

## Article

# An Ecological-Economic Approach to Assess Impacts of the Expansion of Eucalyptus Plantations in Agroforest Landscapes of Northern Ethiopia

Dagm Abate <sup>1,2,\*</sup>, José G. Borges <sup>1</sup> , Susete Marques <sup>1</sup>  and Vladimir Bushenkov <sup>3</sup> 

<sup>1</sup> Forest Research Center and Associated Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal; joseborges@isa.ulisboa.pt (J.G.B.); smarques@isa.ulisboa.pt (S.M.)

<sup>2</sup> College of Agriculture and Environmental Sciences, University of Gondar, Gondar P.O. Box 196, Ethiopia

<sup>3</sup> Research Centre for Mathematics and Applications, University of Évora, Colégio Luis Verney, 7000-671 Évora, Portugal; bushen@uevora.pt

\* Correspondence: dagmabate@isa.ulisboa.pt

**Abstract:** The conversion of fertile croplands to *Eucalyptus* woodlots in Ethiopian highlands, due to its business attractiveness to smallholders, raises concerns related to food production, water resources, carbon and other ecosystem services. This study was therefore designed to examine land allocation and plantation management decisions. Our emphasis was on the analysis of tradeoffs between the economic gains obtained from harvesting *Eucalyptus* timber and food production, carbon and water use. For that purpose, we considered a 1987 ha agroforest landscape in the Amhara region, Northern Ethiopia. With a planning horizon covering nine one-year periods, we developed and used nine Model I single objective linear programming (LP) models, and analyzed tradeoffs between objectives (e.g., land expectation value (LEV), Carbon, volume of ending inventory (VolEI), crop production and water use) using an LP-based Pareto frontier approach. The study revealed that the objective of maximizing the total economic gain from the sale of *Eucalyptus* wood poles favored a complete conversion of the available cropland into *Eucalyptus* woodlots. To meet the minimum annual crop production/consumption/requirements of households in the study area, the land under *Eucalyptus* should be limited to 1772 ha, with a sequestration potential of 1.5 to  $1.57 \times 10^7$  kg yr<sup>-1</sup> of carbon in the aboveground biomass. However, this land cover limit should be decreased to 921 ha so as to limit the total annual water use (for biomass production) below the amount available from rainfall (11,000 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>). Moreover, the study highlighted that maximizing the harvested wood volume or LEV would come at the cost of a decreased aboveground carbon stock and volume of ending inventory and higher total water use. It also provided alternative optimal Pareto-front points, among which decision makers will be able to select their preferred targets. The current study also showed the potential for the application of Pareto frontier approaches to support the development of effective ecological/economic management strategies and the design of land use policies in an Ethiopian context.

**Keywords:** carbon stock; crop production; *Eucalyptus* plantation; linear programming; Pareto frontier; tradeoff; water use



**Citation:** Abate, D.; Borges, J.G.; Marques, S.; Bushenkov, V. An Ecological-Economic Approach to Assess Impacts of the Expansion of Eucalyptus Plantations in Agroforest Landscapes of Northern Ethiopia. *Forests* **2022**, *13*, 686. <https://doi.org/10.3390/f13050686>

Academic Editor: Juan A. Blanco

Received: 7 March 2022

Accepted: 27 April 2022

Published: 28 April 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The area of natural forests and woodlands in Ethiopia has been shrinking, whereas the population and the demand for forest products has rapidly increased [1]. Thus, the establishment of forest plantations has been one of the government's main strategies to deal with the huge gap between forest product supply and demand in the country [2]. Since the beginning of the 20th century, successive governments have attempted to promote the establishment of forest plantations, mainly of *Eucalyptus*, across the country [3,4]. This policy led to large-scale state- and community-owned plantations of *Eucalyptus*. Starting

from the early 1980s, smallholder farmers have been taking the lead in expanding *Eucalyptus* tree planting in the form of woodlots [4–6]. Often farmers grow *Eucalyptus* in areas for which there are few other use options, e.g., areas along the holding boundary or that have small productivity, or else in small woodlots in the front yard or in the garden. In the past three decades, however, owing to the popular acceptance of *Eucalyptus* plantations as an attractive business for smallholders, the conversion of fertile croplands to *Eucalyptus* woodlots is becoming common [7–9]. In most parts of the country, fertile croplands have been converted to *Eucalyptus* woodlots every year, mainly because it is a more lucrative form of income [8]. Moreover, woodlots on agricultural farms are not only used to increase the tree cover but can also be used for climate change mitigation through carbon sequestration [10]. Planting *Eucalyptus* on former cropland can increase aboveground biomass carbon and contribute to climate change mitigation [11].

Nevertheless, the uncontrolled expansion of *Eucalyptus* on crop lands has raised great concern, mainly related to its impact on food production and water resources [12]. A recent study reported that the conversion of cropland into *Eucalyptus* in the central highlands has led to an annual loss of  $4.5 \times 10^7$  kg of wheat production or  $3.1 \times 10^7$  kg of barley, which translates to the grain needs of 70,000 to 100,000 households [13]. Producing more food for a growing population in the coming decades, while at the same time combating poverty and hunger and coping with the impacts of climate change, is the major challenge facing agriculture in Africa. Another issue related to *Eucalyptus* expansion is its impact on water resources, as the species has been reported to have high water consumption, mainly attributed to its fast growth and high biomass production. This implies that carbon sequestration could be another important variable to be considered when analyzing the *Eucalyptus* expansion issue. Moreover, the analysis can now move further from the single objective of maximizing economic gains from wood production to the consideration of multiple objectives such as carbon, water and food, which requires multi-objective optimization.

The decision of whether to facilitate or else to constrain the expansion of *Eucalyptus* requires scientific-based decision support systems. Available studies related to the issue are mainly based on interview-based qualitative justifications, e.g., [8,14], or plot- and household-level comparisons of crop and *Eucalyptus* land uses in terms of economic and ecological variables [6,13,15–17]. There is an opportunity to take advantage of advanced decision support tools to provide more information to policymakers and other stakeholders about the impacts of *Eucalyptus* plantations on timber-related revenues, crop production, carbon and water resources.

Linear programming (LP) is a powerful tool to formulate and solve practical economic problems and is widely applied in management planning in several economic activities [18]. There exists a wealth of literature demonstrating the use of LP in solving forest and land management planning problems [19]. The literature also reports the use of multiple criteria decision analysis (MCDA) for finding solutions to decision problems with multiple conflicting goals or criteria [19,20]. In this case, in decision analysis one sets criteria to address the supply of multiple ecosystem services in a multi-objective forest management planning process, and then adopts an MCDA method to analyze the tradeoffs among these criteria [21]. There are various decision support tools based on MCDA [22]. The tools provide outputs through which end users and scientific researchers can learn and understand the impacts of management plans on the provision of forest ecosystem services [23,24]. For example, the literature reports recent successful applications of the Pareto frontier tool [25]. The Pareto Frontier is an a posteriori MCDA approach in which decision makers are not required to set targets for criteria before being informed of trade-offs among ecosystem services.

MCDA and its application in tradeoff analysis have been extensively used and developed for plantation forest management, including that of *Eucalyptus* forests [25–29]. Borges et al. [25] analyzed tradeoffs between four economic and environmental criteria (objectives), i.e., net present value (NPV), timber supply, cork supply, carbon stock and value of ending inventory. Researchers in Northeast China also used MCDA to examine tradeoffs between carbon, timber and total NPV [30]. A study in the Western Alps charac-

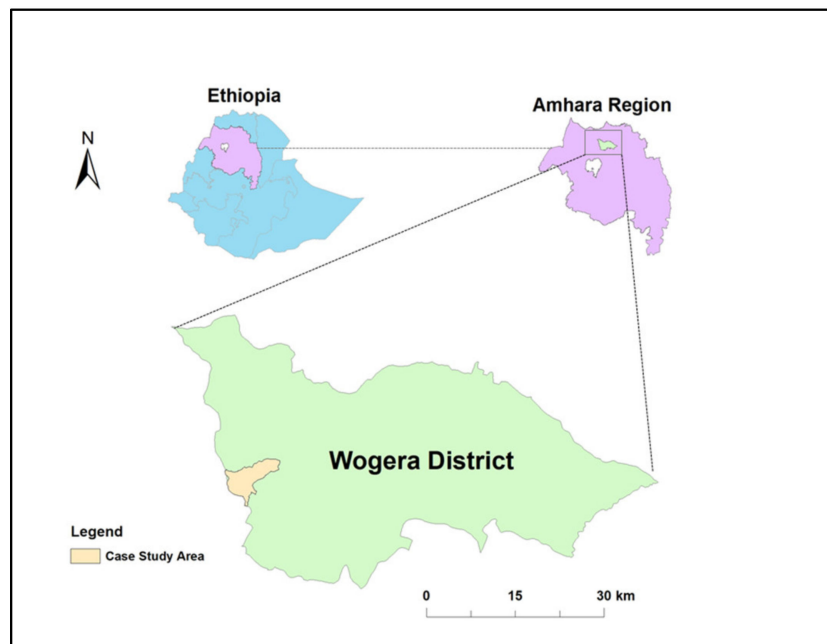
terized trade-offs and synergies between timber production, biodiversity conservation and protection against natural hazards using the Pareto frontier method [31].

However, applications of LP or of MCDA in support of management planning and policy analysis in agroforest landscapes and in developing countries such as Ethiopia are scarce. The current study has therefore attempted to address this gap. It examines the impacts of converting cropland into *Eucalyptus* plantations. Namely, we focus on the impacts of this conversion on economic returns, as well as on the provision of other ecosystem services (e.g., food production, carbon and water). We analyze further the tradeoff between these ecosystem services. The goal of this study is to help identify land allocation and plantation management strategies that may address several criteria simultaneously, while considering the tradeoffs between them. Specifically, this research considers a *Eucalyptus*-dominated agroforest landscape located in northern Ethiopia and uses LP and MCDA to examine land allocation and plantation management alternatives and their impacts on economic gains from harvesting *Eucalyptus* timber, while addressing food production and water use concerns.

## 2. Materials and Methods

### 2.1. Case Study Area

The study was conducted in the agroforest landscape of *Kosoye Amba Kebele* administrative unit of the Wogera district, Northwestern Ethiopia (Figure 1). It is located at 37.36° E longitude and 12.46° N latitude. The altitude ranges from 1100 m to 3040 m a.s.l, with an average altitude of 2812 m a.s.l. The mean annual rainfall is between 1000 and 1200 mm, and the minimum and maximum temperature are 14 °C and 33 °C, respectively. The rainy season extends from June until the end of September, with most of the rain being received in July and August [32].



