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An ecological-economic approach to assess impacts of Eucalyptus Woodlot Expansion in Agroforest Landscapes of Northern Ethiopia

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ABSTRACT

The study is the first optimization-based case study for forest plantations in Ethiopia, aimed at providing evidence to support economic and environment outcome-based decisions for management of existing as well as future *Eucalyptus* plantations to be established by converting current crop lands in the agroforest landscapes of Wogera district, Northern Ethiopia. The study is based on inventory data collected from 60 sample plots of *Eucalyptus* plantation and neighboring crop land distributed across the case study area. The collected data were organized and analyzed to produce a yield table and cashflows over a nine-year planning horizon. Twelve different linear programming models well developed and analyzed for single objective optimization (mainly LEV maximization), whereas Pareto Frontier tool was used to analyze the tradeoff. The main finding was that as far as the objective is to maximize the total economic gain from the sale of Eucalyptus wood poles, *Eucalyptus* plantation is the best and feasible land use as compared to the crop production alternative, and thus, favors a complete conversion of the available crop land into Eucalyptus woodlot. In order to at least meet the annual crop production / consumption requirements of households in the case study area, the total land area under Eucalyptus should be limited to 1772 ha (out of the total 1987 ha). However, this land cover limit should be decreased to 921 ha so as to limit the total annual water use (used for biomass production) below the amount available from rainfall. The current study also showed the potential application of Pareto Frontier to analyze the tradeoff among multiple objectives in Ethiopian context; and found that maximizing the harvested wood volume or LEV would come at the cost of decreased aboveground carbon stock and volume of ending inventory and higher total water use. It also provides different optimal pareto front points among which decision makers will be able to select their preferred targets.

Keywords: *Eucalyptus* Woodlot, Carbon Stock, Crop Production, Water Use, Optimization

RESUMO

Este estudo foi o primeiro feiro na Etiópia em otimização e plantações florestais, com o objetivo de fornecer evidências para apoiar decisões de gestão (económicas e ambientais) de plantações de eucaliptos existentes e futuras a serem estabelecidas pela conversão de atuais terrenos agrícolas na paisagem agroflorestal do distrito de Wogera, norte da Etiópia. O estudo baseou-se em dados de inventário recolhidos em 60 parcelas em plantações de eucalipto e terrenos agrícolas vizinhos distribuídas pelo caso de estudo. Os dados recolhidos foram organizados e analisados de forma a produzir uma tabela de crescimento e fluxos de caixa ao longo de um horizonte de planeamento de nove anos. Doze modelos de programação linear foram desenvolvidos e analisados para otimização de um único objetivo (principalmente maximização de Valor Esperado da Terra (VET), enquanto que a ferramenta FGoal que gera as fronteiras de Pareto usada para analisar os tradeoffs entre múltiplos objetivos. A principal constatação foi que, com o objetivo de de maximizar o ganho económico total, a plantação de eucalipto é a opção mais viável do uso do solo em relação à alternativa de produção agrícola e portanto, favorece uma reconversão total das terras agrícolas disponíveis em povoamentos florestais ocupados com eucalipto. Para atender, pelo menos às necessidades de produção (consumo anual das famílias) na área do caso de estudo, a área total de eucaliptos deve ser limitada a 1772 ha (de um total de 1987 ha). No entanto, este limite de ocupação do solo deve ser reduzido para 921 ha, quanto queremos limitar o uso anual de água (usado para a produção de biomassa) abaixo da quantidade disponível de precipitação. O presente estudo mostrou também o potencial da utilização da ferramenta que constrói as fronteiras de Pareto na análise do tradeoffs entre múltiplos objetivos no contexto etíope. Observou-se que a maximização do volume de madeira cortada ou VET teria o custo da diminuição do stock de carbono acima do solo e do volume de inventário final e um maior uso total de água. Com esta ferramenta podemos também retirar diferentes pontos ideias indo de encontra os níveis desejados dos decisores, em cada objetivo.

Palavras chave: Eucalipto Madeira, Stock de carbono, Produção agrícola, uso da água, Otimização

RESUMO ALARGADO

Estima-se que a Etiópia tenha cerca de 722.000 ha de florestas plantadas, dos quais 70% são plantações de eucalipto. Com isso, A Etiopia é um dos 10 mais importantes produtores de eucalipto do mundo (Amare, 2010). Tem havido um debate controverso sobre os aspectos ecológicos da espécie. O argumento mais comum contra as plantações de eucalipto é o seu impacto na água principalmente para redução na quantidade de disponível para áreas próximas e comunidades a jusante (Mesfin e Wubalem, 2014; Jaleta et al., 2016a, Jaleta et al., 2017). A sua expansão chega ao ponto de converter as atuais agrícolas em povoamentos de eucalipto (Yeshaneh et al., 2013).

A conversão de áreas agrícolas em povoamentos florestais tornou-se prática comum na maior parte do norte da Etiópia, levando uma paisagem agroflorestal dominada por eucaliptal, portanto surge a necessidade de definição de evidencias cientificas para apoiar as decisões de gestão nesta paisagem agroflorestal. Este estudo tentou examinar como os ganhos económicos da conversão de terras com aptidão agricola - de classes de produtividade variadas - em plantações de eucalipto a serem cortadas em diferentes rotações afetando os serviços de ecossistema (carbono e água), e em que medida há compensação entre eles. Isso ajudará a identificar estratégias de gestão por forma a minimizar as compensações.

Especificamente a análise de compensações entre critérios como: valor esperado da terra (VET), volume de inventário final (VolEI), stock de carbono aério e uso da água podem apoiar ambas as decisões de alocação de terra (por exemplo, floresta vs agricultura) e planeamento da gestão florestal. O estudo foi realizado na unidade administrativa Kosoye Amba Kebele do distrito de Wogera, no Estado Regional Nacional de Amhara da Etiópia, a 763 km de Addis Abeba, capital do país.

Este estudo teve como base os dados de inventário recolhidos em fevereiro e março de 2020 numa amostra de 60 parcelas em plantações de eucalipto e terrenos agrícolas vizinhos distribuídas pela área do caso de estudo. Foi feita uma visita preliminar ao local e uma consulta com especialistas em silvicultura no distrito, de forma a garantir que povoamentos de idades diferentes, rotações (alto fuste e talhadia) e produtividade fossem incluídos na seleção das parcelas amostradas. Em relação à produtividade, a área de estudo foi dividida em quatro estratos com base nas informações dos especialistas-chave, bem como na observação durante o reconhecimento da área. Esta informação foi posteriormente considerada para a classificação do local. Nas parcelas de inventário em povoamentos de eucalipto com dimensão de 100m^2

(10m x 10m), foi recolhida a informação do diâmetro da altura do peito (DAP) de todas as árvores existentes, bem como a altura das cinco árvores amostra (duas menores, duas maiores e uma mediana). Além disso, os custos de mão de obra, consumos, corte, transporte, preços de venda da madeira e outros dados de gestão como; geográficos (declive, altitude) e cobertura /uso do solo foram registados com base na observação e entrevistas com os proprietários. Os proprietários das áreas agrícolas vizinhas de povoamentos florestais foram entrevistados e recolhida a informação sobre a sua gestão. Os especialistas chave forneceram também informação sobre a avaliação de mercado das cidades vizinhas, por forma a complementar a informação recolhida em inventário e os dados económicos. Além disso, dados secundários como as imagens de satélite de 2020 (do USGS) e dados pluviométricos também foram adquiridos e utilizados no estudo. Doze modelos de programação linear foram desenvolvidos e analisados para otimização de um único objetivo (principalmente maximização de VET), enquanto que a ferramenta das fronteiras de Pareto foi usada para analisar o tradeoff entre múltiplos objetivos.

A principal constatação foi que, quando o principal objetivo é a maximização do ganho económico total esta se obtém através da venda de madeira de eucalipto, logo a plantação de eucaliptais torna-se mais viável em relação à alternativa de produção agrícola e portanto, favorecendo a conversão. Para suprir as necessidades de produção (consumo anual das famílias na área de estudo), a área máxima de eucalipto deve ser limitada a 1772 ha (de um total de 1987 ha). No entanto, a ocupação por eucalipto deve ser reduzido para 921 ha, de forma a limitar o uso anual de água (usado para a produção de biomassa) abaixo da quantidade disponível de precipitação. O presente estudo mostrou também a potencial aplicação da ferramenta que produz as fronteiras de Pareto para análise de tradeoffs entre múltiplos objetivos no contexto etíope. Aqui detectou-se que a maximização do volume de madeira cortada ou VET teria o custo de diminuir o stock de carbono acima do solo, o volume do inventário final e maior uso total de água. Também fornece diferentes pontos de Pareto ideais, entre os quais os decisores serão capazes de selecionar seus níveis para cada objetivo pretendidos.

No contecto Etiope, este estudo é o primeiro e único, com otimização de múltiplos objetivos. No entanto, existem algumas questões que se recomendam em investigação futura. Uma questão importante é que o uso da água e o modelo de crescimento do eucalipto não tiveram em consideração as alterações climáticas e os efeitos da gestão (por exemplo, fertilização) ao longo do horizonte de planeamento. Porém, realisticamente, um modelo de crescimento e produção deve ser desenvolvido com base em parcelas de inventário permanentes e informações climáticas. Além disso, existem outros objetivos de gestão florestal, como o controlo da erosão, aumento da fertilidade e o impacto sobre a biodiversidade, que também devem ser integrados no modelo. Outro critério importante que pode ser tido em consideração é o stock de carbono no solo e no subsolo e a valorização económica do sequestro de carbono, para capturar o valor económico real da gestão das plantações de eucalipto.

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1. INTRODUCTION

1.1. Background

To address the problem of deforestation and supplement the shortage of supply of products from natural forests, government-initiated afforestation efforts in Ethiopia have been started long years ago- near the end of the nineteenth century (Bekele, 2003). And, almost all state-initiated afforestation efforts were using *Eucalyptus* species as the main species for plantation. Since then, successive restoration programs have been using *Eucalyptus* species. Mainly in the aftermath of the catastrophic drought and famine of the 1970s, there has been extensive restoration and rehabilitation programs including tree planting where the major species was *Eucalyptus*. The country is estimated to have about 722,000 ha of plantation forest, out of which *Eucalyptus* plantation forest comprises 70% percent. With this extent, the country is one of the 10 most important *Eucalyptus*-growing countries in the world (Amare, 2010).

While the introduction and development of *Eucalyptus* tree plantation has mainly been implemented by the government, the practice was expanded from state owned plantations to community woodlots and then to small holder farmers. The species is then reported to become an integral part of most of the Ethiopian farming system and one of the Ethiopian most important tree resources (Pohjonen and Pukkala, 1990). It has been suggested that the development of *Eucalyptus* forestry is crucial in narrowing the gap between forest product demand and supply in the current context of Ethiopia and most African countries.

There has however been a controversial debate on ecological aspects of *Eucalyptus*. The most common argument against planting *Eucalyptus* is its impact on water, mainly reported to reduce the amount of water available for nearby areas and downstream communities (Mesfin and Wubalem, 2014; Jaleta et al., 2016a, Jaleta et al., 2017). There are also, however, positive arguments mentioning higher water use efficiency (Lemenih et al., 2004; Teshome T, 2009; Yitaferu et al., 2013). Even with such controversial concern, there remains a continual practice of planting *Eucalyptus* by small holder farmers across most parts of the country. Studies reported an increasing trend of land allocated by farm households for *Eucalyptus* woodlots (Jaleta et al., 2016b; Bezabih et al., 2019).

The expansion is even to the extent of converting available crop lands into *Eucalyptus* woodlot (Yeshaneh et al., 2013). It has been found that often farmers grow *Eucalyptus* on lands that have little other use options such as farm boundary (demarcation of farm plots), on degraded parts of their land holdings or in small woodlots at front yard or in garden. Since the past two decades, however, conversions of fertile croplands to Eucalypt woodlot are becoming common (Lemenih, 2010; Jenbere et al., 2012; Tefera and Kassa, 2017). The fact that *Eucalypt* planting has increased overtime, mainly on former crop lands, despite the controversial ecological concern implies that the issue is of more economical than ecological. Jenbere et al. (2012) has reported that fertile croplands have been converted to *Eucalyptus* wood lots each year mainly because this is a more lucrative form of income; and most farmers intend to continue to plant *Eucalyptus* in the future. The issue is widely documented for many of the Ethiopian highlands, including the Wogera district, located in the northern part of the country. It has become a common practice to convert crop lands into *Eucalyptus* woodlot, creating a *Eucalyptus*-dominated agroforest landscape in the area. Therefore, there is a need to provide scientific based evidence to support decisions for management of existing as well as future *Eucalyptus* plantations to be established by converting current crop lands in this agroforest landscapes.

