16 villages in West Godavari, totaling approximately 2000 observations. The samples were selected proportional to the forest cover observed from satellite images. The villages were divided into two groups: villages with more than 60 ha of forest cover, and villages with less than 60 ha of forest cover. Please see Schons et al. (2022) for detailed information on the methodology for selecting households, as well as on the chosen villages.

4.2.5. Data descriptives

We divide our descriptive statistics data into three subsections: General information, tree species choice, and crop loss. We start by showing the descriptive statistics in Table 4.1 related to household information, as well as farm characteristics.

Table 4. 1: Household information descriptive statistics

	Frequency	Mean	SD	Min	Max
Age	2213	47.15	12.17	19	90
Years worked on land	2413	21.79	13.55	0	90
Farm ownership (dummy)	2425	0.92	0.07	0	1
Years of schooling	2392	3.19	4.18	0	17
Number of managed plots	2318	1.26	0.60	0	7
Total land area	2425	3.50	7.38	0	300
Total number of animals	2425	3.91	13.92	0	505
Travel time to market	2411	35.68	23.55	0	230
Off-farm workdays	2318	34.49	49.26	0	350
Rain days	2419	122.31	40.49	0	275
Cooperative participation (dummy)	2394	0.11	0.31	0	1
Technical assistance (dummy)	2359	0.05	0.22	0	1
Contract for planting trees (dummy)	2288	0.03	0.18	0	1
Irrigation	1883	0.71	0.45	0	1

The average age of the household is 47.15 years old, and they have been working on the land for approximately 22 years, on average. 92% of our observations were on households that own the managed farms, and they manage, on average, 1.26 plots, which are defined as a managed land with undefined size. Total land area is on average 3.5 ha, and the average number of animals is approximately 4 per interviewed household, on average. Irrigation is available on 71% of the analyzed households. Next, in table 4.2 we present the frequency of each cast group in our data.

Table 4. 2: Castes' frequency

Caste	Frequency
Scheduled class (SCs)	364
Scheduled Tribes (STs)	320
Other background class (Obcs)	873
Forward Caste/Others	837
Total	2,394

Most observations are from "other background class" castes. In table 4.3, we describe the frequency of each tree species choice combined with a dummy variable that describes if the household faced losses in the past year, together with their respective percentage values.

Table 4. 3: Crop loss and crop planting choice

Crop Loss	Ag. Crops	Fiber	Palm	Fruits	Mixed	Total
No	647	137	91	181	82	1,138
Yes	862	36	84	242	33	1,257
Total	1,509	173	175	423	115	2,395
Percentage No	43%	79%	52%	43%	71%	48%
Percentage Yes	57%	21%	48%	57%	29%	52%

Crop loss was greater than no crop loss when looking at agricultural crops (57% of households faced crop loss) and fruit production (57% faced crop loss). For the other tree species, no losses were more common than losses. On the other hand, fiber, palm, and mixed tree species present in one of the household's managed plot presented a higher percentage of "no crop losses", with fiber production being the highest (79%). The higher number of households planting agricultural crops (1,509) compared to planting tree species is expected for a developing country such as India that prioritizes food production, besides the fact that planting trees demand a higher upfront cost and a longer time to obtain the benefits (Schons et al., 2022).

When looking at households that faced crop loss, the most frequent reason was pest invasion, as described in table 4.4.

Table 4. 4: Crop loss reason

Crop loss reason	Frequency
Illegal Harvesting	1
Fire	21
Animal Invasion (Like Monkeys)	21
Other	104
Flood	134
Cyclone	207
Drought	302
Pest Invasion	476
Total	1,266

Although Andhra Pradesh is considered to be a hotspot in terms of pesticides use (Shetty, 2004), we can see that pest invasion is the main cause of crop losses.