**Figure 1.** Location map of the case study area in Wogera district, Northern Ethiopia.

The decision to select the case study area was made in cooperation with the district forestry experts. In this area, the rate of conversion of cropland to *Eucalyptus* woodlots has been relatively high, leading to a substantial area of *Eucalyptus*. It extends over 1987 ha, of which 1327 ha is cropland and 660 is plantation forest. The regional administrative office reports a total of 1350 households in the *Kebele*. Crop production (e.g., wheat, barley and beans) is the main livelihood activity of these households. Small-scale *Eucalyptus* farming has been part of this crop-dominated livelihood system. Its importance increased

over the past couple of decades, in which farm households have reportedly converted their croplands into *Eucalyptus* woodlots. On average, a household in the case study area manages 0.013 ha of *Eucalyptus* woodlots—established mainly on former croplands—which is about 20% of the average household land holding size. The woodlots are a source of cash income, generated from the sale of round wood (the size ranges from 7 to 13 cm DBH) and fuel wood. The case study area is classified into 81 homogeneous analysis areas based on land cover type (e.g., *Eucalyptus*, barley and beans) as well as on eucalypt stand age, productivity and cutting cycle.

## 2.2. Model Building

The goal of this study was to examine land allocation and plantation management alternatives and their impacts on economic gains from harvesting *Eucalyptus* timber, while addressing food production and water use concerns. In the case of the *Eucalyptus* analysis areas, we considered three alternative harvest ages (four, five and six years), whereas in the case of crop analysis areas, we considered two alternatives, e.g., no conversion and conversion to *Eucalyptus* in the beginning of the planning horizon. In the case of the latter, after the conversion, *Eucalyptus* may be harvested at four, five or six years of age. We considered a planning horizon extending over nine one-year periods. Each management alternative in each analysis area corresponded to a decision variable in a Model I linear program [33]:

$$\sum_{j=1}^{M_i} X_{ij} = a_i, i = 1, \dots, N \quad (1)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} w_{ijt} X_{ij} = W_t, t = 1, \dots, T \quad (2)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} carbon_{ijt} X_{ij} = CARB_t, t = 1, \dots, T \quad (3)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} water_{ijt} X_{ij} = WATER_t, t = 1, \dots, T \quad (4)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} crop_{ijt} X_{ij} = CROPPROD_t, t = 1, \dots, T \quad (5)$$

$$LEV = \sum_{i=1}^N \sum_{j=1}^{M_i} lev_{ij} X_{ij} \quad (6)$$

$$TOTWOOD = \sum_{t=1}^T W_t \quad (7)$$

$$VolEI = \sum_{i=1}^N \sum_{j=1}^{M_i} vei_{ij} X_{ij} \quad (8)$$

$$CARBAver = \sum_{t=1}^T CARB_t / T \quad (9)$$

$$WUTOT = \sum_{t=1}^T WATER_t \quad (10)$$

$$WUAnnual = \sum_{t=1}^T WATER_t / T \quad (11)$$

$$CROPTOT = \sum_{t=1}^T CROPPROD_t \quad (12)$$

$$CROPAnnual = \sum_{t=1}^T CROPPROD_t / T \quad (13)$$

$$X_{ij} \geq 0, \forall ij \quad (14)$$

where  $N = 81$ , the total number of analysis areas.

$M_i$  = the number of prescriptions for analysis area  $i$ .

$T = 9$ , the number of planning years.

$X_{ij}$  = number of hectares of analysis area  $i$  assigned to prescription  $j$ .

$a_i$  = total area of the analysis area  $i$ .

$w_{ijt}$  = wood harvested in period  $t$  that results from assigning prescription  $j$  to analysis area  $i$ . This was estimated using a local growth model, with a yield table for seedling and coppice stands in four productivity site classes [34].

$carbon_{ijt}$  = yearly carbon stock at the end of period  $t$  that results from assigning prescription  $j$  to analysis area  $i$  [34].

$water_{ijt}$  = total annual water use in period  $t$  that results from assigning prescription  $j$  to analysis area  $i$  [34].

$crop_{ijt}$  = annual crop production in period  $t$  that results from assigning prescription  $j$  to analysis area  $i$ .

$lev_{ij}$  = land expectation value associated with prescription  $j$  in analysis area  $i$ . Estimated based on information provided by landowners, key informants and merchants (e.g., labor, input, harvesting and transportation costs, as well as product prices). As the major *Eucalyptus* product that farmers produce and sell in the case study area is poles, this product was considered as the target product in the study.

$Ve_{ij}$  = Volume of the *Eucalyptus* inventory at the end of the planning horizon associated with prescription  $j$  in analysis area  $i$ .

Equation (1) states that the sum of number of hectares in an analysis area assigned to each prescription must be equal to the corresponding analysis area's total number of ha  $a_i$ . Equations (2)–(5) define, respectively, the total wood harvested  $W_t$ , the carbon stock  $CARB_t$ , the total water use  $WATER_t$  and the total crop produced  $CROPPROD_t$  in each period  $t$ . Equations (6)–(13) define, respectively, the case study area land expectation value, the total wood harvested, the standing volume of the inventory at the end of the planning horizon, the average carbon stock across planning periods, the total water use in the planning horizon, the average annual water use, the total crop production in the planning horizon and the average annual crop production in the case study area. The inequalities (Equation (14)) state the non-negativity constraints.

The annual crop production was estimated based on the average yield record in the 2018/19–2019/20 campaign year. The yield in this year was one of the lowest recorded over the past decades (mainly attributed to the late onset of rain and high amount of rain during and after crop maturity). Therefore, two additional average yield scenarios were considered—production in 'moderately normal' and 'normal' conditions—based on the information from key informants.

The equations (Equations (1)–(14)) were then used to formulate 12 LP models, with each corresponding to a decision scenario (Table 1). The first (MOD 1) and the fourth models (MOD 4) have an objective function of maximizing LEV and VolEI, respectively, and do not include any constraint. They include only the area constraints (Equation (1), Table 1). The second model (MOD 2) extends MOD1 to include a constraint on the land area to be kept for crop production in order to meet annual crop grain needs by households in the case study area (Equation (15), Table 1).

$$CROPPROD_t \geq MinCropProd * HH, \forall_t \quad (15)$$

where  $CROPPROD_t$  is the total crop produced in each period  $t$ ,  $MinCropProd$  is the annual crop production (for consumption) needs per household, which was reported as 447 kg per year [35], and  $HH$  is the total number of households in the case study area.

A third model (MOD 3) also targets LEV maximization and it includes constraints on the annual water use level (Table 1). As explained earlier, the overuse of water is one of the most commonly reported arguments against *Eucalyptus* tree planting. Hence, in MOD 3, we attempted to set a maximum water use level, equivalent to the case study area's annual rainfall amount, which was intended to balance the water lost or utilized by the plant for biomass production (Equation (16)).

$$WATER_t \leq RF * A, \forall_t \quad (16)$$

where  $WATER_t$  is the total water used for biomass production in each period  $t$ ,  $RF$  is the average annual rainfall amount in cubic meters per hectare (a 30 year average value of 1100 mm per square meter per year or 11,000 cubic meters per hectare per year), and  $A$  is the total land area of the case study, which is 1987 hectare.

**Table 1.** Summary of crop production and decision scenarios and corresponding linear programming (LP) models.

Crop Production Scenarios	Decision Scenarios (LP Models)	Objective Function	Constraint	Equations
Low	MOD 1	MAX LEV	NA	Equations (1)–(14)
	MOD 2	MAX LEV	Minimum annual grain food consumption needs	Equations (1)–(15)
	MOD 3	MAX LEV	Maximum annual water use	Equations (1)–(14) and (16)
	MOD 4	MAX VEI	NA	Equations (1)–(14)
Moderately Normal	MOD 5	MAX LEV	NA	Equations (1)–(14)
	MOD 6	MAX LEV	Minimum annual grain food consumption needs	Equations (1)–(15)
	MOD 7	MAX LEV	Maximum annual water use	Equations (1)–(14) and (16)
	MOD 8	MAX VEI	NA	Equations (1)–(14)
Normal	MOD 9	MAX LEV	NA	Equations (1)–(14)
	MOD 10	MAX LEV	Minimum annual grain food consumption needs	Equations (1)–(15)
	MOD 11	MAX LEV	Maximum annual water use	Equations (1)–(14) and (16)
	MOD 12	MAX VEI	NA	Equations (1)–(14)

The four LP models, MOD 1 to 4, considered the average annual crop production based on the ‘low’ crop production scenario, explained above. For the two other production scenarios, eight additional LP models were developed: four models (MOD 5 to 8) for the ‘moderately normal’ scenario, and another four models (MOD 9 to 12) for the ‘normal’ crop production scenario (Table 1).

In order to gain more insights into the impacts of land allocation and plantation management alternatives, we analyzed tradeoffs between objectives using an LP-based Pareto frontier approach [27]. The approach generates the feasible set in the criteria space for the land allocation and management problem using the estimation refinement method (see [25] for a detailed mathematical description of the Pareto frontier approach and its application in forest management). The approach was used to analyze the tradeoffs between six criteria, e.g., LEV, carbon, VolEI, wood harvested, crop production and water use.

### 3. Results

#### 3.1. Result of Single Objective Optimization

The 12 single-objective LP solutions provide interesting information (Table 2). As expected, the highest LEV and harvested wood values,  $8.46 \times 10^9$  Ethiopian Birr (ETB) and  $8.3 \times 10^5$  m<sup>3</sup>, respectively, were found by the unconstrained LEV maximization models MOD 1, 5 and 9. Nevertheless, in these scenarios there is no crop production—as the whole cropland is allocated for *Eucalyptus* plantations. Moreover, the average annual water use,  $3.76 \times 10^7$  m<sup>3</sup>, is the second highest, next to the unconstrained VolEI maximization scenarios in MOD 4, 8 and 12.