The decision to convert crop land among other things is highly dependent on the financial profitability of the plantation investment, which in turn depends on- as it is a more than one-year investment- the period where costs and revenues occur. As a short rotation plantation, the common rotation is five years. However, there may likely be a need for early (mainly induced by a farmer's need for immediate cash) or late harvestings, whose profitability has not however been analyzed, but crucial for land conversion decisions. Another important but overlooked issue is that all crop lands are supposed to be converted into plantations and expected to have higher return than the crop production alternative. Whereas, the spatial variability in land productivity, and resulting impact on profitability is overlooked. Jagger and Pender (2003) noted that land values have a greater effect on rate of return estimates, implying that the opportunity cost of land is an important consideration when planting *Eucalyptus* trees, which has implications when considering the issue of planting trees on farmlands vs. wastelands. Therefore, the productivity attribute should be considered in profitability analysis, based on which land conversion decision can be made.

While the economic aspect has been reported to be the main driving force for converting crop land into eucalypts on the one hand, and on the other hand, the environmental impact has still been remained controversial (or site specific), the extent of tradeoffs between the economic benefits and environmental services has not been investigated. As already mentioned earlier, one of the most commonly reported environmental issue of *Eucalyptus* plantation is the higher water consumption, which leads to the depletion of scarce water. So, converting crop land, which is assumed to have lower water consumption, into *Eucalyptus* plantation land for economic reason is impacting the water resource base of an area. On the other hand, *Eucalyptus* trees do an excellent job of sequestering CO_2 because they efficiently store carbon in all their live biomass, implying that planting *Eucalyptus* on former crop land would increase above ground biomass carbon, important contribution for climate change mitigation (Mesfin and Wubalem, 2014). However, this is again at the cost of higher water consumption. Therefore, taking this into account, quantitative estimation of such interrelationship among different objectives and depict possible tradeoffs as well as optimal land allocations aiming to minimize the trade-offs are required, which calls for multiple objective optimization analysis of land allocation/management alternatives.

Multiple Criteria Decision Analysis (MCDA) encompasses a collection of different mathematical methods for finding solutions to decision problems with multiple conflicting goals or criteria (Belton and Stewart 2002). By MCDA, it simply means that we set criteria to address the supply of multiple ecosystem services in a multi-objective forest management planning process, and then adopting MCDA method to analyze the tradeoffs among these criteria (Kaim et al., 2018). There exist various modelling tools that are based on MCDA (Sacchelli and Bernetti, 2019). The models provide outputs based on which end users and scientific researchers can learn and understand the impacts of management plans on the provision of forest ecosystem services (Baskent and Jordan, 2002; Baskent et al., 2014). One among the common modelling approach is Pareto Frontier. Pareto Frontier is an a posteriori MCDA approach where the decision makers are not required to set targets for criteria before being informed of trade-offs among ecosystem services. This is very important because the farmers (decision makers) are not required to set targets before being informed about the feasible decision space (production possibility frontier) and the tradeoffs between decision criteria (Kaim et al., 2018).

MCDA and its application in tradeoff analysis have been extensively used and developed for plantation forests management, including *Eucalyptus* (e.g. Garcia-Gonzalo et al., 2015; Borges et al., 2014; Borges et al., 2017; Marques et al., 2017; and Marto et al., 2018). The study of Borges et al. (2014) in Portugal have analyzed tradeoff among four economic and environmental criteria (objectives), i.e. Net Present Value (NPV), timber supply, cork supply, carbon stock and value of ending inventory. A study in North East also used MCDA to examine tradeoff between carbon, timber and total NPV (Dong et al., 2018). A study in the Western

Alps characterized trade-offs and synergies between timber production, biodiversity conservation and protection against natural hazards using Pareto Frontier (Lafond et al., 2017).

However, its application in agroforest landscapes and in developing countries like Ethiopia is not yet documented. The current study has therefore attempted to examine how economic gains from converting lands- of varying productivity class- from crop into *Eucalyptus* plantation to be harvested at different periods affect ecosystem services (carbon and water), and to what extent is the tradeoff between them. This will help to identify plantation management strategies to minimize tradeoffs.

1.2. Objectives

The overall objective of the study is to provide evidence to support economic and environment outcome-based decisions for management of existing as well as future *Eucalyptus* plantations to be established by converting current crop lands in the agroforest landscapes of Wogera district, Northern Ethiopia. It specifically aimed at analyzing tradeoffs between criteria such as Land Expectation Value (LEV), Volume of Ending Inventory (VolEI), Carbon stock (above ground) and water use in order to support both land allocation decisions (e.g., forest vs agriculture) and forest management planning.

2. MATERIALS AND METHODS

2.1. Study site

The study was conducted in the *Kosoye Amba Kebele* administrative unit of the Wogera district in Amhara National Regional State of Ethiopia, 763 kms far from Addis Ababa, the country's capital (Figure 1). The district is located at 37.36 ºE longitude and 12.46 ºN latitude. The altitude ranges from 1100 m to 3040 m a.s.l, with an average altitude of 2,812m a.s.l. The mean annual rainfall is between 1000 and 1200 mm and the minimum and maximum temperature is 14 °C and 33 °C, respectively. The rainy season extend from June until the end of September. most of the rain being received in July and August (Derbe et al., 2018). The agro-ecological distribution looks like: 56% Dega (cold), 26% Woina Dega (moderate), 4% Wurch (frosty) and the rest 13% Kolla (hot). The area of the district is characterized by a crop dominated mixed farming system (i.e. crop and livestock production). The main crops produced in the district are wheat, barley, sorghum, and leguminous crops like bean, peas and lentils. Likewise, it is known by high area coverage of small-scale *Eucalyptus globulus* woodlots. The species is considered as a major cash crop in the study area being one of the major sources of cash income for most households (Derebe et al., 2018; Dessie et al., 2019).

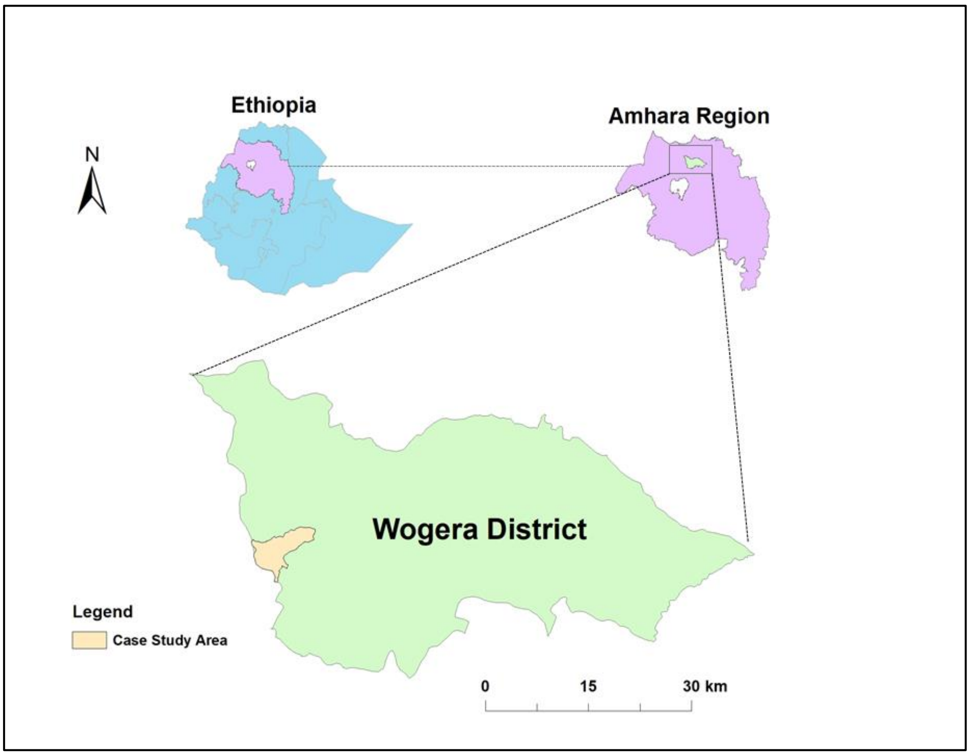


Figure 1 Location map of the case study area, Wogera district, Northern Ethiopia

The agroforest landscape of *Kosoye Amba Kebele* located in the western part of Wogera district was the specific sample site for the current study (Figure 1). The *Kebele* was selected purposively in consultation with informants from district forestry experts, and selected because of the (i) higher coverage of *Eucalyptus* woodlots (ii) higher rates of conversion of crop land and (iii) accessibility for data collection. The case study area extends over 3104.27 ha, of which 1327.19 ha is crop land, 660.12 plantation forest, 409.95 grazing land, 37.49 bush and natural forest and the remaining is bare land and others such as settlement and infrastructure (This land use land cover data was estimated in the current study following the methods described in *Section 2.4*). In Ethiopia, land is owned by the state, which gives the people only use right, either privately or in group (community); hence, there are private (mainly crop lands and Eucalyptus woodlots) and communal land (mainly grazing land). The *Kebele* administrative office reports a total of 1350 households in the case study area. Crop production (e.g., wheat, barley and bean) is the main livelihood activity of these households. Small scale *Eucalyptus* farming has been part of this crop dominated livelihood system, especially over the past couple of decades during which farm households have been reported to convert their crop land into *E. globulus* woodlots. On average, a household in the case study area manages 0.3 ha of *E. globulus* woodlots- established mainly on former crop lands- which is about 20% of the average total land holding of the households. The woodlots are source of cash income generated from the sale of construction wood (size ranges from 7 to 13 cm DBH) and fuel wood.

2.2. Data and collection methods

The study was based on inventory data collected in February and March 2020 from 60 sample plots of *Eucalyptus* plantation and neighboring crop land distributed across the case study area. A preliminary site visit and consultation with forestry experts in the district were first made in order to ensure that stands of different age, cycle (seedling and coppice) and productivity were included in selecting the sample plots. Regarding productivity, the case study area was divided into four strata based on the information from key informants as well as observation during reconnaissance survey. This was further considered for site classification (explained later- *Section 2.3.*). The *Eucalyptus* plots were 10m x 10m square plots, where DBH of all existing trees as well as height of five sample trees (two smallest, two largest and one median trees) were measured. In addition, labor, input, harvesting and transportation costs and values (prices) of logs and other management, geographic (slope, altitude) and land cover/use data were recorded based on observation and interview with the plot owners. For a neighboring crop plot (the nearest from the plantation plot), input and output as well as management related data was recorded from interview with the landowner. Key informant interview and rough market assessment in nearby town market were also carried out in order to supplement the inventory and economic data collected from the plots and plot owners. Besides, secondary data such as the 2020 satellite images (from USGS) and rainfall data were also acquired and used in the study.

2.3. Economic and environmental variables and their estimation

2.3.1. Wood production (Volume)

The estimation of plot level wood production over time involves a certain procedure starting from estimation of total tree height (*H*) and dominant height (*Hdom*), followed by development of Site Index (*SI*) and site classification. Accordingly, the *H* of each tree was estimated using regression equations developed from DBH, separately for each plot. The equation had the following form:

$$H = DBH\frac{1}{(a+b*DBH)} \tag{1}$$

Where, *H* is the total tree height (m), *DBH* is the diameter at breast height (cm), and *a* and *b* are coefficients to be estimated by the regression.

Using the estimated values of tree height (*H*) in Equation (1), dominant height (*Hdom*) was then calculated for each plot, by taking the average height (*H*) of the largest 100 trees per ha. Development of *Hdom* over time, and *SI* were then estimated using a guide curve method, separately for seedling and coppice plots (Pohjonen and Pukkalla, 1988). Schumar's growth function was used to develop the guide curve equation. The function is the most commonly used equation for *Eucalyptus* species in different countries, as well as in Ethiopia. The developed guide curve equation for average development of dominant height (*Hdom*) over Age (t) for seedling stands is:

$$Hdom = 45\, e^{-4.93558\frac{1}{t^{0.918533}}} \tag{2}$$

and for coppice stands

$$Hdom = 30\, e^{-3.716818\frac{1}{t^{1.332842}}} \tag{3}$$

Site index (*SI*) refers to the average *Hdom* at a defined base age, which varies depending on site and purpose of plantation. For the current study, base age of five years was taken, as it is the average rotation age used by farmers in the study area. Accordingly, the average *Hdom* at year of five was taken as *SI*. The evolution of *Hdom* over time was then estimated as a function of Site index (*SI*) and Age (t) as shown in Equation (4) for seedling and (5) for coppice stands.

$$Hdom_t = SI * e^{-4.93558(\frac{1}{t^{0.918533}} - \frac{1}{5^{0.918533}})} \quad (4)$$

$$Hdom_t = SI * e^{-3.716818(\frac{1}{t^{1.332842}} - \frac{1}{5^{1.332842}})} \quad (5)$$

Where, $Hdom_t$ is the dominant height at age *t*, and *SI* is the site index at base age of 5 years.