4.3. Econometric Results

4.3.1. Predicting tree species planting choice

We start our econometric results by presenting the tree species choice model. The independent variables used in our model include the following variables: Years worked on the land to control for the household's experience, schooling year to analyze if education impacts the tree planting choice in one of the managed plots, the time working off-farm since forest, once established, is less work intensive (Schons et al., 2022), herd size, household's age, if the household participates in any cooperative, the castes (where "scheduled classes" caste is our reference group), the plot average area, as well as the number of managed plots, land elevation, the number of neighbors planting trees, and if there is irrigation. Our dependent variable is categorical and planting no tree species (also described as Agricultural crops plantation) is our reference group.

Table 4. 5: Multinomial logit model on crop planting choice.

VARIABLES	Ag. Crop	Fiber	Palm	Fruits	Mixed Trees
Years worked on the Land		0.00207	0.0167	-0.000966	0.0178
		(0.0205)	(0.0120)	(0.00853)	(0.0146)
Years of School		-0.0234	-0.0248	-0.00126	-0.0456
		(0.0533)	(0.0310)	(0.0234)	(0.0337)
Time working off-farm		0.0122**	-0.00260	0.00657***	0.00720***
		(0.00582)	(0.00345)	(0.00195)	(0.00251)
Herd Size		0.0876***	-0.0839***	0.00883	-0.0552
		(0.0311)	(0.0294)	(0.0290)	(0.0650)
Household age		-0.0212	-0.00845	0.00378	-0.0306***
		(0.0194)	(0.0137)	(0.00571)	(0.00912)
Participation in Cooperatives		-0.154	-0.350	-0.184	-0.0279
		(0.831)	(0.562)	(0.248)	(0.416)
Schedule Tribe Caste		-1.333	-0.489	0.0296	-0.428
		(0.834)	(0.356)	(0.256)	(0.342)
OBCS Caste		0.208	-0.893***	-0.449	-0.738
		(0.455)	(0.322)	(0.452)	(0.675)
Forward Caste		0.555	0.191	0.404*	-0.195
		(0.618)	(0.203)	(0.222)	(0.298)
Plot Average Area		0.0837**	0.0350	-0.0892	0.0580**
		(0.0347)	(0.0233)	(0.0621)	(0.0235)
Elevation		0.00453**	0.00421*	0.000951	0.00331
		(0.00207)	(0.00247)	(0.00216)	(0.00693)
Neighbors Planting Trees		-0.0932	0.00153	-0.0606	0.0730**
		(0.268)	(0.0385)	(0.0599)	(0.0291)
Irrigation		-1.293***	2.004***	-1.653***	1.247*
		(0.474)	(0.498)	(0.531)	(0.713)
Average distance to the Market		0.0145	0.00722	0.000686	0.0213***
		(0.00949)	(0.00449)	(0.00721)	(0.00436)
Number of Managed Plots		0.969***	0.524***	0.522**	1.483***
		(0.337)	(0.164)	(0.243)	(0.302)
Constant		-4.795***	-4.389***	-1.267**	-6.020***
		(0.787)	(1.320)	(0.621)	(0.654)
Observations	1,653	1,653	1,653	1,653	1,653

Clustered standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Referring to table 4.5, all the comparisons are made against the reference group (Agricultural crops). Logistic regression parameters are interpreted as the log of odds, which can be represented as the $\log\left(\frac{p(a)}{p(1-a)}\right)$, where the numerator is the probability of "a" succeeding over its probability of failure. To facilitate the interpretation, we take the exponential of the parameters found, so we are left with the odd changes as an independent variable change by 1 unit. We take the exponential of each parameter from table 4.5 and then subtract it by 1 to obtain the percentage change in odd, which is presented in table 4.6.

Table 4. 6: Odds values.

