KARADENİZ TECHNICAL UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

FOREST ENGINEERING DEPARTMENT

INTEGRATING GUM PRODUCTION AND SELECTED FOREST ECOSYSTEM SERVICES INTO FOREST MANAGEMENT PLANS USING LINEAR PROGRAMMING: A CASE STUDY IN SUDAN

MASTER THESIS

Elharith HAGR

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Elharith HAGR

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Chairman	:	**Prof. Mehmet MISIR**	....
Member	:	**Asst. Prof. Uzay KARAHALIL**	....
Member	:	**Assoc. Prof. Hayati ZENGİN**	....

Prof. Dr. Asim KADIOĞLU
Director of Graduate School

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Elharith HAGR
Trabzon, 2019

DECLARATION

I am Elharith HAGR hereby declare that this work, entitled "Integrating Gum Production and Selected Forest Ecosystem Services into Forest Management Plans Using Linear Programing: A case Study in Sudan" is the results of my own research, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University. 12/09/2019

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SUMMARY

INTEGRATING GUM PRODUCTION AND SELECTED FOREST ECOSYSTEM SERVICES INTO FOREST MANAGEMENT PLANS USING LINEAR PROGRAMMING: A CASE STUDY IN SUDAN

Elharith HAGR

Karadeniz Technical University.
The Graduate School of Natural and Applied Sciences
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Supervisor: Asst. Prof. Uzay KARAHALİL
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Nowadays, with the need for multi-objective planning to maximize the utility of forest resources without damaging ecological integrity, the traditional view of forest management has to change. In this study, in addition to the production of wood, which is easy to materially evaluated, other values of forests have been highlighted for the selected study area, Okalma forest in Sudan. Gum arabic production, soil conservation and water production values were tried to integrate into forest management plan in addition to timber production. These values were first connected with forest structure using regression models to generate gum arabic, soil loss, water production and timber production yield tables. Afterwards, a linear programming model was developed to integrate those values and solved by LINGO™. Six alternative planning strategies were generated based on the integration of various objectives such as maximization of gum arabic or timber production with different constraints such as harvest flow or capital amount of ecosystem services. When each strategy was compared; STR2, which aimed to maximize timber production, generated the highest NPV of water production as (€ 1,859.4 million), and STR5 generated the lowest NPV of soil loss as (€ 245.5 thousand) at the end of 25 years planning horizon. Among the strategies used to maximize the gum arabic production, STR1 generated the highest NPV of gum production (€764.3 thousand) at the end of the planning horizon. In conclusion, forest management plans should be objectively designed to include multiple services and products.

Key words: Forest Management, Linear Programming, Gum Arabic Production, Ecosystem Services, Net present value, Okalma Forest**.**

Yüksek Lisans Tezi

ÖZET

SAKIZ ÜRETİMİ VE SEÇİLEN FARKLI EKOSİSTEM HİZMETLERİNİN ORMAN AMENJMAN PLANLARINA ENTEGRE EDİLMESİ: SUDAN ÖRNEĞİ

Elharith HAGR

Karadeniz Teknik Üniversitesi
Fen Bilimleri Enstitüsü
Orman Mühendisliği Anabilim Dalı
Danışman: Dr.Öğr.Üyesi Uzay KARAHALİL
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Orman kaynaklarının ekolojik bütünlüğünün bozulmadan çok amaçlı planlanması gerekliliği nedeniyle, günümüzde geleneksel orman amenajmanı bakış açısı değişmelidir. Bu çalışmada, Sudan'da Okalma ormanı için parasal olarak kolay değerlendirilebilen odun üretimine ek olarak, diğer orman fonksiyonları öne çıkarılmıştır. Odun üretimi yanında, sakız üretimi, toprak koruma ve su üretimi fonksiyonları, orman amenajman planlarınına entegre edilmeye çalışılmıştır. Bahse konu fonksiyonlar, öncelikle orman yapısı ile ilişkiye getirilmiş ve sakız üretimi, toprak kaybı, odun üretimi, ve su üretimi matrisleri oluşturulmuştur. Daha bu fonksiyonların entegre edildiği bir planlama modeli kurulmuş ve LINGO^{TM} yardımıyla çözülmüştür. Odun üretiminin en iyilenmesi veya sakız üretiminin en iyilenmesi gibi amaçlar ile eşit eta akışı ve belirli miktar ve hizmet kısıtı içeren 6 planlama stratejisi geleştirilmiştir. Tüm stratejiler karşılaştırıldığında, 25 yıl sonrasında, odun üretimini maksimize etmeyi amaçlayan STR2, en yüksek su üretimi NBD'i (1,859.4 milyon €) verirken STR5 en düşük toprak kaybının NBD'i vermiştir (245.5 bin €). Sakız üretimini maksimize eden stratejiler arasında, STR1 idare süresinin sonunda en yüksek sakız NBD'i (764.3 bin €) üretmiştir. Sonuçta, orman amenajman planlarının çok amaçlılığı dikkate alacak şekilde planlaması önerilmiştir.

Anahtar Kelimeler: Orman Amenajmanı; Doğrusal Programlama; Orman Fonksiyonları; Sakız Üretimi; Net Bugünkü Değer; Okalma Ormanı.

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ABREVIATIONS

CBOS	Central Bank of Sudan
CFI	Corporate Finance Institute
CIA	Central Intelligence Agency
EPA	Environmental Protection Agency
ES	Ecosystem Services
FAO	Food and Agriculture Organization of the United Nations
FNC	Forestry National Commission
GAC	Gum Arabic Company
GDP	Gross Domestic Product
HCENR	Higher Council for Environment and Natural Resources – Sudan
IEC	Investment Encouragement Commission
IFAD	International Fund for Agricultural Development
MEA	Millennium Ecosystem Assessment
NGWA	National Groundwater Association
NPV	Net Present Value
NWFPs	Non-Wood Forest Products
SCA	Sudanese Customs Authority
WB	The World Bank
WEF	World Economic Forum

1. INTRODUCTION

In the last few decades the world has undergone important changes to our welfare but the environment has paid a high price. Business has flourished through the provision of goods and services to individuals everywhere and plays an significant part in economic development (Rover and Persson, 2014). This global transition has led to substantial net gains in human well-being and economic development (Daily et al., 2009; Rover and Persson, 2014; Masiero et al., 2019). According to MEA (2005), not everybody has benefited from this process of evolution and the majority of the world's species, including humans has been harmed. The complete costs connected with this shift are now becoming evident. There are presently many threats to the world's environment such as water and air pollution, wildlife extinction, losing natural habitat, natural resource depletion, climate change (Anand, 2013; Rover and Persson, 2014; Masiero et al., 2019), and we are presently using the equivalent of 1.5 planets to satisfy our requirements (De Groot et al., 2010; Masiero et al., 2019). Despite the consciousness of these disturbing facts, the destruction of natural capital remains to accelerate (MEA, 2005; Morri et al., 2014; Masiero et al., 2019). The awareness of the degrading setting has not yet been converted from the view of people, businesses and governments into proper and sustainable alternatives.