Looking at the value of *Hdom* of the sample plots, developed by Equations (4) and (5) , clear pattern of variation in *Hdom* was observed among the four site strata that was already classified with the help of key informants in the case study area, as explained in section 2.2 (Page 6). Therefore, the four strata were considered as site classes classified based on productivity. Then, the growth of *Hdom* in these different classes were estimated by multiplying the values with 1.2, 1, 0.8 and 0.6 for site class I, II, III and IV, respectively (Pikkarrainen, 1986; Pohjonen and Pukkalla, 1988). The result was a Site Index (*SI*) value of 16, 14, 12 and 10 for seedling, and 21, 19, 17 and 13 for coppice stands, for site class I, II, III and IV, respectively. And, these values of SI were then inserted in Equations (4) and (5).

After classifying the sites and set *SI* for each site class, the volume of wood per ha (*V*) was estimated for each site class using such variables as Number of stems per ha, density (*N*), Quadratic mean Diameter (D_g), Height of the tree with mean basal area (H_g) and Basal Area (*BA*). The values for these parameters were first determined from the inventory data, which was then used as observed values to develop a regression equation that has a form developed for the same species in Ethiopia (Pohjonen and Pukkalla, 1988). The equations for seedling stands are:

$$N_t = 14296.9074 - 204.0467\, H_{domt} \quad (6)$$

$$D_{gt} = -0.002471 + 0.231626\, H_{domt} + 10.47233\sqrt{N_t} \quad (7)$$

$$lnH_{gt} = 1.485159 + 1.553156\, lnH_{domt} - 0.372392\, lnN_t \quad (8)$$

and for coppice stands:

$$N_t = 56283.4081\, {H_{domt}}^{-0.343682} \quad (9)$$

$$D_{gt} = -5.277482 + 0.056996\, H_{domt} + 1445.67117\sqrt{N_t} \quad (10)$$

$$H_{gt} = 0.240705\, H_{domt} lnD_{gt} + 2.152579\, lnD_{gt} \qquad (11)$$

Where, t is stand age, N_t is the number of stems per hectare, H_{domt} (in meters) is the dominant height, D_g (in centimeters) is Quadratic mean Diameter, and H_{gt} (in meters) is Height of the tree with mean basal area. Basal Area at each stand age 't' (BA_t) is calculated from Quadratic mean diameter (D_{gt}) as follows:

$$BA_t = \frac{\pi {D_{gt}}^2}{4*10000} * N_t \qquad (12)$$

Once the above parameters were calculated, the volume per ha was estimated using the stand volume equation (Eq 13) developed by Pohjonen and Pukkalla (1988) for the same species in Ethiopia.

$$lnV_t = 0.0904 + 0.6778\, lnH_{gt} + 1.027\, lnBA_t \qquad (13)$$

Where, t is stand age, V_t is the volume in cubic meter per ha, H_{gt}- is the Height of the tree with mean basal area (BA_t) in meters. This volume is the total stem volume, which hence didn't include volume of leaves and branches. (The latter is needed to be included in estimating (i) revenues from the sale of leaves and branches for fuel wood, (ii) above ground carbon stock and (iii) water use per kg of biomass, discussed below in section 2.3.2., 2.3.3 and 2.3.4).

2.3.2. Net Present Value (NPV)

Cash flow of *E. globulus* woodlot and crop production alternatives was developed from the cost and selling prices obtained through interview with farmers and as well as market assessment. The main selling product from *Eucalyptus* plantation in the study area are debranched wood for construction (size ranges from 7 to 13 cm DBH) and pruned (residual) branches and leaves for fuel wood. The farmgate price and plantation activities and their respective costs are given in Table 1.

Table 1 Costs of plantation activities and price (farmgate) of the selling products

	Item	Unit	Unit Cost / price in Ethiopian Birr (ETB)
Costs	Land preparation	Per hectare	2000
	Seedling	Per plant	1
	Planting	Per hectare	4800
	Maintenance (Tending)	Per hectare	2000
	Transportation*	Per cubic meter	1412, 1624, 1906, 2118*
Revenues	Stem	Per cubic meter	8472.47
	Fuel wood (branches & leaves)	Per kilogram	5

**Transportation cost varies among sites (i.e. depending on location)*

For agricultural crop production, the three main crop types identified during the survey were considered for calculation: Wheat, Barley and Bean. For each crop type, the annual average production, labor, fertilizer and seed input per hectare of land were calculated.

The cash flow of the two land uses were then used to analyze the financial profitability. One of the most commonly used approach in analyzing and evaluating financial profitability of investments and investment alternatives is Net Present Value (NPV). Net Present Value (NPV) is simply the sum of all discounted net cash flows over an investment period. An NPV of zero implies that the investment is equally profitable over time as an investment with the reference discount rate would have been. A negative NPV implies that an alternate investment at the given discount rate would have been more profitable, and a positive one indicates a higher profitability than the reference alternative. Other things equal, of course, a large NPV is better than an NPV relatively close to zero. By using this analysis, different investment alternatives can be compared with respect to their financial profitability over a given period.

As cropland and forest systems are associated with different temporal horizons, they had to be normalized by considering a perpetual investment period. Accordingly, this research used the Land Expectation Value (LEV), to consider all revenues and costs expected from a tract of land over a perpetual temporal horizon. LEV in forestry is an estimate of the value of a tract of land for growing timber, i.e. it is the NPV of all revenues and costs associated with growing timber on the land (not just those associated with one rotation or other time period). The same also works for agriculture. For the current study, NPV and LEV were calculated as:

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{14}$$

$$LEV = NPV + \frac{NPV}{(1+r)^n - 1} \tag{15}$$

Where, LEV is Land Expectation Value, NPV- Net Present Value, r- discount rate, and n- number of periods (which is one for crop land, and the rotation age for plantation land) to be repeated in perpetuity. A discount rate of 8 %, which was the prevailing interest rate for Ethiopian state bonds at the time of this study was taken.

2.3.3. Carbon stock

The above ground carbon stock is one of the Ecosystem Service (ES) considered in the current study. It is an important ecological indicator used to evaluate the role of any vegetative ecosystem in mitigating climate change. There is no growth model available for estimating carbon stock of *E. globulus* in Ethiopia, except that of Pohjonen and Pukkalla 's (1988) model. This model expressed the change in stem, leaf and branch biomass over time as a function of DBH and height, derived from diameter distribution function, which in our case did not work well because of the limited diameter range in the collected inventory data. Therefore, above ground carbon stock in the current study was estimated from the value of stem volume estimated in Equation (13). This was simply by multiplying stem volume with an average wet wood density of *E. globulus*, 545 kg m^{-3} (Barotto et al., 2017), and then with a factor of 0.52 to obtain the dry stem biomass (Pukkala and Pohjonen, 1989). This was added to the dry biomass of branches and leaves which was considered as 10 percent of stem biomass (Pukkala and Pohjonen, 1989). Finally, the total biomass was converted into carbon stock by multiplying the value with a factor of 0.58.

2.3.4. Water use

As already explained earlier (Section 1.1), the overuse of water is one of the most commonly reported argument against *Eucalyptus* tree planting. Therefore, the overall use of water to produce biomass was the other ES considered in the current study. This was estimated by multiplying the annual standing biomass with the average water use (obtained from literature) of the tree and agricultural crop species considered in the study (Table 2). For *E. globulus*, the biomass of the stem as well as of branches and leaves, estimated as explained in section 2.3.3, were considered. For crops, the average annual grain and residual biomass production obtained through interview and during the inventory (explained in section 2.3.2) were considered.

Table 2 Water use or consumption of water per unit of biomass produced

Tree / crop species	Water use (liter per Kg)	Reference
E. globulus	785	Alemneh *et al.* (2019)
Wheat	830	FAO
Barley	750	>> >>
Bean	714	>> >>

2.3.5. Crop production

As explained earlier the average annual crop production per hectare of each of the three crop types were used in estimating LEV and water use from crop land use alternative. For this, three different crop production scenarios were used. The first was just based on the average production from the past production year, i.e. 2018/19 - 2019/20. It was found during data collection that the production in this year was one of the lowest production levels recorded over the past decades, which was because of the late onset of rain and even high amount of rain during and after crop maturity. Therefore, considering this production as a low production scenario, a second and third production scenarios- production in 'moderately normal' and 'normal' conditions- were set based on the information from key informants (Table 3).

Table 3 Crop production scenarios

Crop type	Site class	Production (kg per ha)		
		Low	Moderately Normal	Normal times
Wheat	I	1900	2700	3600
	II	1200	2400	3200
	III	900	1950	2600
	IV	500	1425	1900
Barley	I	1200	1725	2300
	II	850	1575	2100
	III	650	1425	1900
	IV	350	900	1200
Bean	I	650	750	1000
	II	450	637.5	850
	III	400	487.5	650
	IV	250	300	400

2.4. Land units (stands) and aggregations

As already explained earlier, the 3104 ha case study area was found to comprise such land use classes as Crop, *Eucalyptus* plantation, grazing, bush, natural forest, bare and others (e.g. road, settlements) (Figure 2). This was examined by processing and analyzing Sentinel Satellite image of the study area using Maximum Livelihood Classification method in ArcGIS 10.3.1 soft. The classified raster image was extracted for the case study area, and it was found that crop land covers 1327 ha and *Eucalyptus* covers 660 ha. Further processing and analysis were therefore targeted for the 1987 ha of land (i.e. only crop and *Eucalyptus*).

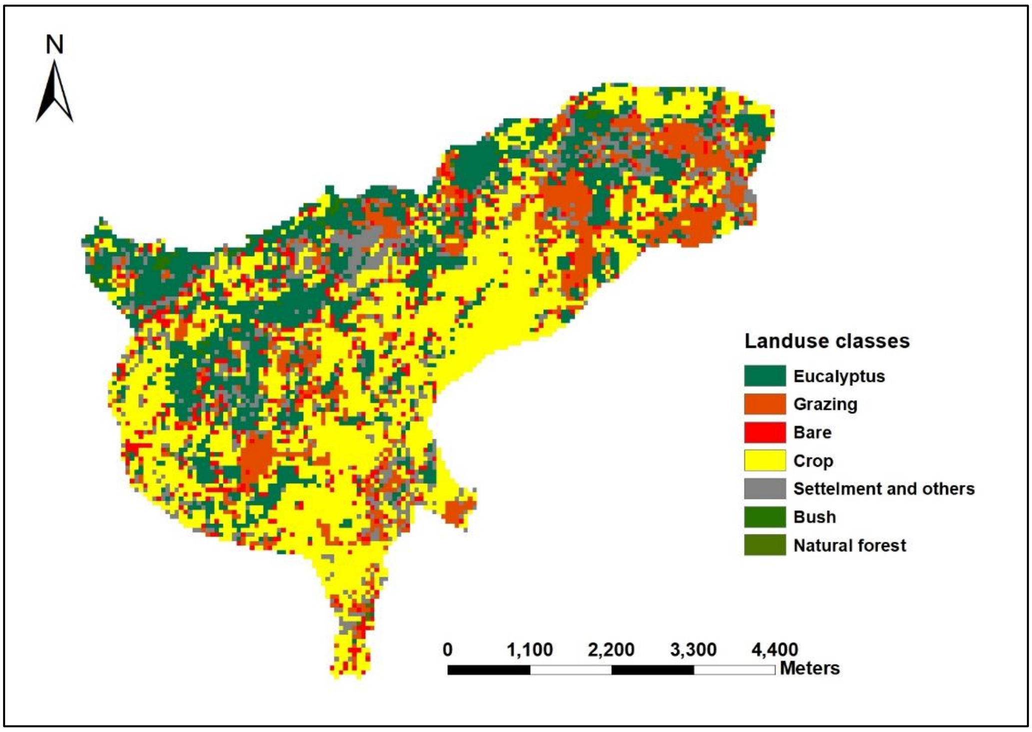


Figure 2 Raster image showing the land use / land cover classes of the case study area

Accordingly, the classified raster image was first converted into polygon map, containing 292 *Eucalyptus* and 276 Crop land polygons. Next step was then to classify or divide the *Eucalyptus* polygons into stands of same age, cutting cycle (rotation) and site class, and the crop polygons into plots of same crop type (wheat, barley or bean) and site class. Accordingly, based mainly on the information from inventory plots and additional field ground truth points, accompanied with the visual observation of composite and google earth images, the *Eucalyptus* land were further divided into a total of 454 stands (Figure 3). The age and area distribution of the stands are shown in Figure 4.