**Table 2.** Optimal values associated with decision scenarios.

Decision Scenarios	LEV (10 <sup>9</sup> ETB *)	TOTWOOD (10 <sup>5</sup> m <sup>3</sup> )	CARBavg (10 <sup>7</sup> kg)	VolEI (10 <sup>4</sup> m <sup>3</sup> )	WUTOT (10 <sup>8</sup> m <sup>3</sup> )	WUAnnual (10 <sup>7</sup> m <sup>3</sup> )	CROPTOT (10 <sup>6</sup> kg)	CROPAnnual (10 <sup>6</sup> kg)
MOD 1	8.46	8.3	1.65	6.19	3.39	3.76	0	0
MOD 2	7.55	7.48	1.5	6.19	3.07	3.41	3.67	0.41
MOD 3	4.36	4.34	1.147	8.81	1.87	2.08	10.35	1.15
MOD 4	7.75	4.14	2.76	50.62	3.48	3.87	0	0
MOD 5	8.46	8.3	1.65	6.19	3.39	3.76	0	0
MOD 6	7.9	7.74	1.54	6.19	3.18	3.53	3.67	0.41
MOD 7	4.42	4.19	1.153	9.41	1.89	2.11	19.39	2.15
MOD 8	7.75	4.14	2.76	50.62	3.48	3.87	0	0
MOD 9	8.46	8.3	1.65	6.19	3.39	3.76	0	0
MOD 10	8.06	7.88	1.57	6.19	3.24	3.6	3.67	0.41
MOD 11	4.46	4.1	1.16	9.33	1.92	2.13	26.2	2.91
MOD 12	7.75	4.14	2.76	50.62	3.48	3.87	0	0

\* LEV—land expectation value in Ethiopian Birr (ETB), TOTWOOD—total harvested wood, CARBavg—aboveground carbon stock, VolEI—volume of ending inventory, WUTOT—total water use in the planning horizon, WUAnnual—average annual water use, CROPTOT—total crop production in the planning horizon, CROPAnnual—average annual crop production.

The inclusion of crop production constraints in scenarios MOD 2, 6 and 10 reduced the values of both *LEV* and the volume of wood harvested as compared to the unconstrained *LEV* maximization models, the reduction being higher in MOD 2 ( $0.91 \times 10^9$  ETB of *LEV* and  $0.82 \times 10^5$  m<sup>3</sup> of wood) and lower in MOD 10 ( $0.40 \times 10^9$  ETB of *LEV* and  $0.42 \times 10^5$  m<sup>3</sup> of wood) (Table 2).

Out of the total 1327 ha of cropland, up to 1112, 1157 and 1200 ha would be converted into *Eucalyptus* land use, in the case of MOD 2, 6 and 10, respectively (Table 3). These scenarios target the economic gain maximization from wood production, while guaranteeing the minimum food consumption requirements of households. With this land allocation, it would also be possible to store  $1.5$  to  $1.57 \times 10^7$  kg yr<sup>-1</sup> of carbon in the aboveground biomass (Table 2), which is equivalent to  $5.5$  to  $5.76 \times 10^5$  t yr<sup>-1</sup> of CO<sub>2</sub>.

**Table 3.** Optimal land allocation in each scenario.

Decision Scenario/Model	Total Land Allocated (In ha)	
	Plantation	Crop
MOD 1	1987	0
MOD 2	1772	215
MOD 3	921	1066
MOD 4	1987	0
MOD 5	1987	0
MOD 6	1817	170
MOD 7	870	1117
MOD 8	1987	0
MOD 9	1987	0
MOD 10	1860	127
MOD 11	857	1130
MOD 12	1987	0

NOTE: before optimization, 660 and 1327 ha were allocated to *Eucalyptus* plantations and to crop production, respectively.

Nevertheless, the land allocations in these scenarios lead to average annual water use values of 3.41, 3.53 and  $3.6 \times 10^7$  m<sup>3</sup> in MOD 2, 6 and 10, respectively. These are lower than the values associated with the unconstrained scenarios, yet they are higher than the case study area's total annual water available from rainfall,  $2.18 \times 10^7$  m<sup>3</sup>.

Scenarios MOD 3, 7 and 11 address the water use concerns by constraining the *LEV* maximization objective by applying a maximum annual water use, a level equivalent to the annual rainfall of the study area. As expected in these scenarios, there is a substantial decrease in *LEV* and the volume of harvested wood, ranging from 47.7% to 50.6% depending on the scenario, when compared to the amount in the unconstrained *LEV* maximization models MOD 1, 5 and 9 (Table 2).

These decision scenarios, on the other hand, are associated with the highest amount of crop production. Given that wheat consumes more water per kg of biomass than *Eucalyptus* (Table 2) and that wheat occupies two thirds of the cropland in the case study area, one might expect a higher value of water consumption in these scenarios. The opposite was found, however, and this can be explained by the higher biomass production per ha of *Eucalyptus* as compared to wheat, as well as to the other two crops (barley and beans), which results in higher total water use. Thus, the models opt to maximize the objective function—*LEV*—while attaining the maximum water use limit by allocating less land for *Eucalyptus* than for crop production (Table 3). Furthermore, only a small proportion of the land under wheat crop was allocated for *Eucalyptus* (3.6%, 0.6% and 0.4% in MOD 3, 7 and 11, respectively), whereas it was much higher in the case of barley (63.7%, 56% and 51.3% in MOD 3, 7 and 11, respectively) and bean crops (20.7% in all three scenarios). This reflects that the reduction in *LEV* due the lower wood production can be compensated for



by allocating more land for the crop type that gives the highest production per ha (Table 3) and LEV (which is wheat) while keeping the maximum water use limit.

The crop production scenarios affect other outcomes, namely, when they include a constraint of water use (MOD 3, 7 and 11) (Table 2). For instance, the highest wood volume amount was in the ‘low’ crop production scenario model, MOD 3 ( $4.34 \times 10^5 \text{ m}^3$ ), whereas the lowest was in the ‘normal’ production scenario model, MOD 11 ( $4.1 \times 10^5 \text{ m}^3$ ). The reverse was found when the scenarios were compared for LEV and total crop production, with the highest being in MOD 11 ( $4.46 \times 10^9 \text{ ETB}$  and  $26.2 \times 10^6 \text{ kg}$ ) and the lowest in MOD 3 ( $4.36 \times 10^9 \text{ ETB}$  and  $10.35 \times 10^6 \text{ kg}$ ). The land conversion/allocation results show that the amount of crop land to be converted into *Eucalyptus* was relatively higher in the case of MOD 3 (261 ha) than in the case of MOD 7 (210 ha) and MOD 11 (197 ha) (Table 3). No additional cropland can be converted into *Eucalyptus* while ensuring that the water use does not exceed the amount available from rainfall. These decision scenarios limit the annual water use, while also contributing to a more even flow of wood and a more even carbon stock compared with the other scenarios (Figures 2–4).

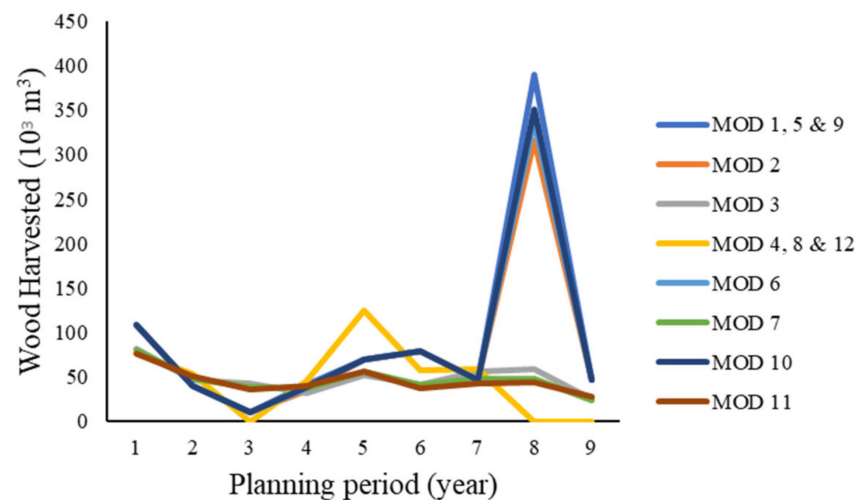


Figure 2. Annual harvested wood by decision scenario.

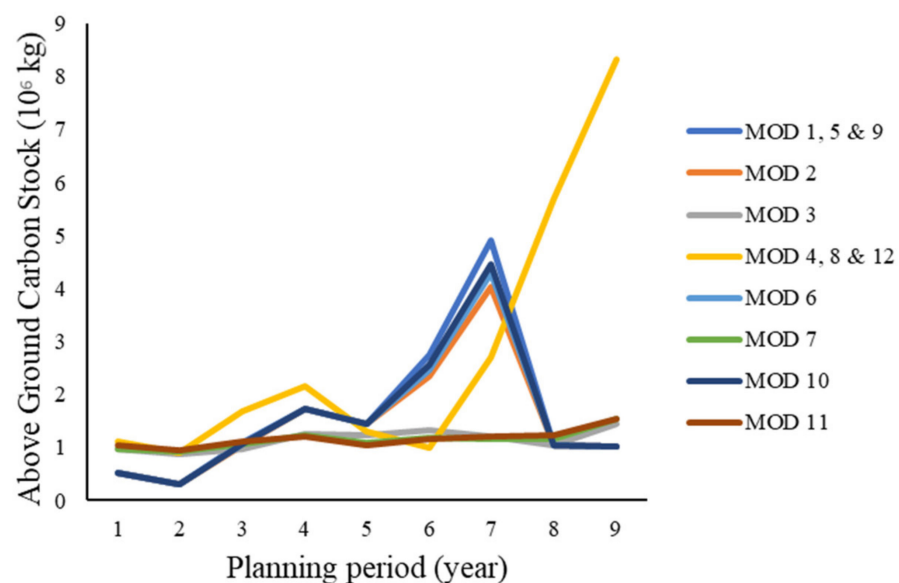


Figure 3. Annual aboveground carbon stock by decision scenario.