As mentioned by the Millennium Ecosystem Assessment (MEA, 2005), everyone in the globe depends entirely on the ecosystems of the earth and the services they provide. Human well-being and the economy are directly and indirectly linked to biodiversity and ecosystems (Rover and Persson, 2014; Mesbah, 2014; Masiero et al., 2019). There is a growing consciousness of the significance of ecosystems and biodiversity (Daily et al., 2009; Holzman, 2012; Rover and Persson, 2014; Masiero et al., 2019). This consciousness arises as ecosystems produce ecosystem services, that are services that benefit the human well-being. These services include provisioning services such as food and water; controlling flooding services such as climate regulation; cultural services such as recreation and ecotourism; and auxiliary services such as pollination (MEA, 2005).

According to (MEA) 2005, an ecosystem is a vibrant complex of plant, animal and microorganism groups and the non-living environment that interacts as a functional unit and humans are an essential component of ecosystems and the benefits that individuals derive from ecosystems are ecosystem services (ES). The concept of ES emerged in the 1970s and since then the word services has been used to denote the benefits offered by ecosystems and to demonstrate their usefulness and/or social and/or economic importance (Hermann, et al., 2011; Roussel, 2019). The Millennium Ecosystem Assessment (MEA) Framework recognized four categories of ES:

1) Provision of services such as food and water
2) Regulation of services such as flood and disease control
3) Social services such as spiritual, recreational and cultural advantages
4) Support of services such as nutrient cycling (Hermann, et al., 2011; Felipe-Lucia, et al., 2018).

Following the Rio Earth Summit 1992, forest services were divided into three main sections: ecological, economic, social-cultural services. Criteria and indicators were developed for each of the three sections as a tool for monitoring and evaluation of forest trends at the national and international levels and they differ varies from one continent to another and from region to regions. All countries participating in the Summit shall commit themselves to exert all possible efforts to achieve the outputs of the Summit and prepare periodic reports to follow up on the progress that is taking place (FAO, 1995; European Commission, 2014). Countries participating in the various ongoing international processes on criteria and indicators for sustainable forest management have been divided into several zones based on the processes in which they are performed. According to that division, Sudan is located within Dry-Zone Africa, which includes 27 other countries and has 7 criteria and 47 indicators in relation to international processes (FAO, 2000). Sudan has endorsed all that was mentioned at the Summit, but there are no data to showing progress on sustainable forest management (HCENR, 2014).

Ecosystems are supportive of all human activities. That support is necessary to preserve human well-being. Timber production, carbon stockpiling, local climate regulation and numerous cultural services associated with recreational activities and nature experience has traditionally targeted by forest management and has shaped the vegetation structure and species composition of many forests of the world (Felipe-Lucia et al., 2018). In the past, societies did not pay much attention to the importance of the ecosystem and ecosystem services were often considered as public property and consequently overused. On the other hand, scientists are assuming that an increase in world population to 8 billion by 2030 could lead to a massive scarcity of food, water, and energy. The awareness of the ecosystem, goods, and services is greatly needed at large extent among decision-makers and the public (Kenter et al., 2016; USGS, 2016; Okada et al., 2019). Therefore, strong arguments have emerged to focus on the different forest values that are important for society.

According to Egoh et al. (2012), there are many criteria and indicators used by the European Commission to estimating the benefits of ecosystems, because many ecosystem services cannot be directly measured, while this is possible by using criteria and indicators. Interactions between these indicators such as soil retention, land cover etc., which can be called intermediary services, produce final services such as water, food, soil protection, and other services. The objective of knowledge of these indicators and criteria is to have a strong and coherent database and knowledge that will help in finding a solution and/or solutions to integrate ecosystem services in forest planning, landscape, and decision making (Egoh et al., 2012).

In Sudan, the local people used their forest very early, like the rest of the world in order to obtain food, gums, medicine, fuel, feed, tanning materials, and building materials. However, the history of forestry in Sudan began in 1901 when the British government established the forestry department. Its main purpose was to secure a good supply of fuelwood for the steamers plying the river Nile. Despite the early establishment of the forestry department, the first forest policy and law in Sudan was in 1932. The forestry sector has undergone several transformations, but the most important was in 1989 when the Forestry National Commission (FNC) was established as an independent body. One of the tasks of the FNC is to develop plans for the management of the country's forests and to increase the sector's contribution to GDP. The FNC manages the country's forest resources according to the so called working plan, which includes wood and non-wood products such as gum, fruits, seeds, etc. It is also the task of the FNC to develop plans for afforestation and reforestation, combating desertification, enacting laws and policies that will preserve forest resources (Sulieman, 1996).

1.1. Forest Values

1.1.1. Gum Arabic

Non-wood forest products are goods and materials from forests that do not require cut down trees to get them. Global attention to non-wood products is growing, because of its support of millions of rural families that depend on it as food and/or income (Tarig et al., 2014; FAO, 2014; Adam, 2016). Non-wood forest products contain many examples including gums (Abdel Nour, 2013; FAO, 2014). One of them is “gum arabic” is also called as Acacia gum (Marlise and Grenha, 2015). Gum Arabic is produced from *Acacia senegal* and *Acacia seyal* (Adam, 2016). Both species spread along with the belt of gum arabic, which includes 12 states in which traditional agriculture is practiced by relying on rainwater (Abdelmagid, 2014; Adam, 2016). In addition to the value of gum arabic, there is a growing demand by the communities for *Acacia senegal* for its various facilities and uses such as traditional medicine and pharmacy, as well as its ability to preserve the soil and improve its fertility by providing it with nitrogen and rites and customs (Sirelkhatem and Gaali, 2009). Gum arabic has also wide industrial applications such as a stabilizer which is added to the soft drinks, an intensifier and a major emulsifier in the food industry (Couteaudier, 2007; Glyn et al., 2008; Marlise and Grenha, 2015). As a consequence, the global demand for gum arabic is always higher than production. On the other hand, the world’s biggest producer of gum arabic is Sudan, holds the monopoly on the global market (Ibrahim and Osman, 2001; Couteaudier, 2007; IFAD, 2009; World Bank, 2012; FNC, 2017; FNC, 2018; URL-1, 2019). According to the GAC (2017), the area in which gum arabic is produced in Sudan covers about one-fifth of the country, equivalent to 520 thousand km^2. Sudan's production of gum Arabic (from both types) fluctuating, but on average ranges between 30 thousand to 60 thousand tons yearly, and export revenues ranging from $ 40 million to over $ 80 million.