Variables	Odds change							
	Fiber		Palm		Fruits		Mixed Trees	
Years worked on the Land	0.21%		1.68%		-0.10%		1.80%	
Years of School	-2.31%		-2.45%		-0.13%		-4.46%	
Time working off-farm	1.23%	**	-0.26%		0.66%	***	0.72%	***
Herd Size	9.16%	***	-8.05%	***	0.89%		-5.37%	
Household age	-2.10%		-0.84%		0.38%		-3.01%	***
Participation in Cooperatives	-14.27%		-29.53%		-16.81%		-2.75%	
Scheduled Tribes Caste	-73.63%		-38.68%		3.00%		-34.82%	
Other Background Class Caste	23.12%		144.24%	***	-36.17%		-52.19%	
Forward Caste	74.19%		21.05%		49.78%	*	-17.72%	
Plot Average Area	8.73%	**	3.56%		-8.53%		5.97%	**
Elevation	0.45%	**	0.42%	*	0.10%		0.33%	
Neighbors Planting Trees	-8.90%		0.15%		-5.88%		7.57%	**
Irrigation	-72.56%	***	641.87%	***	-80.85%	***	247.99%	*
Average distance to the Market	1.46%		0.72%		0.07%		2.15%	***
Number of Managed Plots	163.53%	***	68.88%	***	68.54%	**	340.61%	***

When comparing agricultural crops with fiber production, an increase in the hours working off-farm increases the odds of planting fiber by 1.23%. As the herd size increases by one unit, the odds of planting fiber increases by 9.16% compared to agricultural crops. As the plot average area increases by 1 ha, the odds of planting for fiber increases by 8.73%. With a one foot increase in elevation, the odds of planting for fiber increases by 0.45%. When there is irrigation, the odds of planting for fiber reduce by 72.56%. Finally, as the number of managed plots increases by one unit, the odds of planting fiber increases by 163.53%. When comparing agricultural crops to palm production, “other background class” caste has a 144.24% higher odd than “scheduled class” casts, for example. When comparing fruits to agricultural crops, farmers with irrigation have an 80.85% smaller odd of planting fruits. When comparing mixed trees to planting agricultural crops, an increase in the number of managed plots increases the odds of having mixed trees. On the other hand, an increase in the household’s age is associated with a 3.01% in odds of planting mixed trees.

4.3.2. Predicting crop loss.

We now proceed to the second part of our analysis, where we predict crop loss using socioeconomic as well as revealed preferences to predict the household probability of facing losses. Years of school were used as a proxy for education. We also control the number of plots a household manages. Years working on the land is used to control for how the household experience may affect crop loss, and technical assistance was used to understand if they are also effective in reducing crop losses. Caste was a categorical variable, and we used the “scheduled class” caste as our reference group. We controlled for environmental factors such as the household elevation, rain time, and the presence of irrigation. In terms of practices done at the planting time, we control for the use of fertilizers, herbicides, and the number of crops planted to understand if more biodiverse systems can reduce the probability of facing losses. Although we do not have information on the use of pesticides, we rely on the assumption that households use them given Andhra Pradesh’s label as a pesticide hotspot (Shetty, 2004), also confirmed by a recent study where 91% of interviewed farmers were using pesticides (Jaacks et al., 2022). To test our initial hypothesis that tree planting reduces the probability of facing losses in the farm, we add a categorical variable of tree choice, which is composed of the same variables presented in the model from Part 1. In table 4.7 we present our regression results with robust standard errors.

Table 4. 7: Crop loss regression results.

VARIABLES	Crop Loss
Years schooling	-0.0106
	(0.00830)
Number of Plots managed	-0.0861
	(0.0555)
Years working on land	-0.00419*
	(0.00240)
Technical assistance	0.0613
	(0.225)
Elevation	0.000284
	(0.000499)
Rain time	0.000572
	(0.000790)
Irrigation	-0.103
	(0.0773)
Caste Sts	0.299**
	(0.125)
Caste Obcs	-0.205**
	(0.0938)
Caste Forward/Others	0.105
	(0.0931)
Total land area	-0.00603
	(0.00786)
Fiber	-0.449*
	(0.260)
Palm	-0.196*
	(0.109)
Fruits	0.0332
	(0.0894)
Mixed Trees	-0.348*
	(0.201)
Fertilized	-0.409
	(0.282)
Herbicides	-0.0544
	(0.115)
Number of crops	0.0159
	(0.0955)
Constant	0.888***

	(0.327)
Observations	1,655

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

We now present the Average Marginal Effect result, to understand how a marginal change in each of our independent variables changes the probability of facing a crop loss. This was calculated by taking the marginal effect of each observation in our data, followed by averaging all the results. Final average marginal effect results are presented in table 4.8.