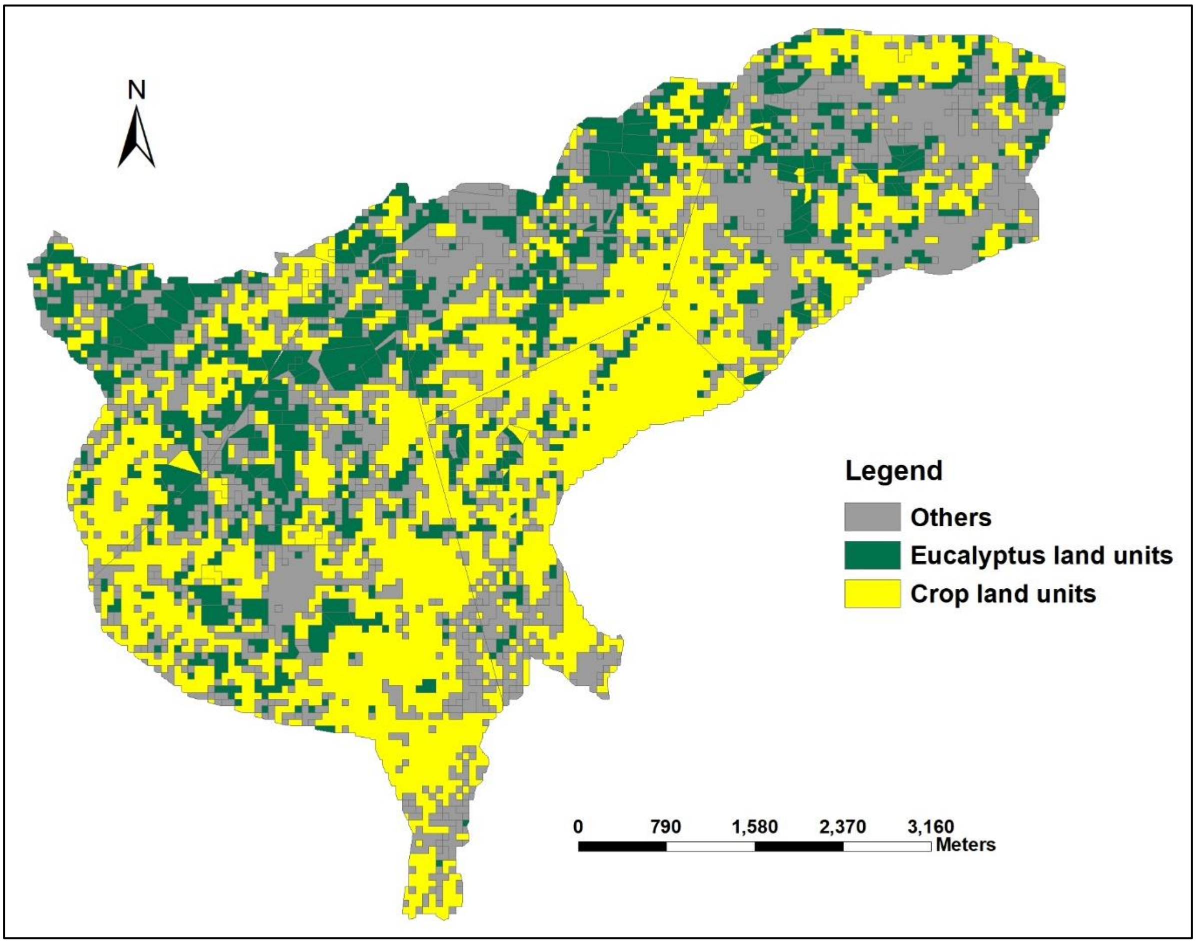


Figure 3 *Eucalyptus* and Crop land units prepared for analysis

For crop land polygons, it was challenging to identify the crop types for all polygons from the satellite and google earth images. So, the type of crop (wheat, barley or bean) was first assigned to those polygons whose location was mapped based on the inventory and ground truth points, and the area covered by each crop type was calculated by summing the area of polygons with similar crop type. Then, the total land identified as crop land, i.e. 1327 ha, was divided proportionally to wheat (849), barley (305) and bean (173) crop lands (the proportionality was also considering the four site classes).

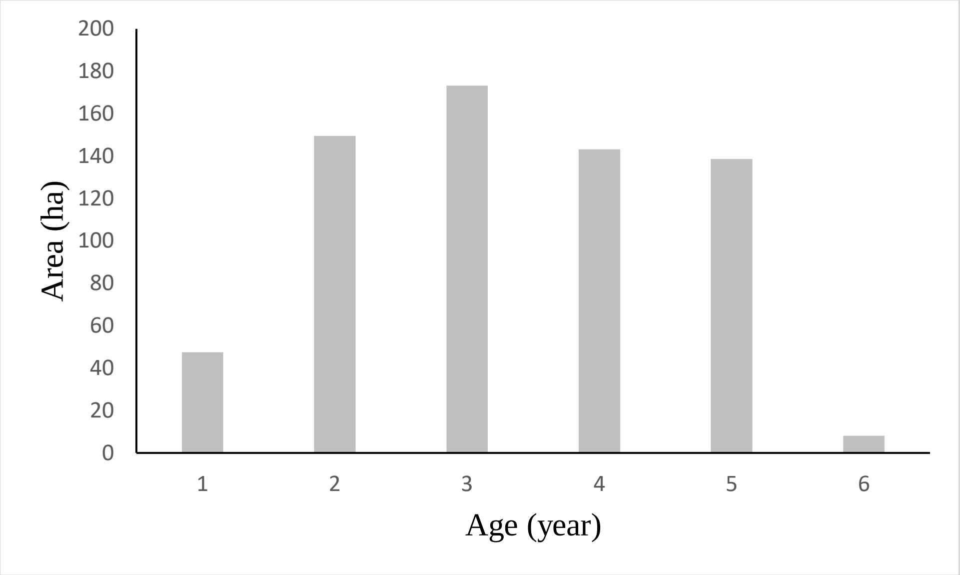


Figure 4 Area (in ha) by age of Eucalypts land units (stands)

A total of 772 land units (454 *Eucalyptus* and 318 Crop land units) were then made ready for analysis (Figure 3). However, for computational reasons and in order to simplify the management problem, the land units in non-contiguous areas of analysis were aggregated into a reduced number according to:

- Four Site class: Site class I, II, III, IV
- Four Land types: *Eucalyptus*, Wheat, Barley and Bean Crop
- Six Stand Ages: 1, 2, 3, 4, 5 and 6 years
- Four Stand type: Seedling, Coppice I, Coppice II and Coppice II

The aggregation process resulted a total of 81 land units, 69 *Eucalyptus* and 12 Crop land units.

2.5. Optimization method

2.5.1 The problem and prescriptions

The main aim to be addressed is to examine plausible land conversion and harvesting strategies that maximize economic gains while looking at the impact on carbon stock and water use in the case study area. Accordingly, a planning horizon extending over 9 years was set, and a set of land management and/or harvesting prescriptions were designed. For already existing *Eucalyptus* land units, the prescriptions were to harvest them at age four, five or six. For crop land units, to keep them as crop land or to convert them at the beginning of the planning horizon into *Eucalyptus* and harvest at four, five or six years. Therefore, the problem consisted of four prescriptions: (i) harvesting at age four, (ii) at age five and (iii) age six, and (iii) keeping the land under crop production. The first three are for all land units, while the last prescription is only for crop land units.

2.5.2. The optimization models

A Linear Programming (LP) Model was used to solve the problem explained above. A total of 237 decision variables- a combination of 81 land units and four prescriptions- were included in the LP model described as follows:

$$\sum_{j=1}^{Mi} X_{ij} = a_i,\ i = 1,.\ .\ .,N \tag{16}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{Mi} w_{ijt} X_{ij} = W_t,\ t = 1,\ldots.,T \tag{17}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{Mi} carbon_{ijt} X_{ij} = CARB_t,\ t = 1,\ldots.,T \tag{18}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{Mi} water_{ijt} X_{ij} = WATER_t,\ t = 1,\ldots.,T \tag{19}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{Mi} crop_{ijt} X_{ij} = CROPPROD_t,\ t = 1,\ldots.,T \tag{20}$$

$$LEV = \sum_{i=1}^{N} \sum_{j=1}^{Mi} lev_{ij} X_{ij} \tag{21}$$

$$TOTWOOD = \sum_{t=1}^{T} W_t \tag{22}$$

$$VolEI = \sum_{i=1}^{N} \sum_{j=1}^{Mi} vei_{ij} X_{ij} \tag{23}$$

$$CARBAver = \sum_{t=1}^{T} CARB_t / T \tag{24}$$

$$WUTOT = \sum_{t=1}^{T} WATER_t \tag{25}$$

$$WUAnnual = \sum_{t=1}^{T} WATER_t / T \tag{26}$$

$$CROPTOT = \sum_{t=1}^{T} CROPPROD_t \tag{27}$$

$$CROPAnnual = \sum_{t=1}^{T} CROPPROD_t / T \tag{28}$$

$$X_{ij} \geq 0, \forall_{ij} \tag{29}$$

Where

N = 81, the total number of land units.
M_i = the number of prescriptions for land unit *i*.
T = 9 the number of planning years.
Xij = number of hectares of land unit *i* assigned to prescription *j*.

a_i = total area of the land unit *i*.
w_{ijt} = wood harvested in period t that results from assigning prescription *j* to land unit *i*.
$carbon_{ijt}$ = yearly carbon stock at the end of period t that results from assigning prescription *j* to land unit *i*.
$water_{ijt}$ = total annual water use in period t that results from assigning prescription *j* to land unit *i*.
$crop_{ijt}$ = annual crop production in period t that results from assigning prescription *j* to land unit *i*.
lev_{ij} = land expectation value associated with prescription *j* in land unit *i*.
vei_{ij} = Volume of the inventory at the end of the planning horizon associated with prescription *j* in land unit *i*.

Equation 16 states that the sum of areas in a land unit assigned to each prescription must be equal to the corresponding land unit area a_i, which also indicates that the whole area from each land unit must be entirely assigned to at least one prescription. Equations 17-20 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 21–28 define, respectively, the case study area land expectation value, the total wood harvested, the standing volume 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 29) state the non-negativity constraints.

The equations (Eq 16 -29) were then used to formulate 12 LP models (Table 4). The first (MOD 1) and fourth models (MOD 4) have an objective function of maximizing LEV and VolEI, respectively, with no constraint (except the area constraint, Eq 16). The second model (MOD 2) has an objective function of maximizing LEV but constrained with a certain land area to be kept for crop production so as to meet annual crop grain needs of the households in the case study area (Eq 30).

$$CROPPROD_t \geq MinCropProd * HH, \forall_t \qquad (30)$$

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 (Worku et al., 2017), and *HH* is the total number of households in the case study area.

A third model (MOD 3) again with LEV maximization but constrained by an annual water use level (Table 4). As already explained earlier, the overuse of water is one of the most commonly reported argument against *Eucalyptus* tree planting. Hence, in MOD 3, it was attempted to set a maximum water use level, equivalent to the case study area's annual rainfall amount, which is supposed to balance the water lost or utilized by the plant for biomass production (Eq 31).

Table 4 Summary of Linear Programming (LP) models formulated in the current study

Crop production scenarios*	Models	Objective function	Constraint	Equations
Low	MOD 1	MAX LEV	NA	Eq (16) - (29)
	MOD 2	>>	Minimum annual grain food consumption needs	Eq (16) - (30)
	MOD 3	>>	Maximum annual water use	Eq (16) - (29), (31)
	MOD 4	MAX VEI	NA	Eq (16) - (29)
Moderately Normal	MOD 5	MAX LEV	NA	Eq (16) - (29)
	MOD 6	>>	Minimum annual grain food consumption needs	Eq (16) - (30)
	MOD 7	>>	Maximum annual water use	Eq (16) - (29), (31)
	MOD 8	MAX VEI	NA	Eq (16) - (29)
Normal	MOD 9	MAX LEV	NA	Eq (16) - (29)
	MOD 10	>>	Minimum annual grain food consumption needs	Eq (16) - (30)
	MOD 11	>>	Maximum annual water use	Eq (16) - (29), (31)
	MOD 12	MAX VEI	NA	Eq (16) - (29)

**Production scenarios / Table 3).*

The approach obviously has drawbacks; not all of the rain fall in the area would remain there (the area where *Eucalyptus* is planted), rather, a certain amount would go off through evaporation and runoff. In addition, it doesn't consider the influence of silvicultural managements on water use. But, it would still be able to show the impact.

$$WATER_t \leq RF * A, \forall_t \qquad (31)$$

Where, $WATER_t$ is the total water used for biomass production in each period t, *RF* is the average annual rainfall amount in cubic meter per hectare (a 30 year average value of 1100 mm per square meter per year or 11000 cubic meter per hectare per year), and *A* is the total land area of the case study, which is 1987.31 hectare.