Gum is produced naturally from the bark of trees but in small quantities (Adam, 2016; Mohammed, 2017). It is often obtained mechanically by wounding (incision) the bark of the trees, it is the widely used mechanism. After this process, the gum appears in a circular or oval shape on the tree (Figure 1). The production of gum from trees starts after the age of 5 years and continues until the trees reach 25-30 years. The gum is collected (Figure 2) and later divided into 3 categories (grades) by colour and size (Mohammed, 2017).

Due to the importance of gum economic and its role in raising the standard of living of the local population, many studies have been conducted about it such as: Elmqvist et al. (2005), Ahmed (2006), Couteaudier (2007), Glyn et al. (2008), Abdel Nour (2013), Abdelmagid (2014), Ahmed et al. (2014), Tarig et al. (2014), Marlise and Grenha (2015), Adam (2016), and many others. Gum is present in all forest plans in Sudan as an indispensable forest producer. Many international organizations working in forestry in Sudan such as FAO (1999), IFAD (2009), World Bank (2012), FAO (2014), World Bank (2016), have raised the income of the local population by planting trees of gum and encouraging them to produce gum arabic.

Figure 1. Gum Arabic is in the tree

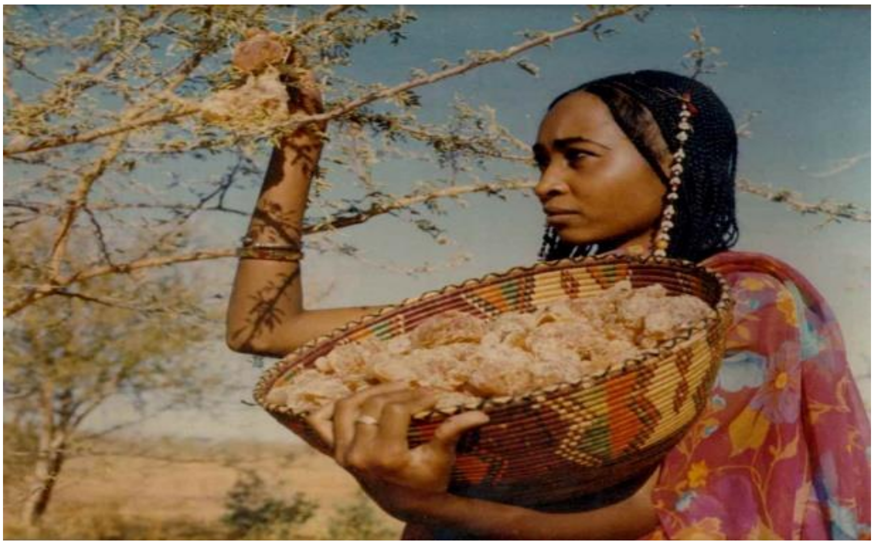

Figure 2. How to take gum arabic from trees

1.1.2 Water Supply

There are different forms of water use by humans, including household uses (cooking, hygiene, etc.), agricultural uses (irrigation), industrial uses and water use for the purpose of generating electricity (Stolton and Dudley, 2007; Keleş, 2018). Despite the knowledge of humans about the importance of water for their lives, but there are many activities that they do and that negatively affect the water supply, for example, the illegal use of water and the use of fertilizers and pesticides, which negatively affect the quantity and quality of water (Thakur and Gupta, 2015; NGWA, 2018; Keleş, 2018).

The quick of population growth and the expanding requests for water, the saving of enough, safe supplies of water is now a main source of global concern. Besides, climate change is already evidenced with decreased rainfall over the most recent 40 years and desertification. The aggregate amount of water in the world is almost 1,400 million km^3 (Keleş et al., 2005; Keleş, 2018; NGWA, 2018; WEF, 2018). That means the Earth has a plenty of water, but only a little rate is usable by humans about 0.3 % (Thakur and Gupta, 2015; NGWA, 2018; Keleş, 2018). As far as water, Sudan is experiencing similar problems with the world. Sudan's estimated annual rainfall since the secession of South has decreased from 1,060 billion cubic meters to about 442 billion cubic meters (URL-2, 2019). There is an urgent increase in demand for water, but it is not available in sufficient quantity and quality for the population. Eighty percent of Sudan's population relies on agriculture, which consumes 97% of the country's water, meaning that livelihoods in Sudan depend entirely on the excessive use of water. Besides, the amount of water for household use is very low as 2%, when compared to the United States, which is almost 13%. In addition to this, as a result of climate change, Nile water supply will be decreased by 20-30% over the next 40 years (URL-2, 2019). In short, Sudan has a critical case of water stress. Therefore, water supply provides an important argument for sustainable forest management (Karahalil et al., 2009; EPA, 2017; URL-2, 2019).

1.1.3. Soil Conservation

The values of soil conservation and water production are two crucial forest services. Forests reduce the rapid runoff of rainwater, which transport the rich surface soils and also to some extent control the power of drying and soil erosion due to wind, thus preventing exhaustion and erosion of the soil (Sharma and Gairola, 2009). Those mentioned forest values become more important especially in countries suffering from forest degradation, having low rainfall, including Sudan. Although Sudan lies within the tropics, the climate ranges from hyper-arid in the north to tropical wet-and-dry in the far southwest (Abubakr et al., 2018). After the secession of the south in 2011, Sudan lost the tropical (equatorial) region, which had high soil fertility and about 200 thousand/ha of natural forest lands are yearly replaced by dryland mechanised agriculture it is the case of all developing countries and Sudan, one of them. Half of the country area (50.7%) is bare rocks and soil (FAO, 2015; FNC, 2018). In addition to this, the Sahara desert is advancing at a rate of about 1.5 km/year (CIA, 2010; FAO, 2015) and also, the estimated that 1.1% of Sudan's forest cover is being degraded annually and large amounts of soil are lost annually due to this deterioration, but there are no accurate figures indicating the annual rate of soil loss in Sudan (Elagib and Martin, 2000). Therefore, Sudan faces ecological crises like desertification and forests play an important role in protecting soil and stopping degradation (FAO, 2015).