Table 4. 8: Average Marginal Effect for crop loss.

Variables	Crop Loss
Years schooling	-0.00407
	(0.00317)
Number of Plots managed	-0.0330
	(0.0212)
Years working on land	-0.00160*
	(0.000918)
Technical assistance	0.0235
	(0.0862)
Elevation	0.000109
	(0.000191)
Rain time	0.000219
	(0.000302)
Irrigation	-0.0396
	(0.0296)
Caste “scheduled class”	0.111**
	(0.0459)
Caste “Other background class”	-0.0803**
	(0.0365)
Caste “Forward/Others”	0.0402
	(0.0358)
Total land area	-0.00231
	(0.00301)
Fiber	-0.174*
	(0.0986)
Palm	-0.0760*
	(0.0427)
Fruits	0.0127
	(0.0341)
Mixed	-0.135*
	(0.0776)
Fertilized	-0.157

	(0.108)
Herbicides	-0.0209
	(0.0442)
Number of crops	0.00610
	(0.0366)
Observations	1,655

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Referring to table 4.8, a one year increase in years working on the land decreases the probability of facing a loss by 0.16%. If from “scheduled class” caste, the probability of facing a loss increases by 11.1%. On the other hand, if the household belongs to “other background classes” caste, the probability of facing a loss reduces by 8%. When planting fiber, the probability of having a loss reduces by 17.4% compared to planting agricultural crops. Palm production presented a statistically significant 7.6% reduction in the probability of having a loss. Lastly, when looking at mixed trees, the probability of having a loss is reduced by 13.5%, when compared to having agricultural crops. Planting fruits did not present a statistically significant result when compared to planting agricultural crops.

4.4. Discussion and Conclusions

We investigate factors that determine rural household tree species planting choice, followed by a model where we analyze how tree planting impacts the probability of having a loss in East and West Godavari districts of Andhra Pradesh, India. To answer our question about tree planting species’ choice, we use a multinomial logit model followed by a margins analysis, while to answer our question about how tree planting may reduce the probability of having loss, we use a probit model, followed by margins analysis.

Starting with the tree choice model, we find evidence that planting trees choice is positively associated with hours working off farm, plot average area, number of plots, elevation, with years worked on land as the most common factors increasing the probability of planting trees compared to planting agricultural crops. However, the presence of irrigation, herd size (when comparing agricultural crops with palm trees), and an increase in age (when comparing agricultural crops with mixed trees) reduce the probability of planting trees compared to agricultural crops.

For the crop loss model in part two, experience represented through years working on the land and tree planting compared to planting agricultural crops, with the exception of fruits, presented a statistically significant reduction in the probability a household will face losses. However, if from “scheduled tribes” class, compared to “scheduled class” caste, the probability of having a loss increases. These results can be used as a guide for policy implementation in protecting vulnerable areas and arranging production systems to reduce crop loss probability and increase food security and income generation in Andhra Pradesh.

Most household farmers that prioritize food production for own consumption are the most vulnerable farmers (Thorlakson & Neufeldt, 2012), and tree planting becomes a difficult option. If we extrapolate the benefits of tree planting by not only considering wood revenue, but also the generation of ecosystem services such as water protection, carbon dioxide sequestration, and wildlife habitat, through payments for environmental services schemes, forests could become a more attractive option. When analyzing our data, although trees are not completely protected against loss caused by extreme weather events and pests, for example, tree planting was found to reduce the probability of facing a loss when compared to agricultural crops (except for trees for fruit production). Our findings enhance the benefits of using trees as a mechanism for income diversification and risk reduction as climate change issues become more common.