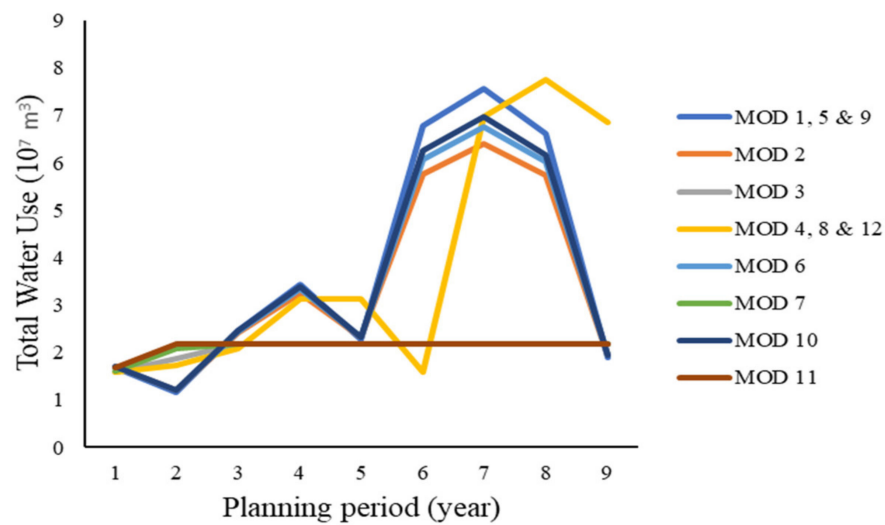


Figure 4. Annual water use by decision scenario.

One might expect a lower volume of ending inventory in the case of scenarios with constraints on water use as a lower amount of land is converted to *Eucalyptus*. The result, however, is the opposite—the volume of the inventory at the end of the planning horizon increased by 42%, 50% and 52% in models MOD 3, 11 and 7, respectively, when compared to the value in the unconstrained LEV maximization scenarios ( $6.19 \times 10^4 \text{ m}^3$ ). The reason for this can better be understood when we see the optimal land conversion/harvesting prescriptions (i.e., convert and harvest at an age of 4, 5 and 6 years) of the model’s solution (Figure 5). The results show that a lower harvesting age (four years) was the optimal prescription in the unconstrained LEV maximization scenarios (MOD 1, 5 and 9) as well as in the case of scenarios with constraints on crop production (MOD 2, 6 and 10). In all these scenarios, the converted crop land was assigned to be managed under a four-year rotation age.

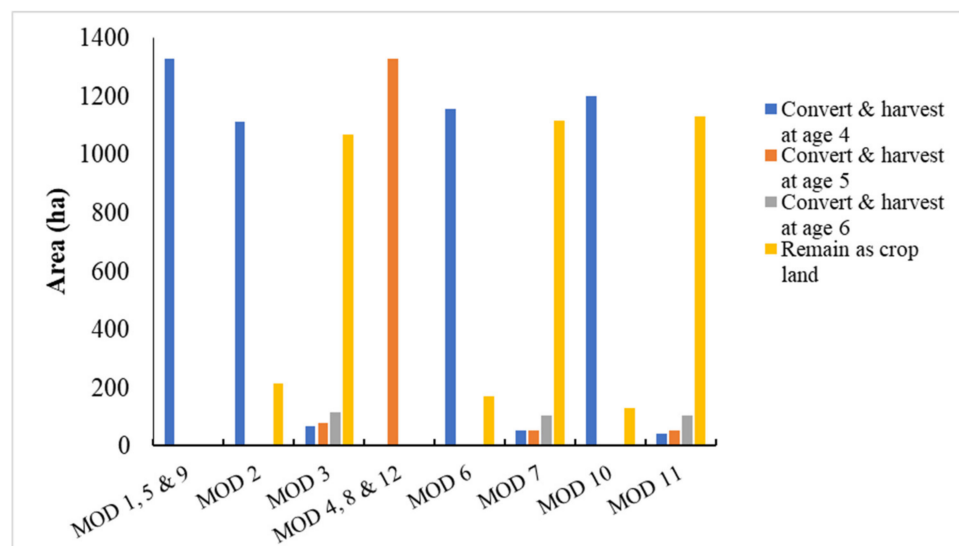


Figure 5. Area assigned to each prescription in each decision scenario.

When the objective was to maximize the standing volume at the end of the planning horizon in MOD 4, 8 and 12, the crop land units were assigned to a conversion to *Eucalyptus* and to be managed under a five-year rotation age (Figure 5). This is related to the age at the end of the planning horizon and the respective standing volume. A hectare of land converted to *Eucalyptus* and managed with a five-year rotation at the end of the planning

horizon will have a stand that is four years old, whereas if that same hectare was converted to *Eucalyptus* and managed with a three- or a four-year rotation, it would have a stand that is one year or three years old, respectively. Those decision scenarios lead to the highest volume of the ending inventory ( $50.62 \times 10^4 \text{ m}^3$ ) as well as the highest aboveground carbon stock ( $2.76 \times 10^7 \text{ kg}$ ). Conversely, they are associated with the lowest volume of harvested wood ( $4.14 \times 10^5 \text{ m}^3$ ). This is half the volume in the unconstrained LEV-maximization scenarios. Nevertheless, the LEV is only 0.71 lower than the LEV in the latter scenarios. This finding is expected, because LEV considers future net revenues of *Eucalyptus* woodlots, which means that the value of the standing volume is included in the estimation, though it is not harvested within the planning horizon.

Constraining the LEV maximization objective by annual water use in MOD 3, 7 and 11 led to higher harvesting ages, which is in contrast with the solutions in the other scenarios (Figure 5). The results show that 43.8%, 48.8% and 52.7% of the total cropland to be converted into *Eucalyptus* was assigned to be managed with six-year rotations in MOD 3, 7 and 11, respectively. The remaining land was allocated for four- and five-year rotations, with 20%–26% for the former and 26%–30% for the latter. For the same reason as explained above in the case of the ending inventory maximization scenarios, the higher number of hectares assigned to higher harvesting ages resulted a higher ending inventory volume in the water-use-constrained LEV-maximization scenarios (MOD 3, 7 and 11) as compared to the unconstrained (MOD 1, 5 and 9) and crop-production-constrained scenarios (MOD 2, 6 and 10), in which more land was allocated to lower harvesting ages (Figure 5). Similarly, the sharp difference in the volume of the ending inventory among the water-use-constrained scenarios also resulted from the different assignments of harvesting prescriptions.

Another important finding in the current study is related to the impact of site productivity classes on decision scenarios. A variation was found only in the solutions from the water-use-constrained LEV-maximization scenarios (MOD 3, 7 and 11). In all these three scenarios, it was from the lower-productivity class sites (class IV sites) that the larger area of crop land was allocated for (or chosen for conversion into) *Eucalyptus* (47.2%, 37.4% and 37.7% of the total 275 ha in MOD 3, 7 and 11, respectively), whereas the entire cropland from site class II was assigned to remain as cropland in all models (Table 4). Most area was assigned to the six-year rotation in site class IV, five-year rotation in site class III and four-year rotation in site class I.

**Table 4.** Optimal land allocation (ha) for different site productivity classes in the case of water-use-constrained LEV-maximization scenarios.

Site Class	Prescriptions *	MOD 3	MOD 7	MOD 11
Site I	P1	68.488	54.07	39.69
	P2	9.112	23.53	0
	P3	0	0	0
	P4	259.8	259.8	297.71
	Total		337.4	
Site II **	P4/Total		482	
Site III	P1	0	0	0
	P2	53.54	30.132	53.54
	P3	0	0	0
	P4	179.25	202.658	179.25
	Total		232.79	
Site IV	P1	0	0	0
	P2	15.43	0	0
	P3	114.43	102.76	103.93
	P4	145.14	172.24	171.07
	Total		275	

\* Prescriptions: P1—harvesting age 4, P2—harvesting age 5, P3—harvesting age 6, and P4—remain as crop land.

\*\* No conversion of cropland.

### 3.2. Trade-Offs between Management Planning Criteria

Unlike single-criterion optimization scenarios, the tradeoff analysis considered multiple objectives—the maximization of *LEV*, the volume of wood harvested, the volume of the ending inventory, aboveground carbon stock and total crop production, as well as the minimization of total water use over the planning horizon. An LP file similar to the one developed for MOD 3, presenting a decision scenario constrained by annual water use, was used to study the tradeoffs between the six criteria.

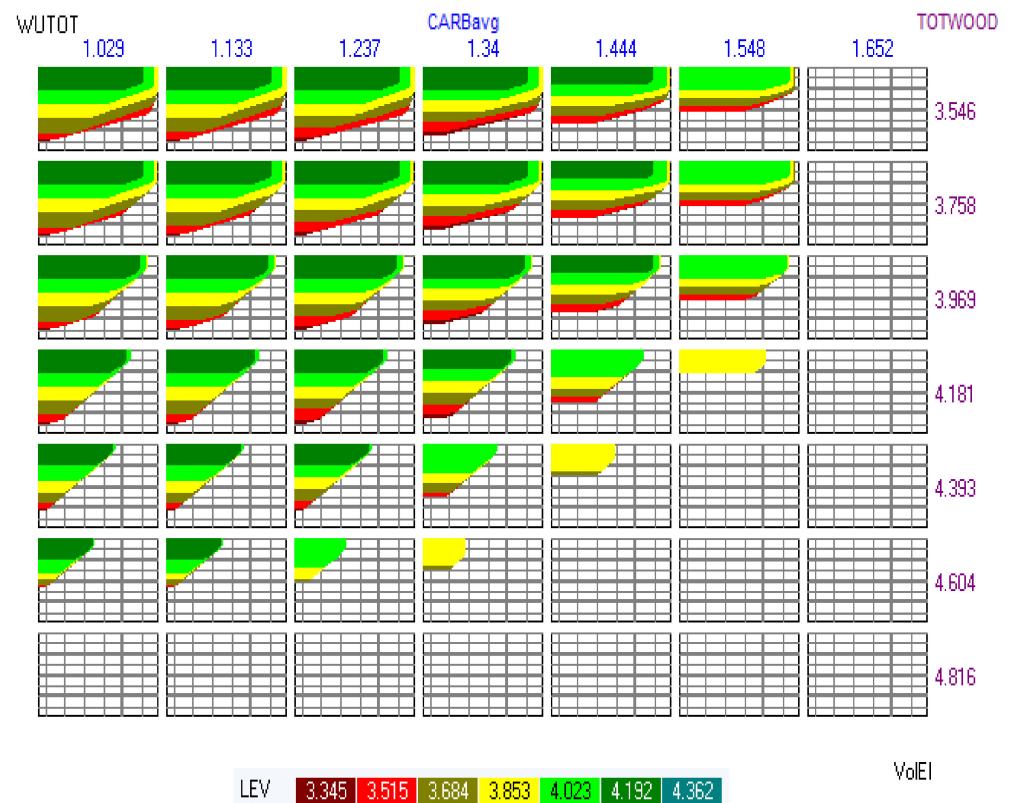
The Pareto frontier tool provided the minimum and maximum values for each criterion. Accordingly, minimum and maximum values of  $3.35 \times 10^9$  and  $4.36 \times 10^9$  ETB, respectively, were found for *LEV*, whereas the values for total wood harvested over the planning horizon ranged from  $3.55 \times 10^5$  to  $4.82 \times 10^5$  m<sup>3</sup>, and for the volume of the ending inventory the values ranged from  $0.13 \times 10^5$  to  $1.37 \times 10^5$  m<sup>3</sup>. For the average aboveground carbon stock, the minimum value was  $1.03 \times 10^7$  kg, whereas the maximum was  $1.65 \times 10^7$  kg. Regarding water use, a minimum of  $1.5 \times 10^8$  m<sup>3</sup> of water would be used over the planning horizon, which corresponds to  $1.6 \times 10^8$  m<sup>3</sup> of water per year (whereas the maximum value was  $1.9 \times 10^8$  m<sup>3</sup> of total water use, corresponding to  $2.1 \times 10^8$  m<sup>3</sup> per year). For the remaining criteria, i.e., crop production, the amount of total crop production over the planning horizon ranged from  $9.02 \times 10^6$  to  $11.92 \times 10^6$  kg, which is equivalent to a yearly production of  $1 \times 10^6$  to  $1.32 \times 10^6$  kg. This minimum crop production amount is by far larger than the minimum crop production requirement (for consumption) for the case study area ( $0.41 \times 10^6$  kg per year).