1.1.4. Timber Production

Wood is the most important forest product known to humans since ancient times and used for various purposes such as for building houses, cooking, and heating. Firewood is the most important form of human use of wood (FAO, 2014). The global consumption of wood energy is increasing steadily (Hassan et al., 2009; Omer, 2018). This increase is evident in developing countries where the population, especially in rural areas relies on firewood (whether it is directly using wood or converting it to charcoal) as a source of energy and as an income source (World Bank, 2016; CIA, 2017). According to United Nations (2019), households consumption of firewood in Sudan is steadily increasing, but in 2016 household consumption reached its highest level (15,9 m^3/year), representing 0.9% of the world consumption, Sudan ranks 25th worldwide in terms of consumption of firewood. That percentage of consumption is significant for a country like Sudan, where forest cover decreased from 29% to 11.6%, and the area covered by forests has declined from 67.3 million hectares to 21.65 million hectares following the secession of Southern Sudan in 2011 (Mohammed 2012; HCENR, 2014). This means increasing pressure on Sudan's forest resources.

According to the HCENR (2014), 90% of Sudan's forests are government-owned, those are managed by FNC by the working plan. These working plans include wood forest products such as firewood, rail planks, construction poles, as well as NWFPs. Sudan's forestry sector contributes 13% of gross domestic product (FNC, 2015; Abubakr et al., 2018). Sudan has the potential to increase that proportion if sustainable forest planning is undertaken (HCENR, 2014).

The human needs of the forest ecosystems are very complex despite the need to integrate ecosystem services other than wood production in landscape planning (Bettinger et al., 2017). However, the production of timber should not be neglected because of its economic, social and cultural significance, especially in developing countries (HCENR, 2014). Wood production is one of forest ecosystem services easy to evaluate economically (Bettinger et al., 2017).

1.2. Modelling and Linear Programming (LP)

Forest management includes many aspects such as tree management, land management, and people management to achieve multiple goals. Therefore, the management of forests has been associated with other topics such as human dimensions and environmental management models. Successful modeling of forest management means understanding forest dynamics and improving management through accurate representation of all parts of the forest ecosystem. Subsequent developments in the modeling allowed the use of techniques such as linear programming and other techniques that allow the model to identify constraints and provide different management alternatives (Wainwright and Mulligan, 2004).

Optimization of forest management plans to accommodate multiple objectives is one of the most important issues discussed in recent years and has occupied researchers and those interested in forest management. Also, when the sustainability of forest resources is mentioned, there was a need to use forest management optimization (optimisation) techniques which helps to use resources efficiently (Kaya et al., 2016; Bettinger et al., 2017). Kaya et al. (2016) and Bettinger et al. (2017) mentioned in their studies that there are many techniques that can be used for the optimization of forest management, including linear programming, mixed-integer programming, heuristics, goal programming, and integer programming. All the techniques mentioned are share in two key points: managing forest resources to accommodate multiple objectives and maximizing the net present value of forest environmental services. Of all the mentioned techniques, linear programming has been the most commonly used in studies that sought to the optimization of forest management by 63.6% (the usage ratio as a technique) followed by heuristics and mixed-integer programming with the same usage ratio (18.2 %) (Kaya et al., 2016).

Numerous studies have demonstrated like William (1984), Zainal and Isa (1990), Gül (1998), Mısır (2001), Gül (2002), Joseph and Keith (2003), Keleş (2003), Karahalil (2003), Yolasığmaz (2004), Keleş et al. (2005), Karahalil et al. (2009), Karahalil (2009), Zengin (2009), Kaya et al. (2016), Bettinger et al. (2017), Değermenci (2018), the ability of linear programming to distinguish between many objectives and the feasibility of linear programming in the management of forest resources according to their capabilities. Linear programming has many advantages, such as providing a quantitative assessment of the goods and services provided by the ecosystem of forests, minimizing deviations from the objective by constraints imposed on the plan, and also provides a comparison between a number of goals and thus helps to make the appropriate decision to achieve a certain objective.

According to Joseph and Keith (2003), (LP) is a mathematical method for discovering ideal solutions to issues with linear equations and inequity. Many researchers are still discussing the feasibility of using linear programming in forest planning. Although, linear programming has been used and applied since the 1960s and over time has been increasingly applied to forest planning problems (Joseph and Keith, 2003). According to William (1984) and Joseph and Keith (2003), linear programming consists of three main pillars:

- Variable,
- Linear objective equation (It expresses the contribution of each variable to the desired result),
- constraint or constraints,

Concisely, linear programming is an optimization (an improvement) technique. It solves the problem of competition for limited resources in an exemplary manner (Joseph and Keith, 2003; Bettinger et al., 2017). This solution is suitable for forest managers, who face the problem of limited resources and the inability to choose an activity without the other and the difficulty to choose to work to achieve a certain goal alone (Zainal and Isa., 1990; Bettinger et al., 2017). For example, the manager may want to increase the production of gum arabic, but this may increase soil loss. Another example, the director may wish to renew the forest, but this may affect water production. Linear programming is designed to help them make decisions and choose between different goals (William, 1984; Zainal and Isa., 1990; Joseph and Keith, 2003; Bettinger et al., 2017).

There are many programs and techniques available to solve the problem of linear programming such as the ‘‘Simplex Method’’ and LINGO^{TM} (Bettinger et al., 2017) and others. In this thesis LINGO^{TM} (2006) was being used to solve the problem of management after the formulation of the problem mathematically. When the problem is resolved using LINGO™ it allows to perform sensitivity analysis and it is displaying the solution report (Bettinger et al., 2017). The solution report can be divided into two parts (Figure 3):

1) Objective Value, Variable Values, and Reduced Costs

The ‘‘Objective Value’’ refers to the highest NPV can be achieved after taking into account the prices and returns and interest rate. ‘‘Variable and Value’’ are indicating the actual schedule of activities (LINDO, 2017; Bettinger et al., 2017).

The reduced cost must be zero or greater than zero and cannot be of negative value because it indicates the amount. When the amount of reduced cost equal to zero this means that all the values have been used and have a positive effect on the objective function and if it has a value greater than zero this means the objective function will be adversely affected by it (LINDO, 2017; Bettinger et al., 2017).