Agroforestry systems can be a resilient alternative to deal with climate change issues (Thorlakson & Neufeldt, 2012) and can provide multiple ecosystem services through high crops and tree functional diversity that can be used to generate socioeconomic and ecological benefits (Hillbrand et al., 2017; Vieira et al., 2009). Besides the generation of income to the local society from crops, tree growth, energy production (Ndayambaje et al., 2012) direct benefits of agroforestry to the environment include the high biodiversity, increase in soil fertility, decrease in soil erosion, water quality protection and improvement (Hillbrand et al., 2017), and the increase in carbon dioxide sequestration compared to crop monocultures or pasture lands (Kirby & Potvin, 2007). Crop revenues, combined with the lower maintenance cost for the tree species, reduce the restoration cost and provide local work for farmers (Vieira et al., 2009). Other examples on how to minimize vulnerability to climate change issues and increase carbon dioxide sequestration include the restoration of degraded area, reduced tillage, the introduction of trees in agricultural crops, erosion control, animal waste recycling, and the use of legumes instead of N fertilization, to cite some of them (Verchot et al., 2007).

To avoid an increase in the environmental issues generated because of the Green Revolution and climate change consequences, we must guarantee the increase in crop production is obtained without additional natural resources' degradation. While we do not transition to a more diverse, resilient, and sustainable system, we must improve our controlling systems to penalizes practices that generate environmental damages, such as soil erosion and loss of biodiversity caused by our current extensive monoculture systems.

4.5. References

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5. CONCLUSIONS

This dissertation provides significant contributions to the field of forestry and environmental economics, offering valuable examples on how we can enhance both environmental and private outcomes in planted forest practices. The novel carbon dioxide sequestration methodology presented in chapter two focuses on deferred rotation age projects and aligns private landowners and social planner's interests, which makes it beneficial to society and shed lights on the challenges related to the determination of an optimal forest harvesting deferral time, which lies on the socially optimal forest deferral for carbon dioxide sequestration benefits. By accounting for the benefit of storing carbon dioxide away from the atmosphere for a longer time in sawtimber products, a more robust contract can now be expanded and tailored to specific land and market characteristics, while decreasing the probability of non-additional and inefficient projects from a social planner's perspective and potentially solving the leakage issue through the increase in forest area due to the expected increase in timber prices. For the simulated data, the chapter highlights the importance of Tauyield on the simulated example (Amateis et al., 2016). Looking forward, it would be crucial to update the assumptions, as new research is developed on each part of the proposed model for ensuring continued accuracy and applicability.

Chapter three addressed the opportunity cost of Streamside Management Zones through a proposed methodology that optimizes SMZ widths by recommending different abatement efforts (SMZ widths) based on the distinct landscape characteristics and desired level of water protection. The chapter highlights the landowner's tradeoff between the desired level of water protection and its consequential SMZ opportunity cost. The research acknowledges the benefits of using simulated data from the WEPP database (Laflen et al., 1997), but also suggests that further research could involve the creation of controlled experiments to address local conditions such as micro-slopes and landscape specificities, combined with local SMZ forest inventories to further validate and refine our optimal SMZ widths suggestions model. Additionally, further research could involve the costs associated with improving BMP implementation practices and their direct implication on the SMZ opportunity cost reduction due to smaller generated erosion. Although the empirical example was used for lands in Virginia, the methodology could also be easily adapted to different landscapes and locations. The results could be used by policymakers when determining what the social net benefits are under different water protection standards and SMZ characteristics.

Lastly, the dissertation highlights how forests can be used to mitigate the negative impacts of climate change on poverty and food production in India. As climate change extreme events and pest attacks become more common, we show that tree planting, besides providing more ecosystem services than agricultural crops, they also reduce the probabilities of facing losses. We highlight the valuable insight derived from more than 2,000 observations locally collected data and, moving forward, it would be pertinent to map the most vulnerable regions and recommend more diverse systems, such as agroforestry, and more precise planting arrangements to protect the most vulnerable crops and societies.