By keeping the value of the crop production criteria at this minimum value, a five-dimensional decision map depicting the tradeoffs among the other five criteria was produced (Figure 6). The overall information from the map is that maximizing carbon stock and/or *VoIEI* would come at the cost of reduced harvested wood volume or *LEV* and increased total water use. The results showed that the amount of carbon stock can be increased from the minimum value of  $1.03 \times 10^7$  kg up to a maximum of  $1.34 \times 10^7$  kg, although ensuring an increase in harvested wood volume from its minimum value of  $3.55 \times 10^5$  m<sup>3</sup> to a maximum value of  $4.60 \times 10^5$  m<sup>3</sup> (Figure 6). However, in order to increase the maximum value of carbon stock from  $1.34 \times 10^7$  to  $1.44 \times 10^7$  kg, the maximum harvested wood volume should be decreased from  $4.60 \times 10^5$  to  $4.39 \times 10^5$  m<sup>3</sup>. For a further increase in the maximum value of carbon stock up to  $1.55 \times 10^7$  kg, there should be an equivalent reduction in the maximum harvested wood volume from  $4.39 \times 10^5$  to  $4.18 \times 10^5$  m<sup>3</sup>. In other words, the maximum carbon stock would decrease from  $1.55 \times 10^7$  to  $1.34 \times 10^7$  kg if it was necessary to increase the maximum harvested wood volume from  $4.18$  to  $4.60 \times 10^5$  m<sup>3</sup> (Figure 6).

Increasing the maximum harvested wood volume could lead to a reduction in *VoIEI*, especially for harvested wood values greater than  $3.97 \times 10^5$  m<sup>3</sup>. For instance, at a maximum harvested wood volume of  $3.97 \times 10^5$  m<sup>3</sup>, there would be a maximum *VoIEI* value equal to  $1.16 \times 10^5$  m<sup>3</sup>, whereas when the wood volume grows to a maximum of  $4.18$  or  $4.60 \times 10^5$  m<sup>3</sup>, the maximum *VoIEI* would be  $0.96 \times 10^5$  or  $0.54 \times 10^5$  m<sup>3</sup>, respectively (Figure 6).

As expected, a change in the maximum values of these criteria was found to impact the water use criteria. At the minimum values of carbon— $1.03 \times 10^7$  kg, wood— $3.55 \times 10^5$  m<sup>3</sup> and *VoIEI*— $0.13 \times 10^5$  m<sup>3</sup>, the minimum water use was  $1.5 \times 10^8$  m<sup>3</sup> (Figure 6). When the carbon stock value grows to a maximum value of  $1.34 \times 10^7$  kg, while keeping the harvested wood volume at  $3.55 \times 10^5$  m<sup>3</sup>, the minimum water use value would be  $1.59 \times 10^8$  m<sup>3</sup>, whereas at a maximum carbon stock value of  $1.55 \times 10^7$  kg, again with the same level of harvested wood, the water use would be at least  $1.70 \times 10^8$  m<sup>3</sup>. This minimum water use is associated with the minimum *LEV* value at each carbon stock level (as shown in the colored slices of the five-dimensional map, Figure 6). Water use values increase with *LEV*. For instance, in the case of the former carbon stock value, the minimum water use value ranges from  $1.59 \times 10^8$  m<sup>3</sup> at an *LEV* value of  $3.45 \times 10^9$  ETB, and  $1.65 \times 10^8$  m<sup>3</sup> at  $3.68 \times 10^9$  ETB up to  $1.81 \times 10^8$  m<sup>3</sup> at

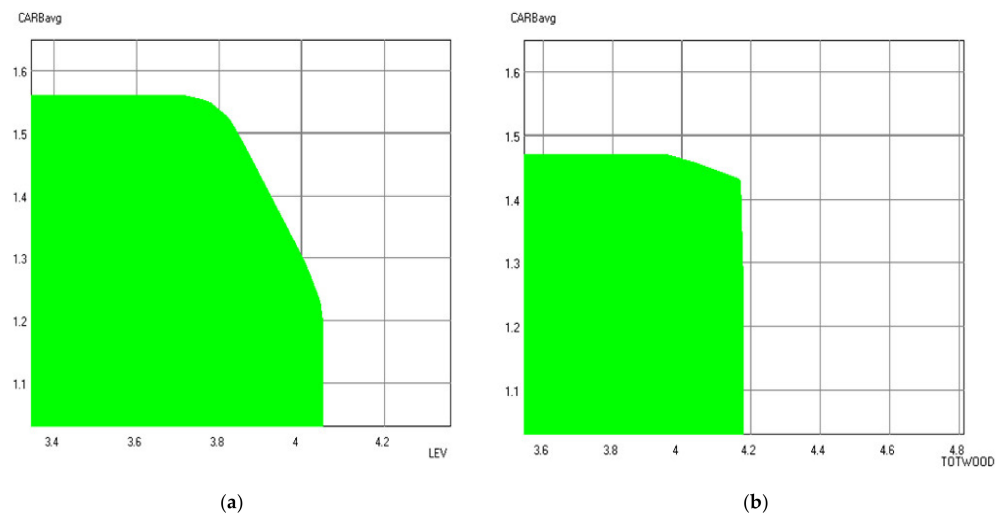
$4.19 \times 10^9$  ETB. In the latter case, it ranges from  $1.70 \times 10^8$  m<sup>3</sup> through  $1.73 \times 10^8$  m<sup>3</sup>, up to 1.81, with an LEV value of  $3.51 \times 10^9$  ETB,  $3.68 \times 10^9$  ETB and  $4.02 \times 10^9$  ETB, respectively.



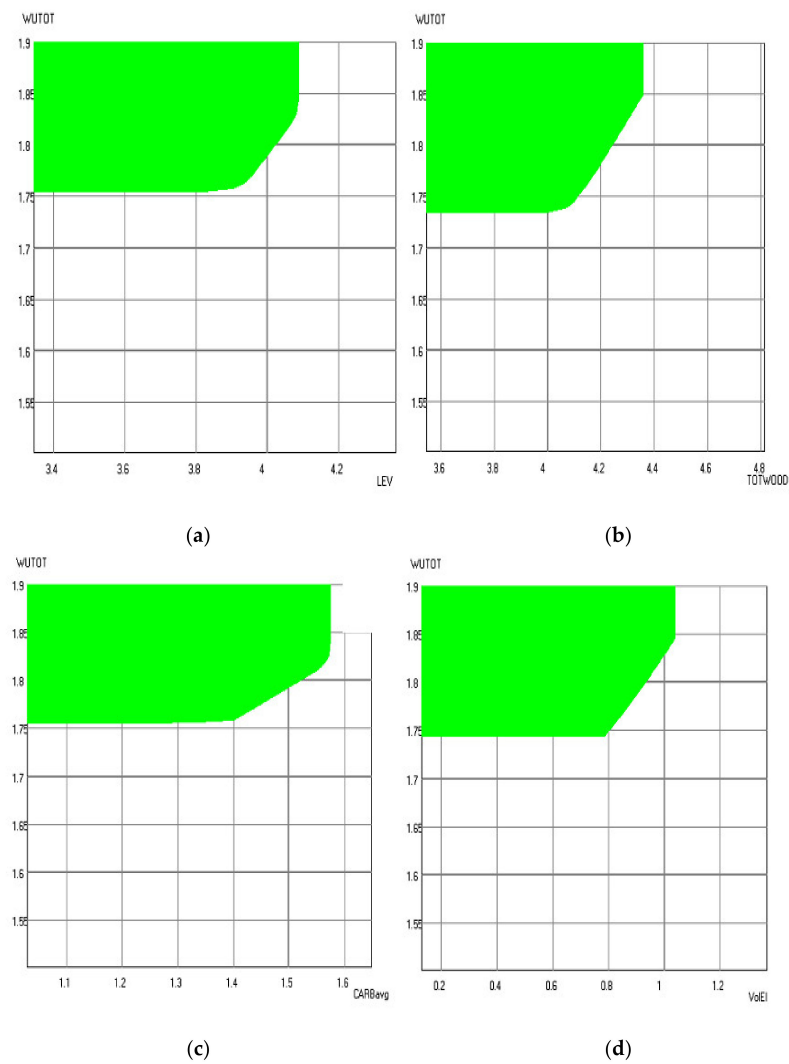
**Figure 6.** Set of five-dimensional decision maps showing the tradeoffs between total water use (WUTOT,  $10^8$  m<sup>3</sup>), aboveground carbon stock (CARBavg,  $10^7$  kg), total harvested wood (TOTWOOD,  $10^5$  m<sup>3</sup>), volume of ending inventory (VolEI,  $10^5$  m<sup>3</sup>) and land expectation value (LEV,  $10^9$  ETB).