2) Slack or Surplus and Dual Prices

When the slack is zero, it means that the constraints used are binding (LINDO, 2017) (for example period1 = 12 ha and period2 = 40 ha), and when the slack is greater than zero, the restrictions used are not binding (for example period1 <= 12 ha or period1 >= 23 ha).

The ‘‘Dual Prices’’ it is one of the most important methods used in the sensitivity analysis. It refers to the possibility of an increase in the objective function value (when the objective function is to minimize some values) if the specified constraint increases by one unit, and also it refers to the possibility of a decrease in the objective function value (when the objective function is to maximize some values) if the specified constraint increases by one unit (LINDO, 2017; Bettinger et al., 2017).

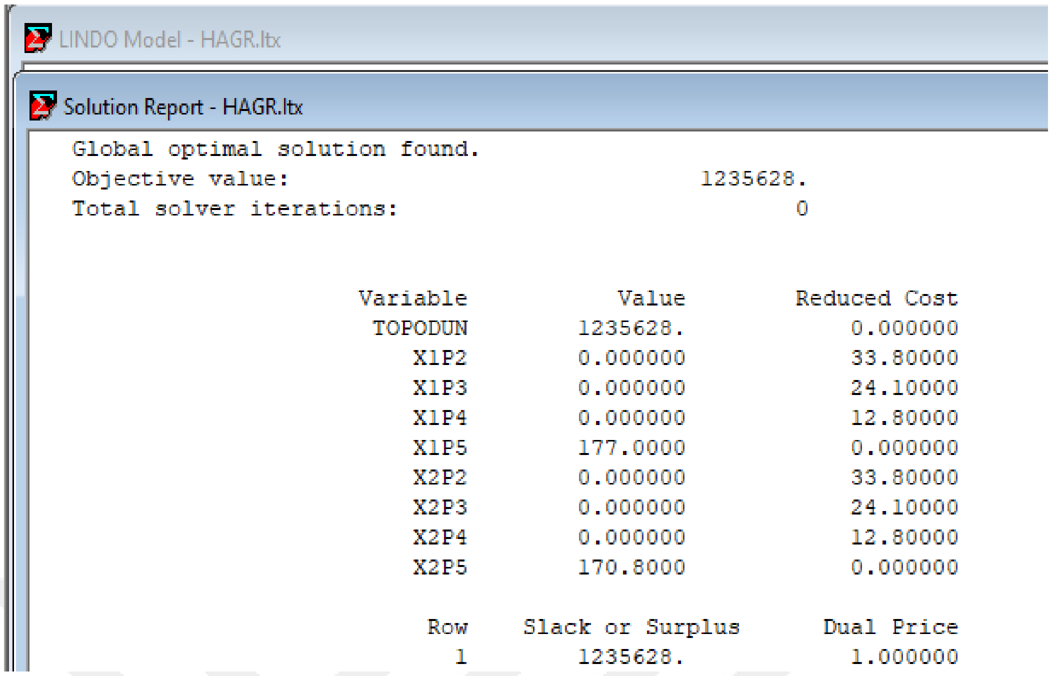

Figure 3. Screen shot of LINGO obtained from STR1 shows the solution report

1.3. Justification and Objectives

In brief, there is an increasing demand for ecosystem services other than wood production. However, ecosystem services are extremely interdependent and often overlapping. Notwithstanding the difficulties, significant progress has been produced over the last decade towards enhanced methods to link changes in ecosystem services to changes in human well-being. Part of this enhancement is caused by modeling methods. Some studies have tried to integrate some forest values such as soil loss (Guo et al., 2001; Mısır, 2001; Karahalil, 2003; Yolasığmaz, 2004; Keleş et al., 2005; Guo et al., 2008; Karahalil et al., 2009; Masiero et al., 2019) water production (Guo et al., 2000; Keleş, 2003; Yolasığmaz, 2004; Keleş et al., 2005; Karahalil et al., 2009; Chisholm, 2010; Zengin et al. 2011; Morri et al., 2014; Değermenci, 2018; Okada et al., 2019; Ge Sun et al., 2019; Masiero et al., 2019) into forest management plans using different techniques. Wangai et al. (2016) reviewed the ES studies in Africa, where they said that ES studies in Africa did not start early, as the first study of ES was conducted in 2005. Subsequently, the studies continued and increased even reached 52 studies on ecosystems and their services and the possibility of integrating them into forest management plans. These studies were concentrated in South Africa, Tanzania, Kenya, and Ethiopia. Until the date of that review 2016, no study had been conducted on the

ES and the possibility of integrating their various services into the forest management plans in Sudan. Moreover, there is no recorded study that examined gum arabic as a forest value and compares it economically with another ES. However, economic analyses for gum arabic displayed that this value can be used as an incentive for increasing focus on ES (Ahmed et al., 2014). Here, modelling techniques can be used in order to manage the forest in a multi-objective and sustainable way. Therefore, the main objectives of this study are:

1) To quantify the gum arabic production value,
2) To integrate the gum arabic production, water production, and soil conservation values into forest management plans as well as timber production,
3) To develop different alternatives based on the four different forest values,
4) To compare each strategy based on NPV (Net Present Value) of four forest values and select the appropriate one considering the capabilities of the forest enterprise.

2. MATERIAL AND METHODS

2.1. Study Area

Okalma forest, located in 12º 30´ 56.3´´- 12º 41´ 44.3´´ north latitudes and 34º 23´ 09.9´´- 34º 16´ 14.6´´ east longitudes in Sinnar State, Sudan, was selected as a study area. The area covers 17,118 ha. On the forest boundary there are mountains, Kardus mount in the south direction and Okalma mount in the south-eastern direction (Figure 4).