Overall, the insights provided in this multidisciplinary dissertation advance our understanding of forest practices' optimization and their potential contributions to adverse climate change and climate change's impact on poverty. The proposed methodologies and findings presented here contribute to the literature and have the potential to inform and improve current forest management practices worldwide, bringing a more sustainable and resilient future to society, while maximizing the benefits of the main stakeholders. We used the most appropriate assumptions and available tools, and highlight that, as we move forward, updated and more accurate research must be used as input in our proposed methodologies to keep enhancing the provided benefits. As climate change challenges persist, it is important keep integrating knowledge from different areas through innovative approaches that can be applied in policymaking and forest management strategies, as they represent a great and lasting impact to both the environment and society.

APPENDICES

Appendix A: Chapter 2 Appendices

Appendix A1: Derivative steps

The landowner’s economic maximization problem is described below:

$$\max_{N}\ pf(T+N)e^{-r(T+N)}+\left[\int_{T}^{T+N}Se^{-rx}dx\right]-C+\frac{pf(T)\ e^{-r(T)}-C}{1-\ e^{-r(T)}}e^{-r(T+N)}$$

Next, we take the first order derivative with respect to time N separated into smaller parts. For the first term ($pf(T+N)e^{-r(T+N)}$), we have:

$FOC\!:\ pf'(T+N)e^{-r(T+N)}-rpf(T+N)e^{-r(T+N)}$

We now proceed to the derivative of the second term ($\left[\int_{T}^{T+N}Se^{-rx}dx\right]$). To derive it, apply the fundamental theorem of calculus and the chain rule, which gives us the term presented below.

$$Se^{-r(T+N)}$$

Finally, for the derivative of the last term ($\frac{pf(T)\ e^{-r(T)}-C}{1-\ e^{-r(T)}}e^{-r(T+N)}$) with respect to N, we have:

$$-\ln\,(1+\mathrm{r})\left[\frac{\big(Pf(T)\big).\,e^{-r(T)}-C}{(1-e^{-r(T)})}\right]e^{-r(T+N)}$$

By combining all three terms, we have:

$$FOC\!:pf'(T+N)e^{-r(T+N)}-rpf(T+N)e^{-r(T+N)}+S*e^{-r(T+N)}-\left(\frac{\ln(1+r)\left[\big(Pf(T)\big).\,e^{-r(T)}-C\,\right]e^{-r(T+N)}}{(1-e^{-r(T)})}\right)=0$$

Here the decapitalization term ($e^{-r(T+N)}$) is a common term in all factors, so it can be eliminated. The term ln(1+r) becomes r, and the inside term ($\frac{\left(Pf(t_{LEV}^{*})\right).e^{-r(T)}-C}{\left(1-e^{-r(T)}\right)}$) is the value of the land considering infinite equal rotations post the private optimal rotation time with a one-time carbon contract assumption. This equation is finally simplified to:

$$FOC:\ pf'(T+N)+S-r*LEV-rpf(T+N)$$

By setting it equal to zero, we have that the optimal rotation happens when the marginal benefit of waiting to harvest (LHS) equals the marginal cost of waiting to harvest (RHS):

$$pf'(T+N)\ +\ S\ =\ rpf(T+N)+\mathrm{r}*LEV$$

Appendix A2: Second-order sufficiency condition

The sufficiency condition for the optimal N to be a maximum solution indeed requires that:

$$\frac{\partial^2 V}{\partial N^2}=\ pf''(T+N)-rpf'(T+N)+\ln(1+r)\,LEV\ (1+r)^{-(T+N)}<0$$

Appendix A3: Tables

Table A.3. 1: Green weight through time for 60 feet site index treatment

Age	Pulp (tons)	Saw (tons)	NPV	LEV
18	47.6	4.8	42.5	72.6
19	50.2	6.6	59.2	98.0
20	52.5	8.8	75.7	121.4
21	54.3	11.2	90.6	141.3
22	55.6	13.9	103.7	157.6
23	56.4	16.8	115.6	171.4
24	57.2	19.9	126.8	183.7
25	57.4	23.2	135.6	192.4
26	57.2	26.5	142.0	197.6
27	57.2	30.0	148.8	203.2
28	**56.7**	**33.4**	**152.7**	**205.0**
29	55.9	36.9	154.7	204.3
30	55.1	40.3	155.4	202.2
31	54.1	43.6	154.3	197.9
32	53.0	47.0	152.8	193.3