These four LP models, MOD 1 to 4, considered the average annual crop production based on the ‘Low’ crop production scenario, explained earlier in section 2.3.5 (Table 3). In order to consider the two other production scenarios (Table 3), eight additional LP models were developed: four models MOD 5 to 8 that considered the ‘Moderately Normal’ scenario, and another four models MOD 9 to 12 that considered ‘Normal’ crop production scenario (Table 4).

2.5.3. Tradeoff analysis

The analysis proceeded from a single objective optimization (in section 2.5.2) to multiple criteria analysis where it was possible to examine the interrelationship between two or more competing objectives. From single objective function of maximizing LEV to the analysis of six criteria (e.g., maximize LEV, average annual carbon stock, volume of ending inventory and crop production, and minimize total water use). The analysis was done based on the Pareto Frontier approach. For the current study, the Pareto Frontier based analysis was done using the FGoal Version 4.2 tool, which reads mathematical models developed in compatible file formats (e.g. LP format) and generates the feasible set in the criteria space for the management problem using the Estimation Refinement Method (See Borges et al., 2014 for detailed mathematical description of the Pareto Frontier approach and its application in forest management). Accordingly, the LP file developed for MOD 3, a model constrained by annual water use, was imported to the FGoal tool where six criteria corresponding to the six objectives (LEV, Carbon, VEI, Crop production and Water use) were set. The tool produces Pareto frontier graphs, displayed as decision maps, which can be bi-dimensional (for two criteria) or three, four, up to six dimensional maps. These graphical maps show the degree to which manipulating one criterion needs accepting sacrifices in the achievements of other/s, which is the trade-offs among objectives (Garcia et al., 2015).

2.6. Summary of Software used in the study

The entire data organization and analysis process in the current study were accomplished by using four main software: ArcGIS, MS Excel 365, WordPad, CPLEX and FGoal Ver 4.2. ArcGIS 10.3.1 was used to create land units (polygons) and associate attribute values for each polygon. MS Excel was used to analyze the tree inventory and production (input -output) data and produce coefficient values for the target ES (LEV, wood, Carbon, water, crop production and VEI). Excel was also used to write all equations (using CONCAT function) which was then exported to a WordPad where the LP models were written and saved as .lp file. CPLEX software was then used to solve the optimization problems (i.e. LP models) and export results as a solution file. Finally, FGoal Ver. 4.2. was used to analyze tradeoffs among objectives.

3. RESULTS AND DISCUSSION

3.1. Single Objective Optimization

The 12 LP solutions provide interesting information (Table 5). The highest *LEV* and harvested wood, 8.46 X 10^9 ETB and 8.3 X 10^5 m^3, respectively, were found by the unconstrained LEV maximization models MOD 1, 5 and 9. But with null crop production - as the models allocated the whole crop land for *Eucalyptus* plantation - and high amount of average annual water use, 3.76 X 10^7 m^3, the second highest next to the unconstrained *VolEI* maximization models MOD 4, 8 and 12. The result implies that as long as the objective is to maximize the economic gains from land resource, Eucalyptus plantation is the best and feasible land use as compared to the crop production alternative, and thus, it favors a complete conversion of the available crop land into Eucalyptus woodlot. Given that crops (wheat, barley and bean) are the main source of the people's staple food in the case study area, complete conversion of crop land will have a substantial impact on the availability of food in the case study area. In the highlands of Ethiopia, Alemneh et al. (2019) reported that the conversion of crop land into Eucalyptus has led to a loss of 4.5x10^7 kg of wheat production or 3.1x10^7 kg of barley production annually, which translates to the grain needs of 70,000 to 100,000 households. So, this clearly shows that decisions regarding eucalyptus expansion must consider its impact on food security.

The inclusion of crop production constraint in models MOD 2, 6 and 10 reduced the values of both *LEV* and volume of wood harvested as compared to the unconstrained LEV maximization models, the reduction being higher in MOD 2 (0.91 X 10^9 ETB of LEV and 0.82 X 10^5 m^3 of wood) and lower in MOD 10 (0.40 X 10^9 ETB of LEV and 0.42 X 10^5 m^3 of wood) (Table 5). The lower reduction of LEV and wood in MOD 10 implies that with a normal crop production scenario, a relatively small area of crop land is enough to meet the minimum crop production constraint, and hence more land is 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.

Looking at the model's solution on crop land conversion, out of the total 1327.19 ha of crop land, up to 1112.28, 1157.05 and 1199.59 ha, in MOD 2, 6 and 10, respectively, can be converted into Eucalyptus land use (Table 6) so that the economic gain maximization from wood production and the minimum food consumption requirement of households of the case study area could be achieved. With this land allocation, it could also be possible to store 1.5 to 1.57 X 10^7 kg yr^{-1} of carbon in the above ground biomass (Table 5), which is equivalent to 5.5 to 5.76 X 10^5 t yr^{-1} of CO_2. This implies that if the crop land conversion into Eucalyptus is regulated by landscape level ecologic-economic the potential of the Eucalyptus-agriculture mosaic landscape to simultaneously address economic, food security, and climate change mitigation can be achieved.

Table 5 Optimal values of the LP models

LP Models	LEV (10^9 ETB)	TOTWOOD (10^5 m^3)	CARBAver (10^7 Kg)	VolEI (10^4 m^3)	WUTOT (10^8 m^3)	WUAnnual (10^7 m^3)	CROPTOT (10^6 Kg)	CROPAnnual (10^6 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

Furthermore, the 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 better than the normal scenario could help to attain the food security target in a small area of land so that more land can be allocated for Eucalyptus, leading to a higher economic gain as well as contribution for carbon sequestration. Pressing concern with the land allocation in these models is, however, the average annual water use amount of 3.41, 3.43 and 3.6 X 10^7 m^3 in MOD 2, 6 and 10, respectively, which was actually lower than the amount in the unconstrained models but much higher than the case study area's total annual water available from rainfall, 2.18 X 10^7 m^3.

Table 6 Optimal land allocation by each LP model

Model	Total land allocated (in ha)	
	Plantation	Crop
MOD 1	1987.31	0
MOD 2	1772.4	214.91
MOD 3	921.12	1066.19
MOD 4	1987.31	0
MOD 5	1987.31	0
MOD 6	1816.77	170.14
MOD 7	870.61	1116.7
MOD 8	1987.31	0
MOD 9	1987.31	0
MOD 10	1859.71	127.6
MOD 11	857.28	1130.03
MOD 12	1987.31	0

***NOTE**: before optimization 660.12 and 1327.19 ha were allocated to eucalypt plantations and to crop production, respectively*

Models MOD 3, 7 and 11 address the water use concerns by constraining the LEV maximization objective by a maximum annual water use, a level equivalent to the annual rainfall of the study area. The models- as expected- resulted a significant decrease in LEV and volume of harvested wood, ranging from 47.7 to 50.6 % depending on the model, as compared to the amount in the unconstrained LEV maximization models MOD 1, 5 and 9 (Table 5). These models on the other hand had the highest amount of crop production. Given wheat was considered to consume more water per kg of biomass than Eucalyptus (Table 2) on the one hand, and wheat occupies two thirds of the crop land in the case study area on the other hand, an increase in total wood production and decrease in crop production could be expected from these constrained models. The opposite was found however, and this can be because of the higher biomass production per ha of Eucalyptus as compared to wheat as well as the other two crops (barley and bean), which means higher total water use. So, assigning a unit of land for

Eucalyptus (wood production) would increase the total water use much higher than assigning same unit of land for crop production. 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 6). Furthermore, the result also shows that 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 of the three models). This reflects that the reduction in LEV because of low wood production could as maximum as possible be compensated by allocating more land for the crop type that gives the highest production per ha (Table 3) and LEV (which is wheat) while still keeping the maximum water use limit.

There was a variation in model solutions among the water use constrained models MOD 3, 7 and 11, indicating the effect of crop production scenarios (Table 5). For instance, the highest wood volume amount was found in the 'Low' crop production scenario model MOD 3 ($4.34 X 10^9 m^3$), while the least was in the 'Normal' production scenario model MOD 11 ($4.1 X 10^9 m^3$). The reverse was found when the models are compared in terms of LEV and total crop production; the highest being in MOD 11 ($4.46 X 10^9$ ETB and $26.2 X 10^6$ kg) and the lowest in MOD 3 ($4.36 X 10^9$ ETB and $10.35 X 10^6$ kg). When we see the models solution for land conversion / allocation (Table 6), the amount of crop land to be converted into Eucalyptus was relatively higher in MOD 3 (261 ha) than in MOD 7 (210.49 ha) and MOD 11 (197.16 ha). According to the model result, it is only this amount of crop land- out of the total 1327.19 ha- that can be converted into Eucalyptus so that the water use cannot exceed the amount available from rainfall. These models not only limit the annual water use, but also sustain a less fluctuating supply of wood and carbon stock than the other models (Fig 6, 7 and 8).