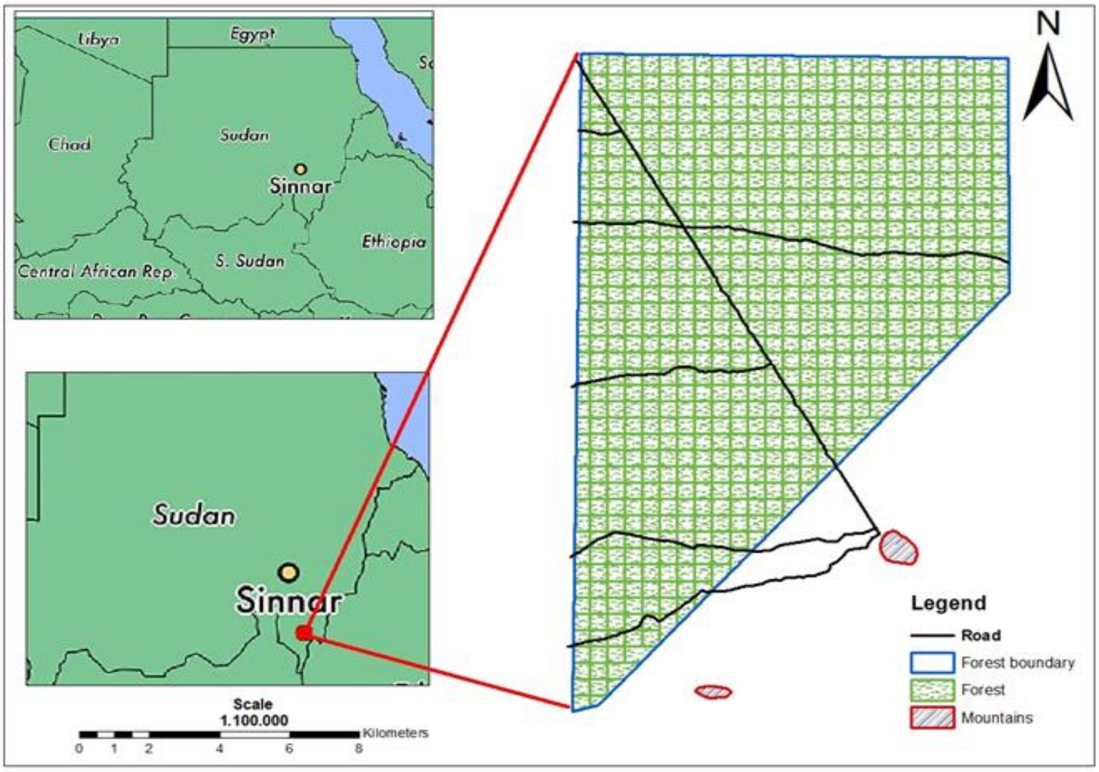

Figure 4. Location of the study area

The soil is a dark alkaline clay, which swells and becomes extremely sticky when wet, but develops wide and deep cracks when dry. The annual rainfall rate is between 400-700 mm between June and October. The most important tree species present is *Acacia senegal* which produces gum arabic, *Acacia seyal* produces gum arabic as well as firewood and charcoal. Other species within the study area; *Balanites aegyptiaca*, *Acacia mellifera*, *Adansonia digitata*, *Cordia sinensis*, *Capparis deciduas*, *Maerua angolensis*, *Anogeissua leiocarpus, Grewia tenax* and *Acacia nilotica* (Badi, 2016).

The Okalama Forest is a forest owned by the Government of the Sudan and managed by the Forestry Commission of Sennar State. It was registered as a state forest in 1953. The first plan to management Okalma forest was established in 1976. Its purpose was to provide the local population with forest products (wood and non-wood), and also there was an economic objective of producing firewood and gum arabic. In 2016, the Faculty of Forestry, University of Khartoum, developed a ten-year plan for manage Okalma forest. According to reports from the Forestry National Commission, the forest is subject to a large population attack because there are 7 villages located on the border of the forest (University of Khartoum, 2016).

2.2. Material

Forest inventory data were used, collected for the preparation of Okalma Forest Management Plan designed for the period of 2016-2025 to determine the current forest structure (University of Khartoum, 2016). The total area of the land is 17,118.6 ha within 30 stands (polygons), 12 stands used for production gum and the rest of the stands used for wood production and at the same time used for soil protection purposes. The stands with large spaces were divided into smaller stands so that they were easy to handle, so the total number of stands was 100. The total number of trees are 6,510,835 (excluding regeneration). The number of regeneration trees are 2,714,702. The total volume of forest (stock) 396,200 m^3. The average volume of trees per hectare 23 m^3/ha and the average number of trees per hectare 380 tree/ha. Geographical Information Systems were used in the storage, processing, and analysis of the data related to the planning unit.

2.3. Methods

In addition to final harvesting decisions, the planning process requires the inclusion and analysis of a number of microprocessors, to achieve one or more objectives. Objectives and constraints can be associated with economic values, commodities, ecological values, or social concerns (Bettinger et al., 2017). In order to compare the outputs of different alternatives considering selected forest values, decision making techniques provides good advantages. Among the several optimization techniques, linear programming has been widely used to accommodate forest values into forest management plans as it is a powerful tool for generating an optimal solution which enables further sensitivity analyses (Weintraub and Romero, 2006; Kaya et al., 2016; Bettinger et al., 2017).

To achieve the desired objectives of the use of linear programming technique, forest values were tried to associate with stand structure. Several equations generated by previously conducted studies were used. The equations used were based on the basal area, diameter at breast height (dbh), age and volumes of trees. Based on those parameters, yield matrices for *Acacia seyal* stands were developed. Mentioned parameters of *Acacia seyal* were obtained from the Okalma forest database (University of Khartoum, 2016).

2.3.1. Determining Timber Production Value

Current timber production values were taken from the forest management plan. However, future yields for the following periods were estimated with the help of current age and volume of the stands. Since, there is no yield tables or growth models for the focus tree species, *Acacia seyal*. In this study, planning horizon determined as 25 years and planning period set as 5 years. In addition, allowable cut was taken as 10% of the related stand volume. Stands younger than 25 years exempted from harvesting, thus rotation age was 25 years.

Since, there is no growth and yield models or tree volume tables for *Acacia seyal*. (Eq. 1) was developed based on the relationship between volume and age to calculate the volume of *Acacia seyal*.

$$Y = 1.5538x - 2.7355 \quad (R^2 = 0.27) \qquad \text{(Eq. 1)}$$

Where;

Y= volume (m^3).

X= age (years).

The timber yield matrix of stand 1 with 177 ha areas is given in Table 1.

Table 1. Coefficients of timber production volume for stand 1

Stand = 1; Id = 1 , Age = 20 , Area = 177 ha					
Periods		P2	P3	P4	P5
I		3.2	3.2	3.2	3.2
II		40.0	4.0	4.0	4.0
III		0.5	47.7	4.7	4.7
IV		1.2	0.5	55.5	5.5
V		2.0	1.2	0.5	63.3

The above matrix refers that, stand 1 is in 20 age. The planning horizon is 25 years, and the stands younger than 25 years are exempt from the final harvest. Therefore, in P2 specifically period I is exempt from the final harvest, there is just thinning harvest and its amount is 3.2 m^3/ha. As for period II, because the planning horizon has been completed, the final harvest or final cut was done and its amount is 40 m^3/ha. After the regeneration, the stand becomes at the age of 5 and is the age of the beginning of the rotation age. And in the next period is added 5 years (planning period) and the age of stand becomes 10, and so for the rest of the periods (Table 1).