The tradeoffs can better be understood if we look at a bi-dimensional map, showing tradeoffs between two criteria, while fixing the values of the other criteria. For illustration, some bi-dimensional maps were produced to depict tradeoffs between carbon and LEV; carbon and harvested wood; and between water use and LEV, wood and carbon (Figures 7 and 8). Accordingly, the map for LEV and carbon stock (Figure 7a) shows that the maximum aboveground carbon stock that can be stored per year is almost  $1.56 \times 10^7$  kg, corresponding to a value of  $3.34 \times 10^9$  ETB of LEV. Moving forward along the horizontal axis of the map, it is shown that LEV can be increased up to  $3.716 \times 10^9$  ETB without decreasing the amount of carbon stock. A further increase in LEV above this value would result in a reduction in carbon stock. For instance, an increase in LEV from  $3.716 \times 10^9$  to  $3.778 \times 10^9$  ETB (1.65%) resulted a corresponding decrease in carbon stock from  $1.562 \times 10^7$  to  $1.552 \times 10^7$  kg (0.60%). Furthermore, a change in LEV from  $3.999 \times 10^9$  to  $4.040 \times 10^9$  ETB (1.002%) is reflected in a decrease in carbon stock from  $1.3 \times 10^7$  to  $1.235 \times 10^7$  kg (5.28%).

Carbon stock also had a tradeoff with harvested wood volume, but mainly at higher values of the latter (Figure 7b). Up to a wood volume value of  $3.98 \times 10^5$  m<sup>3</sup>, carbon stock can be increased—to a maximum of  $1.471 \times 10^7$  kg—without decreasing the harvested wood volume. After this value, a 2.15% increase in the amount of harvested wood, from  $3.98 \times 10^5$  to  $4.045 \times 10^5$  m<sup>3</sup>, led to a 0.92% reduction in carbon stock, from  $1.471 \times 10^7$  to  $1.458 \times 10^7$  kg, whereas a 0.07% increment of harvested wood, from  $4.170 \times 10^5$  to  $4.174 \times 10^5$  m<sup>3</sup>, led to a 9.77% reduction in carbon stock, from  $1.374 \times 10^7$  to  $1.252 \times 10^7$  kg. At the maximum harvested wood volume, which was  $4.18 \times 10^5$  m<sup>3</sup>, the corresponding carbon stock amount would become  $1.03 \times 10^7$  kg.



**Figure 7.** Illustration of two-dimensional decision map showing tradeoffs between aboveground carbon stock (CARBavg,  $10^7$  kg) and (a) LEV ( $10^9$  ETB) and (b) total harvested wood volume (TOTWOOD,  $10^5$  m<sup>3</sup>).

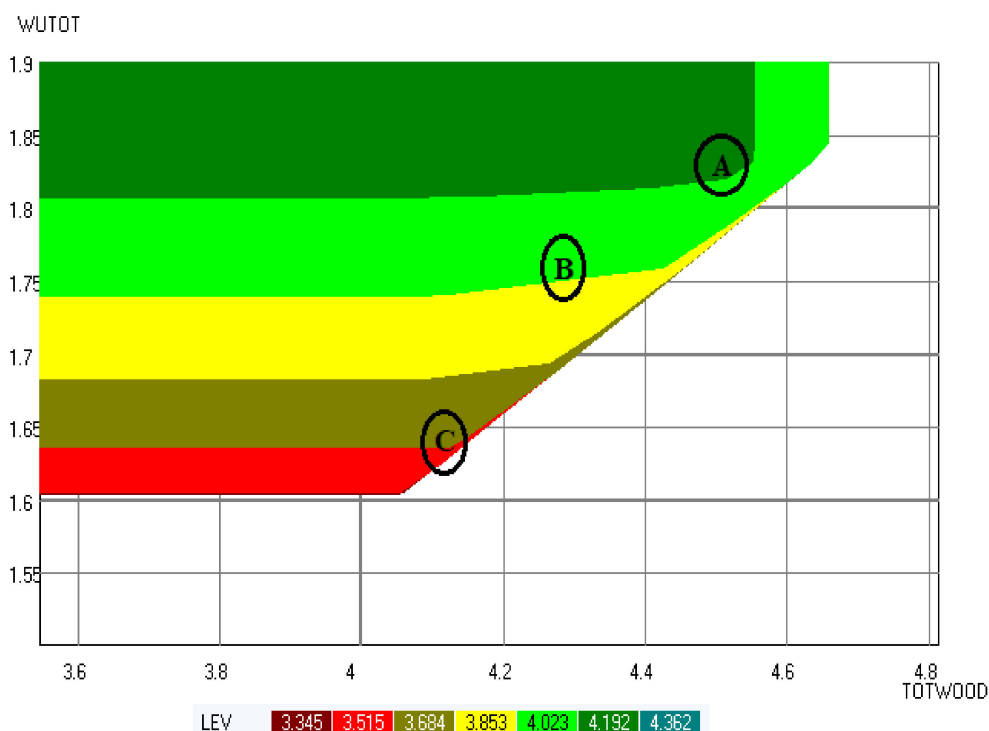


**Figure 8.** Illustration of two-dimensional decision maps showing tradeoffs between total water use (WUTOT,  $10^8$  m<sup>3</sup>) and (a) LEV ( $10^9$  ETB), (b) total harvested wood volume (TOTWOOD,  $10^5$  m<sup>3</sup>), (c) carbon stock (CARBavg,  $10^7$  kg), and (d) volume of ending inventory (VolEI,  $10^5$  m<sup>3</sup>).



Similarly to the results discussed previously, total water use was increased with an increase in LEV, harvested wood volume, carbon stock and ending inventory criteria (Figure 8a–d). According to the result, starting from an LEV value of  $3.8 \times 10^9$  ETB, an increase in LEV increased the total water use. For instance, a change in LEV from  $3.832 \times 10^9$  to  $3.934 \times 10^9$  ETB (2.62%) results in a corresponding increase in total water use from  $1.756 \times 10^8$  to  $1.763 \times 10^8$  m<sup>3</sup> (0.38%) (Figure 8a). On the other hand, a change in LEV from  $4.063 \times 10^9$  to  $4.086 \times 10^9$  ETB (0.54%) is reflected in an increase in total water use from  $1.819 \times 10^8$  to  $1.844 \times 10^8$  m<sup>3</sup> (1.37%). Likewise, a 2.04% increase in the amount of harvested wood, from  $4.00 \times 10^5$  to  $4.083 \times 10^5$  m<sup>3</sup>, led to a 0.34% increase in total water use, from  $1.735 \times 10^8$  to  $1.741 \times 10^8$  m<sup>3</sup>, whereas a 1.95% increase in harvested wood, from  $4.083 \times 10^5$  to  $4.164 \times 10^5$  m<sup>3</sup>, led to a 1.58% increase in total water use, from  $1.741 \times 10^8$  to  $1.769 \times 10^8$  m<sup>3</sup> (Figure 8b).

The conversion of cropland into *Eucalyptus* is driven by economic gains and yet it impacts water use, an important issue in the case study area. Thus, for illustration, we compared different possible Pareto front points in water use–LEV–harvested wood three-dimensional decision maps (Figure 9). Point ‘A’ is characterized by a high economic gain (in terms of LEV) of  $4.193 \times 10^9$  ETB, but with high water use ( $1.824 \times 10^8$  m<sup>3</sup>), resulting from the higher harvested wood volume ( $4.51 \times 10^8$  m<sup>3</sup>) and lower carbon stock ( $1.24 \times 10^7$  kg) (Table 5). At Point ‘C’, a lower economic gain ( $3.701 \times 10^9$  ETB of LEV) and lower total water use ( $1.642 \times 10^8$  m<sup>3</sup>) can be observed, which is mainly because of the lower harvested wood volume ( $4.118 \times 10^5$  m<sup>3</sup>). The Pareto frontier analysis also provides information about how much of the total land of the study area can be covered with *Eucalyptus* and cropland so as to attain the aforementioned values of the criteria. Accordingly, at Point ‘A’—i.e., the point with the highest LEV value but at the expense of higher water consumption—the area of land under *Eucalyptus* plantation would be 835 ha, and 1152 ha of cropland, which means only 175 ha of the current cropland (out of 1337 ha) could be converted into *Eucalyptus*. If it is necessary to limit the total water use up to  $1.642 \times 10^8$  m<sup>3</sup>, i.e., at Point ‘C’, there will be a reduction in LEV; and the land under *Eucalyptus* should not be more than 696 ha, which means that only 34 ha of the current cropland should be converted.



**Figure 9.** Pareto front points in a three-dimensional decision map showing tradeoffs among LEV, harvested wood and total water use.

**Table 5.** Solutions in the feasible set for the selected points (points selected in Figure 9).

Criteria	Point A	Point B	Point C	Change from Point A to B	Change from Point A to C
LEV ( $10^9$ ETB)	4.193	4.019	3.701	0.174	0.492
TOTWOOD ( $10^5$ m <sup>3</sup> )	4.51	4.274	4.118	0.236	0.392
CARBAvg( $10^7$ Kg)	1.237	1.308	1.368	−0.071	−0.131
VoIEI ( $10^5$ m <sup>3</sup> )	0.602	0.681	0.567	−0.079	0.035
WUTOT ( $10^8$ m <sup>3</sup> )	1.824	1.755	1.642	0.069	0.182
WUAnnual ( $10^7$ m <sup>3</sup> )	2.027	1.95	1.824	0.077	0.203
CROPTOT ( $10^6$ Kg)	11.347	11.564	11.839	−0.217	−0.492
CROPAnnual ( $10^5$ Kg)	12.608	12.849	13.155	−0.241	−0.547
LandUnderEuc (ha)	835	765	696	70	139
LandUnderCrop (ha)	1152	1222	1291	−70	−139

#### 4. Discussion

The approach presented in the current study employed single- and multiple-objective optimization (trade off analysis) to examine land conversion and management alternatives with respect to the impact on economic and ecological variables. The results from the single-objective optimization models, reflecting 12 decision scenarios, highlight that as long as the objective is to maximize the economic gains from land resources, *Eucalyptus* plantation is the best and feasible form of land use as compared to the crop production alternative. This objective leads to a complete conversion of the available cropland into *Eucalyptus* woodlots.