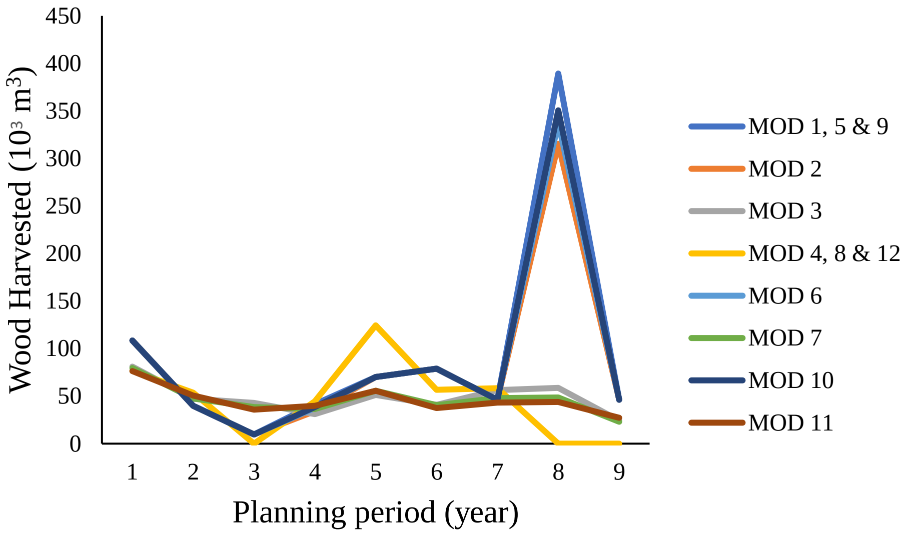


Figure 5 Evolution of annual harvested wood by model

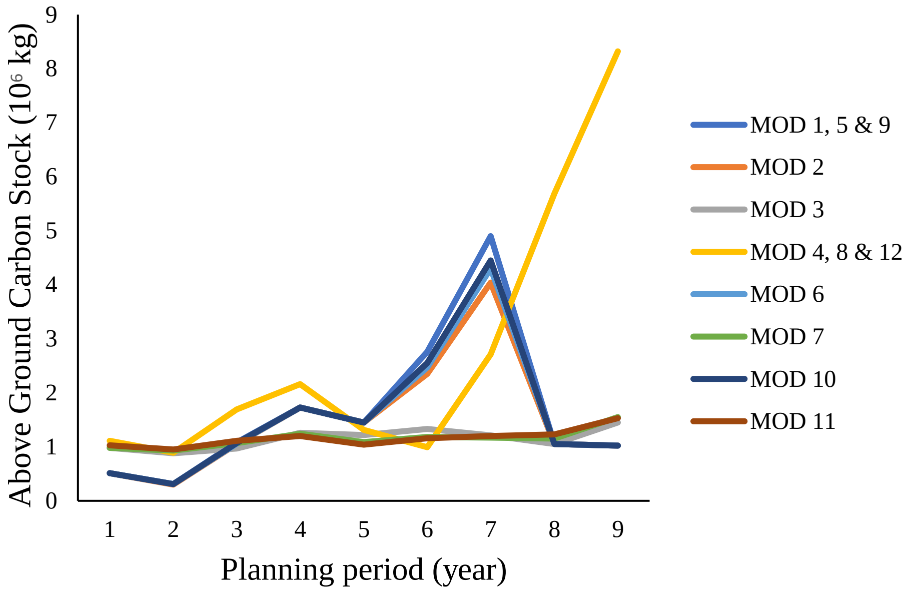


Figure 6 Evolution of yearly above ground carbon stock by model

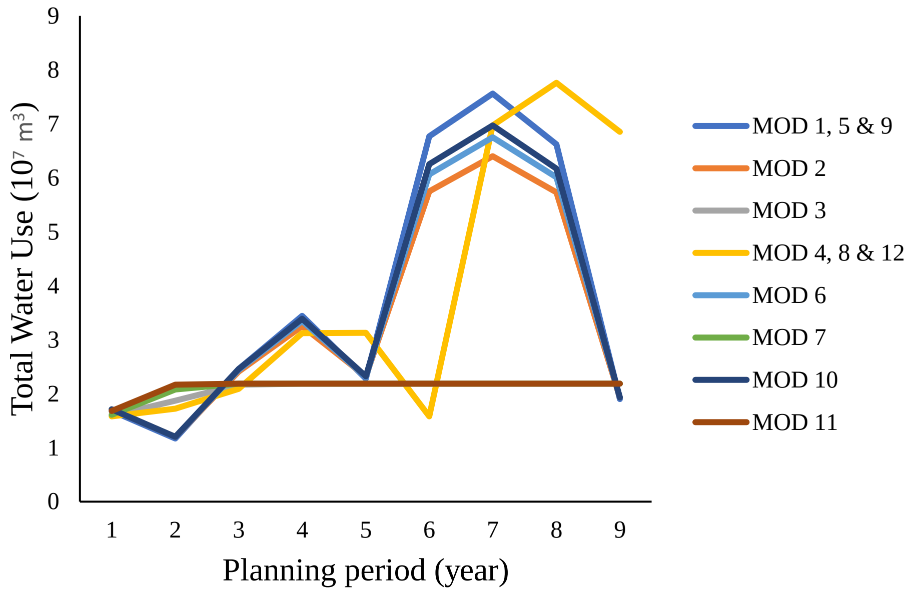


Figure 7 Evolution of annual water use by model

The reduction in land allocated for Eucalyptus and volume of harvested wood with increasing crop production, i.e. from ‘Low’ crop production scenario MOD 3 to ‘Moderate’ MOD 7 and to ‘Normal’ scenario model MOD 11, could again be related to the magnitude of contributions from the crop land uses for the objective function, i.e. LEV maximization, while keeping the maximum water use limit. As this contribution may increase with crop production, allocation of a unit of land for crop land use in the case of ‘Normal’ crop production scenario (MOD 11) could contribute more for the objective function, LEV maximization, than that of ‘Moderately Normal’ (MOD 7) and ‘Low (MOD 3) production scenarios. The result is then higher land allocation for crop land uses by MOD 11, hence, higher total crop production and total water use (but not beyond the limit), and lower volume of wood harvested as compared to MOD 3 and 7.

With lower land allocation for Eucalyptus by water use constrained models as compared to unconstrained models, a reduction in volume of ending inventory could be expected. The result, however is the opposite, where the volume of inventory at the end of the planning horizon was found to increase by 42, 50 and 52 % in models MOD 3, 11 and 7, respectively, as compared to the value in the unconstrained LEV maximization models (6.19 X 10^4 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 age 4, 5 and 6 years) of the model’s solution (Fig 8). The result shows that shorter harvesting age (four years) was found to be the optimal prescriptions in the unconstrained LEV maximization models MOD 1, 5 and 9 and models constrained by crop production MOD 2, 6 and 10, with all the converted crop land were assigned to be managed under a four year rotation age. This means the additional biomass that could potentially be resulted from letting the plantation grow for one or two years more is not much enough to increase the discounted net revenue. Important point to be noted here is that the selling product considered in the study is construction pole, not timber, so the result could be different if other wood products that needed to be larger in size are considered.

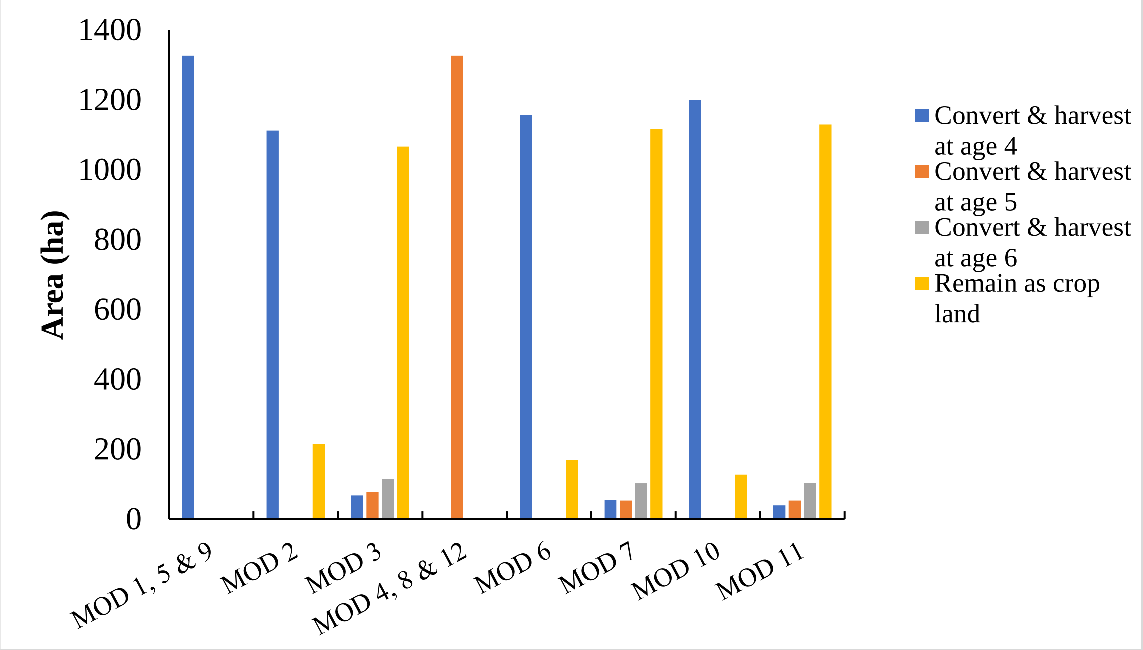


Figure 8 Optimal land size allocated for crop land units under the four prescriptions in each LP model

When the objective was to maximize the standing volume at the end of planning horizon in MOD 4, 8 and 12, the crop land units were assigned to be managed under a five-year rotation age (Fig 8). This actually be related to the age at the end of the planning horizon and the respective standing volume- which increases with age: so, a land managed with a five year rotation age would be harvested once in the planning horizon and its age at the end of the planning horizon would be three and one years older than if it was managed with four and six years rotation age, respectively. With this optimal solution, the models had not only the highest volume of ending inventory (50.62 X 10^4 m^3) but also highest above ground carbon stock (2.76 X 10^7 kg). Expectedly, these models had the least volume of harvested wood (4.14 X 10^5 m^3). The volume of harvested wood in these models is half the volume in the unconstrained LEV maximization models, however, the LEV is only 0.71 less than the LEV in the latter models. This finding is expected, because LEV considers future net revenues of Eucalyptus woodlots, which means the value of the standing volume is included in the estimation though not harvested within the planning horizon. Hence, if it was the standard NPV, which depends only on the amount of wood harvested within the period, the models will be of the least among all.

Constraining the LEV maximization objective by annual water use in MOD 3, 7 and 11, more tendency towards a longer harvesting age was observed, which is in contrast with the solution in the other models (Fig 8). The result shows that 43.8, 48.8 and 52.7 % of the total crop land to be converted into Eucalyptus were assigned to be managed with six years rotation age in MOD 3, 7 and 11, respectively. The remaining land was allocated for four- and five-years rotation age, 20 - 26 % for the former and 26 - 30 % for the latter. For the same reason as explained above for the ending inventory maximization models, the higher land allocation for longer harvesting age resulted a higher volume of ending inventory in the water use constrained LEV maximization models MOD 3, 7 and 11 as compared to the unconstrained (MOD 1, 5 and 9) and crop production constrained models (MOD 2, 6 and 10) where more land was allocated for shorter harvesting age (Fig 8). Similarly, the sharp difference in the volume of ending inventory among the water use constrained models was also resulted from the different land allocation for the harvesting prescriptions.

Another important finding in the current study is that related to the models' optimal solution for different site (productivity) classes, among which a variation was found only in the solutions from the water use constrained LEV maximization models MOD 3, 7 and 11. In all of these three models, it was from the lower productivity class- site class IV- that larger area of crop land was allocated for (to be converted into) Eucalyptus (47.2, 37.4 and 37.7 % of the total 275 ha in MOD 3, 7 and 11, respectively), whereas, the entire crop land from site class II was assigned to be remained as crop land in all models (Table 7). Regarding the optimal prescriptions, all or larger area of land was assigned for the six-year rotation age in site class IV, five-year rotation age in site class III and four-year rotation age in site class I.

Table 7 Optimal land allocation (ha) for different site classes, result of water use constrained LEV maximization models

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. ** The entire crop land is assigned to be remained as crop land.*

3.2. Tradeoff Among Multiple Objectives

Unlike the single criterion optimization models with only one objective, i.e. maximize LEV (or Volume of Ending Inventory, VolEI), the tradeoff analysis here considered multiple objectives, maximization of *LEV*, Volume of wood harvested, Volume of Ending Inventory, Above ground carbon stock and total crop production, and minimization of total water use in the planning horizon. A LP file similar with the one developed for MOD 3, a model constrained by annual water use, was used to study the tradeoff using FGoal tool where six criteria corresponding to the six objectives were set.

The FGoal analysis output provided the minimum and maximum values for each objective. Accordingly, a minimum and maximum values of 3.35 X 10^9 and 4.36 X 10^9 ETB, respectively, was found for LEV. Whereas, the values for total wood harvested in the planning horizon ranged from 3.55 X 10^5 to 4.82 X 10^5 m^3, and for volume of ending inventory it was from 0.13 X 10^5 to 1.37 X 10^5 m^3. For average above ground carbon stock, the minimum value was 1.03 X 10^7 kg, while the maximum was 1.65 X 10^7 kg. Regarding water use, it was found that a minimum of 1.5 X 10^8 m^3 of water would be used in the planning horizon, which is 1.6 X 10^8

m^3 of water per year (whereas, the maximum value is the value equal to the maximum water use constraint, set in the model, i.e. 1.9 X 10^8 m^3 of total water use in the planning horizon or 2.1 X 10^8 m^3 per year). For the remaining criteria, i.e. crop production, the amount of total crop production in the planning horizon ranged from 9.02 X 10^6 to 11.92 X 10^6 kg, which is equivalent to a yearly production of 1 X 10^6 to 1.32 X 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 X 10^6 kg per year).