Price per cubic meter (m^3) of firewood, after subtracting all costs, amounted to €3 (Sinnar State, 2019). The conversion from Sudanese pounds to Euros according to the prices of the Central Bank of Sudan (CBOS, 2019).

2.3.2. Determining Soil Loss Value

To calculate the amount of soil loss for the stands, the formula developed by Karahalil (2003) based on Universal Soil Loss Equation (USLE) was used (Equation 2).

$$\ln SL = 2.553079 - 0.065*BA \quad (R^2 = 0.67) \qquad \text{(Eq. 2)}$$

Where;

ln =Natural logarithm

SL = Approximate soil loss (tonnes/ha/year)

BA=Basal area (m^2/ha)

Due to the absence of direct values of the basal area, the (dbh) to obtain (BA) was used.

To calculate basal area (Equation 3) was used:

$$BA = (Pi/4)*dbh^2 \qquad \text{(Eq. 3)}$$

Where;

BA= Basal area (m^2/ha)

Pi= returns the value of Pi = 3.14

dbh= diameter at breast height (m)

The soil loss matrix for stand 1 is given in Table 2.

Table 2. Coefficients of soil loss volume for stand 1

Id = 1 , Age = 20 , Area = 177 ha					
Periods		P2	P3	P4	P5
I		12.836	12.836	12.836	12.836
II		12.843	12.834	12.834	12.834
III		12.842	12.843	12.831	12.831
IV		12.841	12.842	12.843	12.828
V		12.839	12.841	12.842	12.843

Here, in P2 for example, when the stand was exempted from the final harvest specifically in the period I, because his age is 22.5 (20 age of stand + 2.5 half age of period), the amount of soil loss was 12.836 tonnes/ha, and when the final harvest was done in period II, the amount of soil loss was 12.843 tonnes/ha (Table 2), and age of stand is 2.5 years. This amount and age will remain constant every regeneration occurs because when the regeneration occurs, the stand age is 5 years, but the half age of the period (2.5) was taken, assuming the regeneration can occur at any time of the period. In period III the amount of soil loss was 12.842 tonnes/ha (Table 2), and age of stand is 7.5 years (2.5 years, age of previous period + 5 years as an age of period), and so for the rest of the periods.

Soil productivity is often used to assess the cost and benefits of soil conservation as well as the costs of soil erosion (Mısır et al., 2007; Karahalil et al., 2009; Kuhlman, 2014). The soil is not exchanged in the market (Karahalil et al., 2009) only in certain cases for example when used in nurseries. Forest values other than timber were tried to express as monetary value by logical estimations. Therefore, in this study, the cost of soil per tonnes was calculated from the nursery of the Faculty of Forestry, University of Khartoum (it is sandy/clay soil taken from the sides of the rivers). Price per tonnes of soil after subtracting all costs amounted to €1.5 which is the price used in this study.

2.3.3. Determining Water Production Values

In order to estimate the amount of water production, Equation (4) was used developed by Karahalil (2009).

$$\ln WP = 8.7493 - 0.0151 * dg \ (R^2 = 0.22) \qquad \text{(Eq.4)}$$

Where;

WP = Water production value (m^3/ha/year)

dg = dbh (mean diameter at breast height) (cm)

The water production matrix for stand 1 is given in Table 3. Water production values were determined in the same way as soil loss values, but using equation 4.

Table 3. Coefficients of water production volume for stand 1

Id = 1 , Age = 20 , Area = 177 ha					
Periods		P2	P3	P4	P5
I		5249.2	5249.2	5249.2	5249.2
II		5724.5	5137.1	5137.1	5137.1
III		5602.2	5724.5	5026.6	5026.6
IV		5481.7	5602.2	5724.5	4918.5
V		5364.6	5481.7	5602.2	5724.5

There were no specific local or regional prices for each category of water use, which included drinking, agriculture and industrial or commercial use. According to Investment Encouragement Commission in Sudan, the minimum of water usage in all sectors is 60 m^3 and the minimum price is 95 SDG and all usage more than minimum usage multiply in 2 (IEC, 2019). The price of 1 m^3 of water should be determined to build the economic values of water production, so the water price is calculated on this basis resulting in €3.5 per cubic meter and this figure used in calculation of water production NPV.

2.3.4. Determining Gum Arabic Production Values

To calculate gum yield from the stands, the formula developed by Mohammed and Rohle (2011) based on diameter at breast height was used (Eq. 5).

$$Y = 6.386 + 0.983*X \quad (R^2 = 0.25) \qquad \text{(Eq.5)}$$

Where;

Y= gum yield (kg/ha),

X= dbh (cm).

The (dbh) for each age obtained by equation (6)

$$y = 0.2871x + 5.6939 \ (R^2 = 0.43) \quad \text{(Eq.6)}$$

Where;

y = dbh (cm),

x = age class.

The gum production matrix for stand 1 is given in Table 4.

Table 4. Coefficients of gum production volume for stand 1

Id = 1 , Age = 20 , Area = 177 ha					
Periods		P2	P3	P4	P5
I		18.3	18.3	18.3	18.3
II		12.7	20.0	20.0	20.0
III		14.1	12.7	21.2	21.2
IV		15.5	14.1	12.7	22.5
V		17.0	15.5	14.1	12.7

Gum arabic production values were determined in the same way as soil loss values, but using equation 5 and 6. Price per kg of gum arabic from the producer (farmer) directly and after subtracting all costs amounted to €1.5 (Sinnar State, 2019).

2.3.5. Creating NPV for the Selected Forest Values

To the assessment of forest conditions economically, there are many commonly used methods through which economic analysis is conducted (Türker, 2013; Bettinger et al., 2017; CFI, 2019). Economic analysis of alternatives guides forest managers to the optimal goal that achieves the highest return with the lowest costs and therefore the plans earn strong arguments for implementation. It also helps to predict future costs and revenues. The economic analysis of the alternatives is indispensable because any management activity needs to allocate time and money (Kaya et al., 2016). Bettinger et al. (2017) mentioned in their study several ways in which the state and conditions of the forest could be evaluated economically, such as: Net Present Value, Present and Future Values, Prices and Costs, Internal Rate of Return, Benefit/Cost Ratio, Equal Annual Equivalent, Soil Expectation Value, Forest Taxation and finally Environmental and Social Evaluation of Natural Resources. Because there may be costs and revenues associated with completing the current plan (current rotation), the landowners always want to know the current value of the land (Bettinger et al., 2017; Roussel, 2019). In this thesis, NPV was selected as an economic valuation method for alternatives.