Given that crops (wheat, barley and beans) are the main source of the people's staple food, the complete conversion of cropland will have a substantial impact on the availability of food in the case study area. In the highlands of Ethiopia, the conversion of cropland into *Eucalyptus* has led to losses of  $4.5 \times 10^7$  kg of wheat production or  $3.1 \times 10^7$  kg of barley production annually [13], which translates to the grain needs of 70,000 to 100,000 households. Therefore, this clearly shows that decisions regarding *Eucalyptus* expansion must consider its impact on food security. Regarding the harvesting prescriptions, the models preferred shorter harvesting periods, with all the converted cropland assigned to be managed under a four-year rotation age. This means that the additional biomass that could potentially result from extending the rotation is not sufficient to offset the loss of discounted net revenues. An important point to be noted here is that the selling product considered in the study is construction poles, not timber, so the result could be different if other wood products that needed to be larger were considered. This, however, requires further investigation.

Constraining the LEV maximization objective with a certain crop production amount (equivalent to the annual household food consumption requirement) resulted in a reduction in LEV and wood, with the reduction being lower in MOD 10 (the normal crop production scenario). This indicates that with a normal crop production scenario, a relatively small area of cropland is enough to meet the minimum crop production constraint, and hence more land can be allocated for *Eucalyptus* land use, the result of which is higher wood production and LEV as compared to models considering the two other crop production scenarios, MOD 2 and 6. With this land allocation, it could also be possible to store  $1.5$  to  $1.57 \times 10^7$  kg yr<sup>−1</sup> of carbon in the aboveground biomass, which is equivalent to  $5.5$  to  $5.76 \times 10^5$  t yr<sup>−1</sup> of CO<sub>2</sub>. If the conversion of cropland into *Eucalyptus* is regulated by landscape level ecologic/economic objectives, the potential of the *Eucalyptus*-agriculture mosaic landscape to simultaneously address economic, food security and climate change mitigation objectives can be achieved. This potential integration of economic and climate change mitigation objectives through plantation and woodlots has been suggested by other authors [10,11]. Furthermore, an increase in land allocation for *Eucalyptus* with increasing crop production—i.e., from MOD 2 to 10—also indicates that agricultural measures to enhance crop production could help to attain the food security targets in a small area of

land so that more land can be allocated for *Eucalyptus*, leading to a higher economic gain while contributing towards carbon sequestration.

Water use is one of the most important aspects discussed in relation to *Eucalyptus* expansion in Ethiopia [36]. In the current study, we attempted to address water use concerns by constraining the LEV maximization objectives by impose a maximum annual water use value, a level equivalent to the annual rainfall in the study area, i.e., decision scenarios MOD 3, 7 and 11. This approach obviously has drawbacks, as not all of the rainfall in the area would remain there (the area in which *Eucalyptus* is planted); rather, a certain amount would exit this area through evaporation and runoff. In addition, it does not consider the influence of silvicultural options on water use. However, it is able to depict the relationship/impact. Accordingly, the constrained scenarios, as expected, resulted in a significant decrease in LEV and the volume of harvested wood as compared to the unconstrained ones. Moreover, there was a significant reduction in the amount of land allocated for *Eucalyptus*.

The reduction in land allocated for *Eucalyptus* and of the volume of harvested wood was associated with the increase in crop productivity, i.e., from the 'low' crop production scenario (MOD 3) to the 'moderate' (MOD 7) and 'normal' (MOD 11) scenarios. This could be related to the magnitude of contributions from the uses of cropland towards the objective function, i.e., LEV maximization, while maintaining the maximum water use limit. As this contribution may increase with crop production, the allocation of a unit of land for crop use in the case of the 'normal' crop production scenario (MOD 11) could contribute more towards the objective function, LEV maximization, than that of 'moderately normal' (MOD 7) and 'low (MOD 3) production scenarios. The result is thus a higher allocation of land for cropland uses by MOD 11, and hence, higher total crop production and total water use (but not beyond the limit), and a lower volume of harvested wood as compared to MOD 3 and 7.

The multiple-objective optimization process, carried out using the Pareto frontier approach, also revealed that maximizing carbon stock and/or VoleI would come at the cost of reduced harvested wood volume or LEV and increased total water use, with the tradeoff being more evident at larger values of the criteria. We determined the possibility of increasing carbon stock without greatly affecting the LEV up to a certain amount, beyond which the tradeoff would begin. Such a tradeoff between the economic returns from wood and carbon stock has also been reported in other optimization studies, e.g., [37,38]. However, it is important to note that different patterns of relationship might have been observed in the current study if the monetary value of carbon sequestration was included in the estimation of LEV; this should therefore be addressed in future optimization studies. Similarly, carbon stock also demonstrated a tradeoff with harvested wood volume, but mainly at higher values of the latter. The reduction in carbon stock with larger wood biomass harvests was also reported in a *Eucalyptus*-dominated stand in Portugal [29]. The authors reported that higher levels of total harvested wood lead to a lower number of trees and thus a lower capacity to store carbon.

Similarly with the results discussed above, total water use was found to increase with an increase in LEV, harvested wood volume, carbon stock and ending inventory criteria. The implication of this is that an increase in wood production by converting cropland into *Eucalyptus* plantations would continue to be a threat to water availability in the study area. This finding highlights the importance of future research on hydrological models to fine-tune the estimation of these tradeoffs. Moreover, this result is consistent with the findings of other authors. For instance, Zengin et al., (2015) [39] employed an optimization technique and considered water yield (discharge), and found that the wood production and carbon stock of *Eucalyptus* and Pine plantations had a greater trade-off with the water yield. Similarly, a study on *Pinus elliotii* forests in the southeastern USA reported similar relationship patterns for timber production, carbon sequestration and water yields [40].

In line with the current study, a study in the central highlands of Ethiopia reported that, considering a biomass production estimate of  $\sim 16,000 \text{ kg ha}^{-1} \text{ yr}^{-1}$ , *Eucalyptus* woodlots would consume  $12,560 \text{ m}^3$  of water per hectare per year, or  $1256 \text{ mm m}^{-2} \text{ yr}^{-1}$ , which was

on the same order as the total annual rainfall in their study area, and was substantially higher than estimated evapo-transpiration from crops and grasslands in the area [41]. The authors stressed that this raises a concern for the viability of local streams. Moreover, as the study region is located in the headwaters of the Blue Nile basin, this potentially has broader implications for water resources in a contentious trans-boundary basin. Therefore, the current and future extent of *Eucalyptus* patches need to be considered in water resource management [36].

## 5. Conclusions

In this study, we examined land conversion policies (from cropland to *Eucalyptus* plantations) under several decision scenarios. These scenarios were used to consider economic gains, as well as other ecosystem service objectives (carbon, wood and water use). Based on this analysis, we concluded that as far as the objective is to maximize the total economic gains, *Eucalyptus* plantations are the best form of land use when compared to the crop production alternative. This scenario favors a complete conversion of the available cropland into *Eucalyptus* woodlots.

However, in order to at least meet the annual crop production/consumption requirements of households in the case study area, the total *Eucalyptus* land should be limited to 1772 ha (out of the total 1987 ha), with a sequestration potential of 1.5 to  $1.57 \times 10^7$  kg yr<sup>-1</sup> of carbon in the aboveground biomass. This limit could actually be increased with higher crop productivity. However, this land cover limit should be decreased to 921 ha so as to limit the total annual water use (for biomass production) below the amount available from rainfall (11,000 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>).

Based on the tradeoff analysis, maximizing the harvested wood volume or LEV would come at the cost of a decreased aboveground carbon stock and volume of the ending inventory and higher total water use. This study further research highlights the potential for the application of Pareto frontier approaches to support the development of effective ecological/economic management strategies and the design of land use policies in an Ethiopian context.

There are, however, some issues that should be addressed in future research. One important issue is that the water use and stand growth model did not take into account climate change and management effects. Realistically, however, a growth and yield model should be developed based on permanent sample plots and climate information. In addition, there are other forest management objectives such as controlling erosion or soil losses, enhancing soil fertility and the impact on biodiversity, which should be integrated into the model as well.

**Author Contributions:** Conceptualization, D.A. and J.G.B.; methodology, D.A., J.G.B., S.M. and V.B.; software, D.A., J.G.B., S.M. and V.B.; validation, D.A. and J.G.B.; formal analysis, D.A. and J.G.B.; data curation, D.A. and J.G.B.; writing—original draft preparation, D.A. and J.G.B.; writing—review and editing, D.A., J.G.B., S.M. and V.B.; visualization, D.A., J.G.B. and S.M.; supervision, J.G.B. and S.M.; project administration, J.G.B. and S.M.; funding acquisition, J.G.B. and S.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by the NOBEL project, grant agreement number 773324, which is part of the ERA-NET Cofund ForestValue, by the Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) within the H2020 Work Programme (H2020-MSCA-RISE-2020/101007950) (DecisionES), by the University of Gondar Research Grant, by the MEDFOR Master Programme on Mediterranean Forestry and Natural Resources Management (Erasmus+: Erasmus Mundus Joint Master Degrees, Project 20171917), by the Portuguese Science Foundation (FCT), Portugal, namely, through the Ph.D. grant of Dagm Abate (UI/BD/151525/2021), by the FCT—Fundação para a Ciência e a Tecnologia, I.P. in the scope of Norma Transitória—DL57/2016/CP1382/CT15, by a project MODFIRE—A multiple criteria approach to integrate wildfire behavior in forest management planning with the reference PCIF/MOS/0217/2017, and by another FCT grant of CIMA, grant number UIDB/04674/2020 and the Forest Research Center Project UIDB/00239/2020 and the University of Gondar grant agreement UOGRCS/2021.