33	51.8	50.1	149.0	186.2
34	50.7	53.2	144.6	178.6
35	49.2	56.0	138.2	168.8
36	47.9	58.7	131.4	158.8
37	46.6	61.4	124.3	148.8
38	45.1	63.8	115.6	137.1
39	43.8	66.1	106.8	125.5
40	42.2	68.1	97.0	113.1
41	40.9	70.0	87.2	100.8
42	39.7	71.7	77.0	88.4
43	38.1	73.1	66.2	75.5
44	36.8	75.2	57.9	65.5
45	35.5	75.9	45.8	51.5

Table A.3. 2: Green weight through time for low 90 feet index treatment.

Age	Pulp (tons)	Saw (tons)	NPV	LEV
18	44.3	41.8	966.3	1653.3
19	43.8	48.9	1004.4	1662.3
20	42.7	55.9	1035.9	1662.5
21	41.7	63.3	1065.1	1661.5
22	**40.7**	**70.3**	**1087.9**	**1653.0**
23	39.4	77.4	1106.0	1639.9
24	38.1	84.2	1118.4	1621.0
25	36.8	90.7	1125.7	1597.5
26	35.5	96.8	1128.1	1569.5
27	34.2	102.9	1128.2	1541.0
28	33.0	108.3	1122.7	1507.2
29	31.7	113.4	1113.3	1470.5
30	30.4	118.2	1102.0	1433.7
31	29.1	122.5	1086.6	1393.8
32	27.8	126.3	1068.6	1352.5
33	26.5	129.6	1048.3	1310.2
34	25.2	132.7	1027.4	1269.0
35	24.2	135.3	1004.6	1227.1
36	23.2	137.3	980.5	1185.2
37	21.9	139.0	955.2	1143.1
38	20.9	140.3	929.5	1102.1
39	19.8	141.5	904.8	1063.4
40	19.1	142.1	879.4	1025.0
41	18.0	142.4	853.6	987.2
42	17.2	142.4	828.5	951

43	16.5	142.0	803.7	916.1
44	15.5	141.5	779.0	882.1
45	15.0	141.0	756.7	851.5

Table A.3. 3: Marginal benefit with different SDR assumptions and marginal abatement cost of deferred forest rotation age – 60 feet SI.

Age (years)	MB(SDR=5%)	MB(SDR=2%)	MB(SDR=1%)	MAC
27	190.0	76.0	38.0	-4.9
28	165.9	59.0	22.0	1.9
29	159.5	58.9	22.7	7.0
30	166.4	73.2	38.2	15.5
31	157.5	70.7	36.8	17.5
32	164.4	86.0	53.9	29.1
33	146.7	73.0	41.5	33.2
34	162.2	99.3	70.9	45.5
35	145.3	86.7	59.0	50.0
36	137.7	84.9	58.5	53.2
37	142.3	98.7	75.3	65.4
38	127.4	86.8	63.8	69.6
39	130.3	98.6	78.7	79.0
40	116.7	87.0	67.5	82.9
41	111.8	87.2	69.3	89.3
42	114.0	98.1	83.7	98.0
43	95.8	77.2	61.1	81.8
44	101.0	92.5	80.7	118.8

Table A.3. 4: Marginal benefit with different SDR assumptions and marginal private cost of deferred forest rotation age – 75 feet SI.