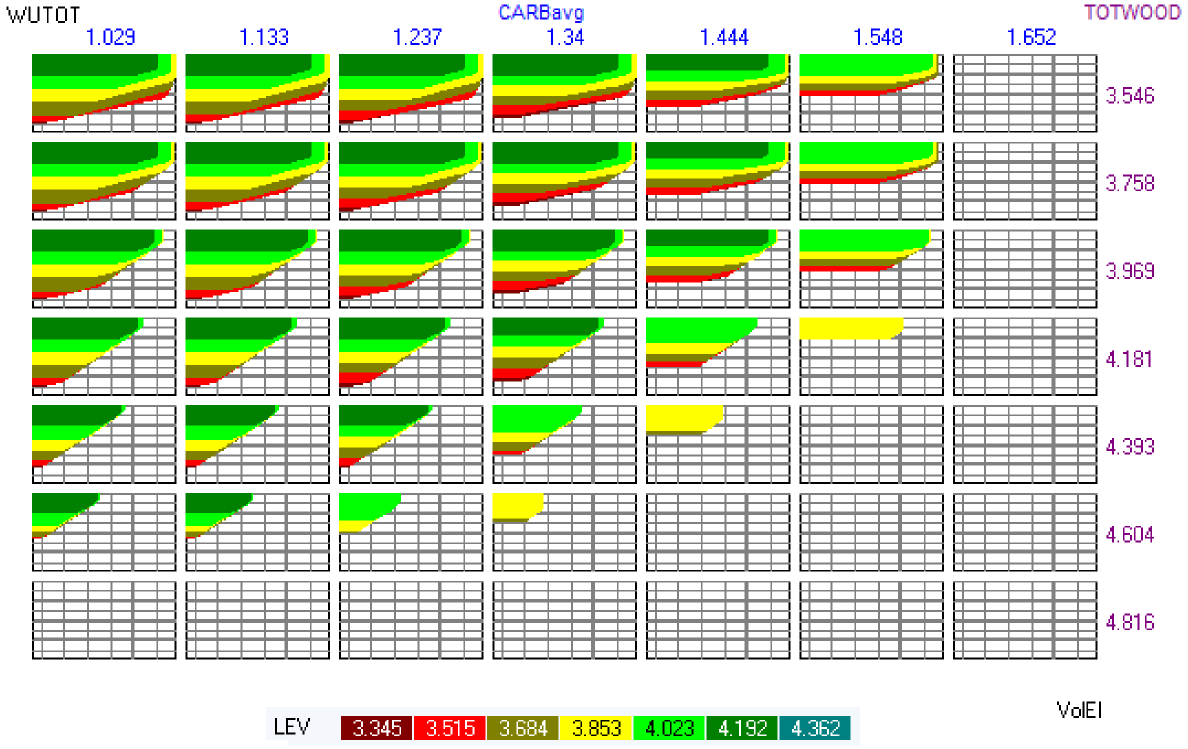


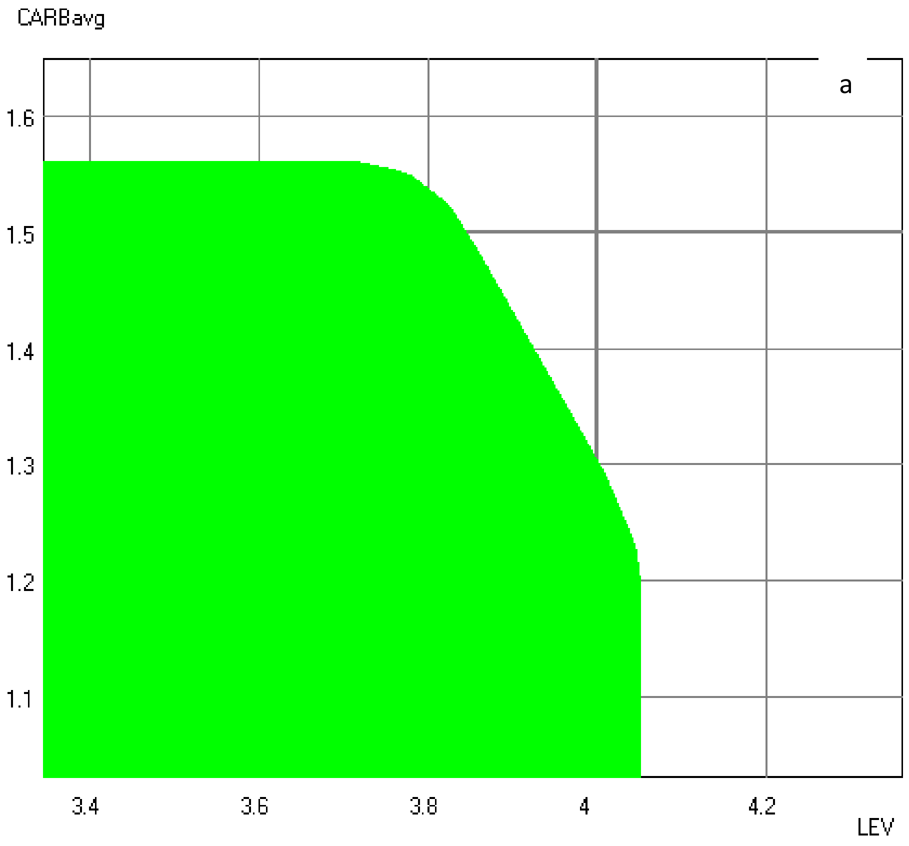
Figure 9 Five dimensional decision map showing the tradeoff between total water (WUTOT, 10^8 m^3), above ground carbon stock (CARBavg, 10^7 kg), total harvested wood (TOTWOOD, 10^5 m^3) and Volume of ending inventory (VolEI, 10^5 m^3) and Land Expectation Value (LEV, 10^9 ETB)

By keeping the value of the crop production criteria at this minimum value, a five-dimensional decision map depicting tradeoff among the other five criteria was produced (Fig 9). The overall information from the map is that maximizing carbon stock and/or VolEI would come at the cost of reduced harvested wood volume or LEV and increased total water use. But, a more significant tradeoff between any of these two criteria was observed at larger values; and for some criteria, the tradeoff is also influenced by another criteria. The finding showed that the amount of carbon stock can be increased from the minimum value of 1.03 X 10^7 kg up to a maximum of 1.34 X 10^7 kg, while keeping the increase in harvested wood volume from its minimum value of 3.55 X 10^5 m^3 up to a maximum value of 4.60 X 10^5 m^3 (Fig 9). However, in order to increase the maximum value of carbon stock from 1.34 X 10^7 to 1.44 X 10^7 kg, the maximum harvested wood volume should be decreased from 4.60 X 10^5 to 4.39 X 10^5 m^3. For further increase in the maximum value of carbon stock up to 1.55 X 10^7 kg, there should be an equivalent reduction of the maximum harvested wood volume from 4.39 X 10^5 to 4.18 X 10^5 m^3. In other word, the maximum carbon stock would be decreased from 1.55 X 10^7 to 1.34 X 10^7 kg if it is needed to increase the maximum harvested wood volume from 4.18 to 4.60 X 10^5 m^3 (Fig 9)

The result also showed that increasing the maximum harvested wood volume with or without impacting the values of carbon stock could to led to a reduction in VolEI, especially for wood values greater than 3.97 X 10^5 m^3. For instance, at a maximum harvested wood volume of 3.97 X 10^5 m^3, there would be a maximum VolEI value equal to 1.16 X 10^5 m^3; whereas, when the wood volume grows to a maximum of 4.18 and 4.60 X 10^5 m^3, the maximum VolEI would be 0.96 X 10^5 and 0.54 X 10^5 m^3, respectively (Fig 9).

As expected, the change in the maximum values of one or combination of these criteria were found to impact the water use criteria, which is needed to be as minimum as possible (as the objective was to minimize water use). At the minimum values of carbon- 1.03 X 10^7 kg, wood- 3.55 X 10^5 m^3, and VolEI- 0.13 X 10^5 m^3, the minimum water use was 1.5 X 10^8 m^3 (Fig 9). When the carbon stock value grows to a maximum value of 1.34 X 10^7 kg, while keeping the harvested wood volume at 3.55 X 10^5 m^3, the minimum water use value would be 1.59 X 10^8 m^3; whereas, at a maximum carbon stock value of 1.55 X 10^7 kg, again with the same level of harvested wood, the water use would be at least 1.70 X 10^8 m^3. This minimum water use is actually corresponding to the minimum LEV value- that can be attained in each carbon stock level (as shown in the colored slices of the five-dimensional map, Fig 9)- and hence, increases with increasing LEV. For instance, in the case of the former carbon stock value, the minimum water use value ranges from 1.59 X 10^8 m^3 at a LEV value of 3.45 X 10^9 ETB, and 1.65 X 10^8 m^3 at 3.68 X 10^9 ETB up to 1.81 X 10^8 m^3 at 4.19 X 10^9 ETB. In the latter case, it ranges from 1.70 X 10^8 m^3 through 1.73 X 10^8 m^3 up to 1.81 at a LEV value of 3.51 X 10^9 ETB, 3.68 X 10^9 ETB and at 4.02 X 10^9 ETB, respectively.

The tradeoff could better be understood if we look at a bi-dimensional map, showing tradeoff between two criteria, while fixing the values of the other criteria. For illustration, some bidimensional maps were produced to depict tradeoff between Carbon and LEV, Carbon and harvested wood, and between water use and LEV, wood, carbon (Fig 10 and 11). Accordingly, the map for LEV and Carbon stock (Fig 10a) shows that the maximum above ground carbon stock that can be stored per year is almost 1.56 X 10^7 kg, corresponding to a value of 3.34 X 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 X 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 X 10^9 to 3.778 X 10^9 ETB (1.65%) resulted a corresponding decrease in carbon stock from 1.562 X 10^7 to 1.552 X 10^7 kg (0.60%). Further, a change of LEV from 3.999 X 10^9 to 4.040 X 10^9 ETB (1.002%) is reflected in a decrease in carbon stock from 1.3 X 10^7 to 1.235 X 10^7 kg (5.28%). Such tradeoff between economic return from wood and carbon stock is also reported in another optimization studies (e.g. Keleş and Başkent, 2005; Raymer et al., 2006). However, important to note that different finding could be 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.



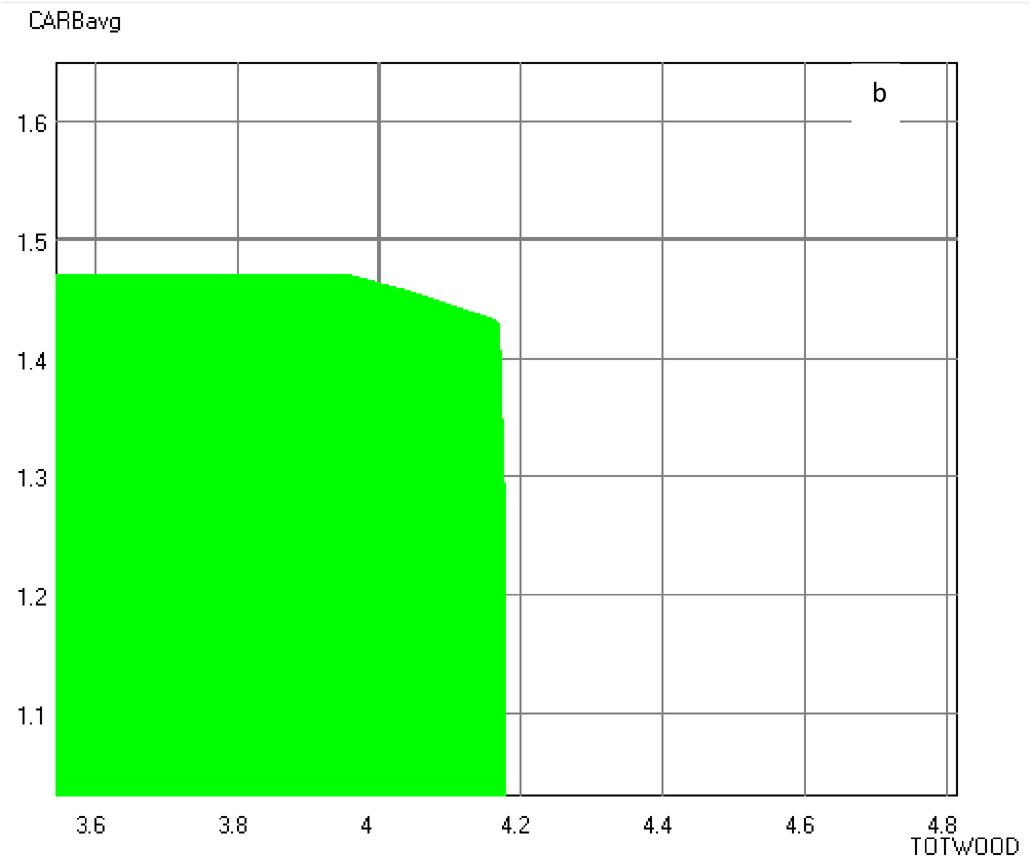


Figure 10 Illustration of two dimensional decision map showing tradeoff between Above ground carbon stock (CARBavg, 10^7 kg) and (a) LEV (10^9 ETB) and (b) Total harvested wood volume (TOTWOOD, 10^5 m^3).

Carbon stock also had a tradeoff with harvested wood volume, but mainly at higher values of the later (Fig 10b). Up to a wood volume value of 3.98 X 10^5 m^3, carbon stock can be increased- to a maximum of 1.471 X 10^7 kg- without decreasing harvested wood volume. After this value, a 2.15% increase in the amount of harvested wood, from 3.98 X 10^5 to 4.045 X 10^5 m^3, led to a 0.92% reduction in carbon stock, from 1.471 X 10^7 to 1.458 X 10^7 kg; whereas, a 0.07% increment of harvested wood, from 4.170 X 10^5 to 4.174 X 10^5 m^3, led to a 9.77% reduction of carbon stock, from 1.374 X 10^7 to 1.252 X 10^7 kg. At the maximum harvested wood volume, which was 4.18 X 10^5 m^3, the corresponding carbon stock amount would become 1.03 X 10^7 kg. The reduction in carbon stock is Finding similar result in a E. globulus dominated stand in Portugal, Marto et al. (2019) discussed that higher levels of total harvested wood signify less trees and then lesser capacity to store carbon.