**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Ministry of Environment Forest and Climate Change. Ethiopia Forest Sector Review, Focus on Commercial Forestry and Industrialization. Technical Report. 2017. Available online: [www.ethiopia.gov.et](http://www.ethiopia.gov.et) (accessed on 12 January 2022).
2. Bekele, M. *Forest Plantations and Woodlots in Ethiopia*; Working Paper Series; African Forest Forum: Nairobi, Kenya, 2011; Volume 1.
3. Pohjonen, V.; Pukkala, T. *Eucalyptus globulus* in Ethiopian forestry. *For. Ecol. Manag.* **1990**, *36*, 19–31. [[CrossRef](#)]
4. Mekonnen, Z.; Kassa, H.; Lemenih, M.; Campbell, B. The role and management of *Eucalyptus* in lode hetosa district, central Ethiopia. *For. Trees Livelihoods* **2007**, *17*, 309–323. [[CrossRef](#)]
5. Achalu, N. Farm Forestry Decision—Making Strategies of the Guraghae Households, Southern-Central Highlands of Ethiopia. Ph.D. Dissertation, Technische University Dresden, Agriculture Natural Resource Extension, Dresden, Germany, 2004.
6. Duguma, L.A.; Hager, H. Farmers’ assessment of the social and ecological values of land uses in central highland Ethiopia. *Environ. Manag.* **2011**, *47*, 969–982. [[CrossRef](#)] [[PubMed](#)]
7. Lemenih, M. Growing ulycyp by smallholder farmers in Ethiopia. In Proceedings of the Congress on *Eucalyptus* Species Management, History, Status and Trends in Ethiopia, Addis Ababa, Ethiopia, 15–17 September 2010; Gil, L., Tadesse, W., Tolosana, E., López, R., Eds.; Ethiopian Institute of Agricultural Research: Addis Ababa, Ethiopia, 2010.
8. Jenbere, D.; Lemenih, M.; Kassa, H. Expansion of *Eucalyptus* farm forestry and its determinants in Arsi Negelle District, South Central Ethiopia. *Small Scale For.* **2012**, *11*, 389–405. [[CrossRef](#)]
9. Tefera, B.; Kassa, H. Trends and driving forces of *Eucalyptus* plantation by smallholders in the Lake Tana Watershed of Ethiopia. In *Social and Ecological System Dynamics*; AESS Interdisciplinary Environmental Studies and Sciences Series; Stave, K., Goshu, G., Aynalem, S., Eds.; Springer: Cham, Switzerland, 2017. [[CrossRef](#)]
10. Ahimbisibwe, V.; Auch, E.; Groeneveld, J.; Tumwebaze, S.B.; Berger, U. Drivers of household decision-making on land-use transformation: An example of woodlot establishment in Masindi District, Uganda. *Forests* **2019**, *10*, 619. [[CrossRef](#)]
11. Mesfin, A.; Wubalem, T. *Eucalyptus in Ethiopia: Risk or Opportunity?* Ethiopian Institute of Agricultural Research: Addis Ababa, Ethiopia, 2014; ISBN 9789994453914.
12. Dessie, G.; Erkossa, T. *Eucalyptus in East Africa: Socio-Economic and Environmental Issues*; Working Paper FP46/E; FAO: Rome, Italy, 2011.
13. Alemneh, T.; Benjamin, Z.; Simane, B.; Ambelu, A. Changing Patterns of Tree Cover in a Tropical Highland Region and Implications for Food, Energy, and Water Resources. *Front. Environ. Sci.* **2019**, *7*, 1. [[CrossRef](#)]
14. Tadesse, S.A.; Tafere, S.M. Local people’s knowledge on the adverse impacts and their attitudes towards growing *Eucalyptus* woodlot in Gudo Beret Kebele, Basona Worena district, Ethiopia. *Ecol. Process.* **2017**, *6*, 37. [[CrossRef](#)]
15. Chanie, T.; Collick, A.S.; Adgo, E.; Lehmann, C.J.; Steenhuis, T.S. Eco-hydrological impacts of *Eucalyptus* in the semi humid Ethiopian Highlands: The Lake Tana Plain. *J. Hydrol. Hydromech.* **2013**, *61*, 21–29. [[CrossRef](#)]
16. Yitaferu, B.; Abewa, A.; Amare, T. Expansion of *Eucalyptus* woodlots in the fertile soils of the highlands of Ethiopia: Could it be a treat on future cropland use? *J. Agric. Sci.* **2013**, *5*, 97–103. [[CrossRef](#)]
17. Jaleta, D.; Mbilinyi, B.P.; Mahoo, H.F.; Lemenih, M. Effect of *Eucalyptus* expansion on surface runoff in the central highlands of Ethiopia. *Ecol. Process.* **2017**, *6*, 1. [[CrossRef](#)]
18. Mohammadi, Z.; Limaie, S.M.; Shahraji, T.R. Linear programming approach for optimal forest plantation. *J. For. Res.* **2017**, *28*, 299–307. [[CrossRef](#)]
19. Kaya, A.; Bettinger, P.; Boston, K.; Akbulut, R.; Ucar, Z.; Siry, J.; Merry, K.; Cieszewski, C. Optimisation in Forest Management. *Curr. For. Rep.* **2016**, *2*, 1–17. [[CrossRef](#)]
20. Belavenutti, P.; Romero, C.; Diaz-Balteiro, L. A critical survey of optimization methods in industrial forest plantations management. *Sci. Agric.* **2018**, *75*, 239–245. [[CrossRef](#)]
21. Kaim, A.; Anna, F.C.; Volk, M. A review of multi-criteria optimization techniques for agricultural land use allocation. *Environ. Model. Softw.* **2018**, *105*, 79–93. [[CrossRef](#)]
22. Sacchelli, S.; Bernetti, I. Integrated management of forest ecosystem services: An optimization model based on multi-objective analysis and metaheuristic approach. *Nat. Resour. Res.* **2019**, *28*, 5–14. [[CrossRef](#)]
23. Baskent, E.Z.; Jordan, G.A. Forest landscape management modeling using simulated annealing. *For. Ecol. Manag.* **2002**, *165*, 29–45. [[CrossRef](#)]
24. Baskent, E.Z.; Keles, S.; Kadiogullari, A.I. Challenges in developing and implementing a decision support systems (ETcAP) in forest management planning: A case study in Honaz and Ibradi, Turkey. *Scand. J. For. Res.* **2014**, *29*, 121–131. [[CrossRef](#)]
25. Borges, J.G.; Garcia-Gonzalo, J.; Bushenkov, V.; McDill, M.E.; Marques, S.; Oliveira, M.M. Addressing multicriteria forest management with Pareto Frontier methods: An application in Portugal. *For. Sci.* **2014**, *60*, 63–72. [[CrossRef](#)]
26. Garcia-Gonzalo, J.; Bushenkov, V.; McDill, M.E.; Borges, J.G. A decision support system for assessing trade-offs between ecosystem management goals: An application in Portugal. *Forests* **2015**, *6*, 65–87. [[CrossRef](#)]



27. Borges, J.G.; Marques, S.; Garcia-Gonzalo, J.; Rahman, A.U.; Bushenkov, V.; Sottomayor, M.; Carvalho, P.O.; Nordstrom, E.M. A multiple criteria approach for negotiating ecosystem services supply targets and forest owners' programs. *For. Sci.* **2017**, *63*, 49–61. [[CrossRef](#)]
28. Marques, S.; Marto, M.; Bushenkov, V.; McDill, M.; Borges, J.G. Addressing wildfire risk in forest management planning with multiple criteria decision-making methods. *Sustainability* **2017**, *9*, 298. [[CrossRef](#)]
29. Marto, M.; Reynolds, K.M.; Borges, J.G.; Bushenkov, V.A.; Marques, S.; Marques, M.; Barreiro, S.; Botequim, B.; Tomé, M. Web-based forest resources management decision support system. *Forests* **2019**, *10*, 1079. [[CrossRef](#)]
30. Dong, L.B.; Lu, W.; Li, Z.G. Developing alternative forest spatial management plans when carbon and timber values are considered: A real case from northeastern China. *Ecol. Model.* **2018**, *385*, 45–57. [[CrossRef](#)]
31. Lafond, V.; Cordonnier, T.; Mao, Z.; Courbaud, B. Trade-offs and synergies between ecosystem services in uneven-aged mountain forests: Evidences using Pareto fronts. *Eur. J. For. Res.* **2017**, *136*, 997–1012. [[CrossRef](#)]
32. Derbe, T.; Sisay, Y.; Genanew, A. Factors influencing smallholder farmers adoption of *Eucalyptus* woodlot in Wogera District, North Gondar Zone, Amhara Regional State of Ethiopia. *IJSRM Int. J. Sci. Res. Manag.* **2018**, *6*, 566–574. [[CrossRef](#)]
33. Johnson, K.N.; Scheurman, H.L. Techniques for prescribing optimal timber harvest and investment under different objectives—Discussion and synthesis. *For. Sci.* **1977**, *23* (Suppl. S1), a0001–z0001.
34. Abate, D.F. An ecological-economic approach to assess impacts of *Eucalyptus* woodlot expansion in agroforest landscapes of Northern Ethiopia. Master's Thesis, School of Agriculture, University of Lisbon, Lisbon, Portugal, 2020.
35. Worku, I.H.; Dereje, M.; Minten, B.; Hirvonen, K. Diet transformation in Africa: The case of Ethiopia. *Agric. Econ.* **2017**, *48*, 73–86. [[CrossRef](#)]
36. Enku, T.; Melesse, A.M.; Ayana, E.K.; Tilahun, S.A.; Abate, M.; Steenhuis, T.S. Groundwater use of a small *Eucalyptus* patch during the dry monsoon phase. *Biologia* **2020**, *75*, 853–864. [[CrossRef](#)]
37. Keleş, S.; Başkent, E.Z. Modelling and analyzing timber production and carbon sequestration values of forest ecosystems: A case study. *Pol. J. Environ. Stud.* **2007**, *16*, 473–479.
38. Raymer, A.K.; Gobakken, T.; Solberg, B.; Hoen, H.F.; Bergseng, E. A forest optimisation model including carbon flows: Application to a forest in Norway. *For. Ecol. Manag.* **2009**, *258*, 579–589. [[CrossRef](#)]
39. Zengin, H.; Asan, Ü.; Destan, S.; Engin Ünal, M.; Yeşil, A.; Bettinger, P.; Değermenci, A.S. Modeling harvest scheduling in multifunctional planning of forests for longterm water yield optimization. *Nat. Resour. Model.* **2015**, *28*, 59–85. [[CrossRef](#)]
40. Cademus, R.; Escobedo, F.J.; McLaughlin, D.; Abd-Elrahman, A. Analyzing trade-offs, synergies, and drivers among timber production, carbon sequestration, and water yield in *Pinus elliotii* forests in Southeastern USA. *Forests* **2014**, *5*, 1409–1431. [[CrossRef](#)]
41. Zaitchik, B.F.; Simane, B.; Habib, S.; Anderson, M.C.; Ozdogan, M.; Foltz, J.D. Building climate resilience in the Blue Nile/Abay Highlands: A role for earth system sciences. *Int. J. Environ. Res. Public Health* **2012**, *9*, 435–461. [[CrossRef](#)]