Age (years)	MB(SDR=5%)	MB(SDR=2%)	MB(SDR=1%)	MAC
24	183.7	73.5	36.7	-2.1
25	156.9	53.5	17.7	8.7
26	140.4	42.3	7.0	17.5
27	150.6	59.0	24.7	30.7
28	147.3	61.9	28.5	42.2
29	141.7	62.2	29.7	49.5
30	151.0	79.8	49.4	66.6
31	136.5	69.7	39.9	75.9

32	133.6	73.0	44.5	88.1
33	140.0	88.5	62.7	102.9
34	124.0	75.0	49.4	105.1
35	122.6	80.2	56.5	120.8
36	119.1	82.5	60.6	131.5
37	123.3	96.0	77.4	144.3
38	104.0	75.2	55.4	148.8
39	105.7	84.7	67.7	153.9
40	103.3	88.2	73.5	166.9
41	92.9	78.5	63.8	171.8
42	95.5	89.7	78.7	181.4
43	85.6	79.9	68.7	185.1
44	82.1	80.3	70.9	190.9

Table A.3. 5: Marginal benefit with different SDR assumptions and marginal private cost of deferred forest rotation age – 90 feet SI.

Age (years)	MB(SDR=5%)	MB(SDR=2%)	MB(SDR=1%)	MAC
19	102.8	2.7	-30.6	-0.4
20	96.9	-0.3	-34.0	1.7
21	99.2	5.1	-28.8	16.5
22	110.0	20.1	-13.5	27.6
23	111.0	25.4	-8.0	43.2
24	111.4	30.3	-2.7	58.2
25	112.3	36.0	3.6	74.8
26	108.4	36.3	4.4	82.5
27	111.5	45.1	14.4	104.7
28	111.8	51.0	21.4	122.0
29	108.8	52.7	24.1	132.0
30	110.2	60.4	33.4	152.7
31	109.4	65.5	40.2	168.9
32	108.3	70.4	46.9	184.8
33	104.3	71.1	48.9	192.6
34	97.0	66.6	45.0	209.0
35	95.5	70.6	50.9	222.5
36	100.0	84.5	68.6	237.6
37	91.2	76.9	61.3	246.8
38	86.5	75.5	61.1	249.1

39	79.9	70.5	56.5	262.0
40	82.9	82.1	72.2	273.4
41	74.8	73.8	63.7	278.4
42	72.2	75.0	66.7	285.2
43	74.0	84.9	80.8	293.7
44	60.1	63.1	54.8	283.9

Appendix B: Chapter 3 Appendix

$$\frac{\partial \mathcal{L}}{\partial w^*} = \frac{-P_P+\tau(h)-[P_P-C]}{1-e^{-rt}} + \lambda.\,\mathrm{E.\,SR}'(w^*)$$

$$\frac{\partial \mathcal{L}}{\partial w^* w^*} = \lambda(\mathrm{E.\,SR}''(w^*)) < 0$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = 0$$

Appendix C: Chapter 4 Appendix

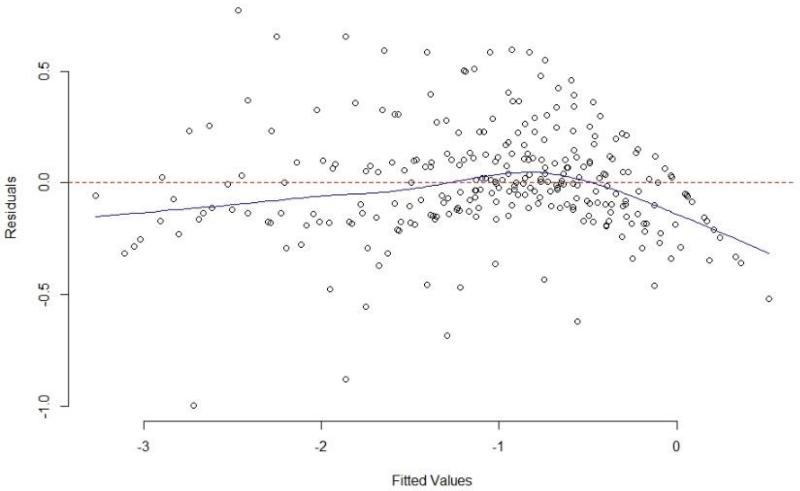

Figure D. 1: Predicted vs. residuals graph.