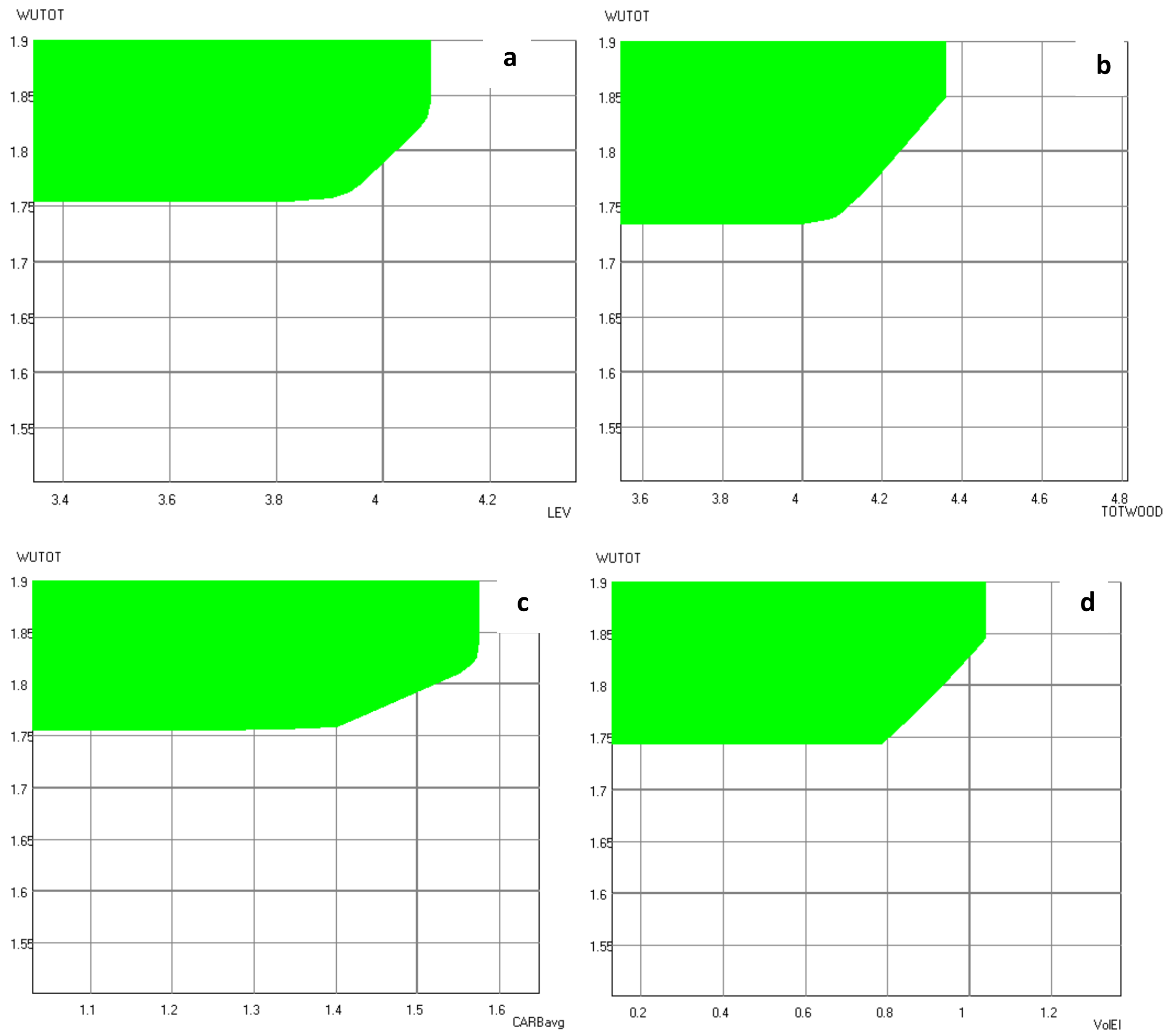


Figure 11 Illustration of two dimensional decision map showing tradeoff between Total Water Use (WUTOT, 10^8 m^3) and (a) LEV (10^9 ETB), (b) Total harvested wood volume (TOTWOOD, 10^5 m^3), (c) Carbon stock (CARBavg, 10^7 kg), and (d) Volume of Ending Inventory (VolEI, 10^5 m^3).

Similar with what has been discussed earlier, total water use was found to increase with an increase in LEV, harvested wood volume, carbon stock and ending inventory criteria (Fig 11a-d). Such positive relationship should however be considered as a tradeoff since the objective was to minimize the water use. According to the result, starting from a LEV value of 3.8 X 10^9 ETB, an increase in LEV increased the total water use. For instance, a change in LEV from 3.832 X 10^9 to 3.934 X 10^9 ETB (2.62%) results a corresponding increase in total water use from 1.756 X 10^8 to 1.763 X 10^8 m^3 (0.38%) (Fig 11a). Whereas, a change of LEV from 4.063 X 10^9 to 4.086 X 10^9 ETB (0.54%) is reflected in an increase in total water use from 1.819 X 10^8 to 1.844 X 10^8 m^3 (1.37%). Likewise, a 2.04% increase in the amount of harvested wood, from 4.00 X 10^5 to 4.083 X 10^5 m^3, led to a 0.34% increase in total water use, from 1.735 X 10^8 to 1.741 X 10^8 m^3; whereas, a 1.95% increment of harvested wood, from 4.083 X 10^5 to

4.164×10^5 m^3, led to a 1.58% increase in total water use, from 1.741×10^8 to 1.769×10^8 m^3 (Fig 11b). This result therefore implies that an increase in wood production by converting crop land into Eucalyptus plantation will continue to be a threat for water availability in the study area even though it needs to be verified by a further hydrological model.

A recent study in central highlands of Ethiopia reported that considering a biomass production estimate of ∼16,000 kg ha−1 yr−1, Eucalyptus woodlots would consume 12,560 m^3 of water per hectare per year, or 1,256mm m^{-2} yr^{-1}, which was on the same order as the total annual rainfall in their study are AEZ, and was substantially higher than estimated evapotranspiration from crops and grasslands in the area (Zaitchik et al., 2012). The authors stressed that this raises a concern for the viability of local streams and, considering the study region's location in the headwaters of the Blue Nile basin, potentially has broader implications for water resources in a contentious transboundary basin.

As the main concern in the study area is economic gain through converting land into Eucalyptus while dealing with the water use issue, an attempt has been made in the current study to compare different possible pareto front points in a water use - LEV - harvested wood three-dimensional decision map, in which three pareto front points representing different levels of harvested wood, water use and LEV was selected for illustration (Fig 12). Based on the solutions of each pareto points (Table 8), it was found that Point 'A' is characterized to have high economic gain (in terms of LEV) 4.193×10^9 ETB, but with high water use (1.824×10^8 m^3), resulted from higher harvested wood volume (4.51×10^8 m^3), and lower carbon stock (1.24×10^7 kg). Whereas, at Point 'C', a lower economic gain (3.701×10^9 ETB of LEV) and lower total water use (1.642×10^8 m^3) were found, which is mainly because of the lower amount of harvested wood volume (4.118×10^5 m^3). The pareto frontier analysis also provides information about how much of the total land of the study area can be covered with Eucalyptus and crop land so as to attain the aforementioned values of the criteria. Accordingly, the result shows that at Point 'A'- i.e. the point with the highest LEV value but at the expense of higher water consumption, land under Eucalyptus plantation would be 835 ha, and 1152 ha under crop land, which means only 175 ha of the current crop land (out of 1337 ha) can be converted into Eucalyptus. If it is needed to limit the total water use up to 1.642×10^8 m^3, i.e. at Point 'C', there will be a reduction in LEV, the land under Eucalyptus should not be more than 696.27 ha, or only 34.15 ha of the current crop land should be converted.

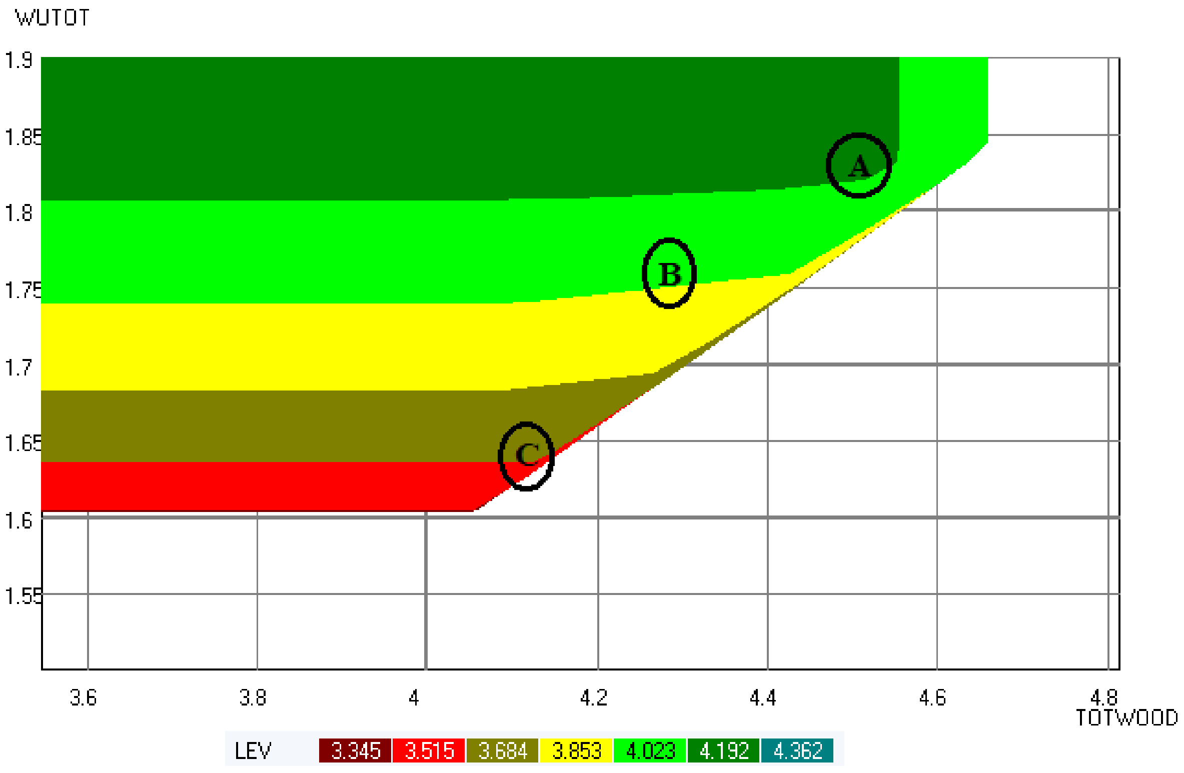


Figure 12 Different pareto front points in a three-dimensional decision map showing tradeoff among LEV, harvested wood, and Total water Use

Table 8 Solutions in the feasible set for the selected points. (Points selected in Figure 12)

Criteria	**Point A**	**Point B**	**Point C**
LEV (10^9 ETB)	4.193	4.019	3.701
TOTWOOD (10^5 m^3)	4.51	4.274	4.118
CARBAvge(10^7 Kg)	1.237	1.308	1.368
VolEI (10^5 m^3)	0.602	0.681	0.567
WUTOT (10^8 m^3)	1.824	1.755	1.642
WUAnnual (10^7 m^3)	2.027	1.95	1.824
CROPTOT (10^6 Kg)	11.347	11.564	11.839
CROPAnnual (10^5 Kg)	12.608	12.849	13.155
LandUnderEuc (ha)	835.17	764.99	696.27
LandUnderCrop (ha)	1152.14	1222.32	1291.04

4. CONCLUSION AND RECOMMENDATION

The study is the first optimization-based case study for forest plantations in Ethiopia. It has examined the optimal land conversion (from crop to *Eucalyptus*) and harvesting plans with the objective to maximize economic gains as well as other ecosystem service objectives (carbon, wood and water use). Based on the optimization analysis, the study concluded that as far as the objective is to maximize the total economic gain from the sale of Eucalyptus wood poles, Eucalyptus plantation is the best and feasible land use as compared to the crop production alternative, and thus, favors a complete conversion of the available crop land into Eucalyptus woodlot. In order to at least meet the annual crop production / consumption requirements of households in the case study area, the total land area under Eucalyptus should be limited to 1772 ha (out of the total 1987 ha). This limit can 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.

The current study also showed the potential application of Pareto Frontier to analyze the tradeoff among multiple objectives, i.e. in addition to economic gains from the sale of Eucalyptus wood products, for Eucalyptus plantations in Ethiopia. Based on the analysis result, we can conclude that maximizing the harvested wood volume or LEV would come at the cost of decreased aboveground carbon stock and volume of ending inventory and higher total water use.

The study is the first ever single as well as multiple objective optimization study applied in the context of Ethiopia. There are however, some issues that the study recommends for future research. One important issue is that the water use and stand growth model didn’t take into account climate change and management effects (e.g. fertilization) in the planning horizon. 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 loss, enhancing soil fertility and the impact on biodiversity that may have to be integrated into the model as well. Besides, future studies should incorporate soil and belowground carbon stock and also address the economic valuation of carbon sequestration so as to capture the real economic value of Eucalypt plantation management. The current study has attempted to examine the tradeoff solutions by selecting possible pareto front points. However, it would also be better to incorporate preferences of farmers and other stakeholders, i.e. target levels of achievements for each objective, and compare solutions.

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