In order to compare monetary outputs of the four selected forest values, NPV value matrices were also developed. NPV is used to assist decide the worth of investment, project or any series of cash flows. It's a comprehensive metric since all revenues, expenditures and capital costs connected with an investment in Free Cash Flow are taken into consideration, and it also takes into account the timing of each flow of cash flows, which can affect the current value. The Net present value should be greater than zero. When NPV equals 0 this means that revenue equals costs (Bettinger et al., 2017; CFI, 2019).

$$NPV = (V * P)/ (1+r)^n \qquad \text{(Eq.7)}$$

Where;

NPV = Net present value,

V = Output of timber, soil loss, water and gum arabic. Those values were calculated by equations 1, 2, 4, 5 respectively.

P= Price (€),

r = Interest rate (1.6%, 3%, 12%),

n = The difference of future periods from the beginning period (years).

In the calculation of NPV, three different approaches were adopted, thus different interest rates were considered. Some researchers (Türker, 2013) recommend using the increment level for the determination of interest rate. In our study, the mean increment rate is 1.6%. The second approach 3%, where some studies in forestry, indicated that the interest rate ranges between 1.5 and 5% (Türker, 2013). The third approach includes using an increase in price levels. The increase rate in the price levels in Sudan recorded various levels, reaching a high of 17.30% in October 2003 and an average interest rate of 12.08% between 2003 and 2018 (URL-3, 2019). In this study, 12% was accepted as an interest rate for Sudan (Ahmed et al., 2014). NPV matrices considering different interest rates are given in Table 13, Table 14, and Table 15.

Table 5. Coefficients of the use of 3% as an interest rate to calculate NPV for stand1

Periods	NPV of Allowable Cut (€)				
	Decision variables				
		P2	P3	P4	P5
I		8.9	8.9	8.9	8.9
II		96.1	9.6	9.6	9.6
III		1	98.8	9.7	9.7
IV		2.15	0.9	99.2	9.8
V		3	1.85	0.77	97.6

Table 6. Coefficients of the use of 1.6% as an interest rate to calculate NPV for stand1

Periods	NPV of Allowable Cut (€)				
	Decision variables				
		P2	P3	P4	P5
I		9.2	9.2	9.2	9.2
II		106.5	10.6	10.6	10.6
III		1.3	117.5	11.5	11.5
IV		2.7	1.4	126.3	12.5
V		4.2	2.5	1	132.8

Table 7. Coefficients of the use of 12% as an interest rate to calculate NPV for stand1

Year	NPV of Allowable Cut (€)				
	Decision variables				
		P2	P3	P4	P5
I		7.3	7.3	7.3	7.3
II		51.29	5	5	5
III		0.4	34.7	3.4	3.4
IV		0.5	0.21	22.9	2.3
V		0.47	0.3	0.2	14.8

It is noted in Table 5, Table 6 and Table 7 that the NPV values of the allowable cut change whenever the values of "n" are changed in equation 7, and also change, whenever the volume of allowable cut changes in Table 1. Large amounts, such as 51.29 Euros in Table 7, specifically in P2, and more specifically in Period II, mean that a final harvest was done because the rotation age is complete.

2.3.6. General Structure of the Model

To help develop the model that would facilitate forest management, 6 alternative planning strategies have been developed with different characteristics and solved by

LINGO™ (LINGO, 2006). To develop linear programming ‘‘Model I’’ approach was used (Keleş et al., 2005; Karahalil et al., 2009; Bettinger et al., 2017).

Based on previous assumptions, subsequent equations are used to form the model

Objective functions

Zmax = TH; Zmax = TG (Eq.8)

$$\sum_{j=1}^{n}\left(\sum_{i=1}^{m} aij\ xij\right) - NPVH\,jt = 0 \qquad \text{(Eq. 9)}$$

$$\sum_{j=1}^{n}\left(\sum_{i=1}^{m} bij\ xij\right) - NPVG\,jt = 0 \qquad \text{(Eq. 10)}$$

$$\sum_{j=1}^{n}\left(\sum_{i=1}^{m} cij\ xij\right) - NPVW\,jt = 0 \qquad \text{(Eq. 11)}$$

$$\sum_{j=1}^{n}\left(\sum_{i=1}^{m} dij\ xij\right) - NPVS\,jt = 0 \qquad \text{(Eq. 12)}$$

$$\sum_{j=1}^{n}\sum_{i=1}^{m} Hj - TH = 0 \qquad \text{(Eq. 13)}$$

$$\sum_{j=1}^{n}\sum_{i=1}^{m} Gj - TG = 0 \qquad \text{(Eq. 14)}$$

$$\sum_{j=1}^{n}\sum_{i=1}^{m} Nj - TW = 0 \qquad \text{(Eq. 15)}$$

$$\sum_{j=1}^{n}\sum_{i=1}^{m} NSj - TH = 0 \qquad \text{(Eq. 16)}$$

$$\sum_{i=1}^{m}\left(\sum_{j=1}^{n} xij\right) <= T\mathrm{i} \qquad \text{(Eq. 17)}$$

$$(-(1-y)NPVHj + NPVH_{j+1}) \geq 0 \qquad \text{(Eq. 18)}$$

$$(-(1-y)NPVHj + NPVH_{j+1}) \leq 0 \qquad \text{(Eq. 19)}$$

$$\sum_{j=1}^{n}\sum_{i=1}^{m} xij - Aj = 0 \qquad \text{(Eq. 20)}$$

$$Xij \geq 0 \qquad \text{(Eq. 21)}$$

Where;

Xij = Area of stand i cut in period j (ha);

aij = Net present value of one ha timber production of stand i cut in period j (€);

bij = Net present value of one ha gum arabic production of stand i cut in period j (€);

cij = Net present value of one ha approximate water production of stand i cut in period j (€);

dij = Net present value of one ha approximate soil loss of stand i cut in period j (€);

Accounting variables:

NPVHjt: Total Net present value of timber production in period j with different Interest rates (t = 3%, 1.6% and 12%) (€).

NPVGjt: Total Net present value of gum arabic production in period j with different Interest rates (t = 3%, 1.6% and 12%) (€).

NPVWjt: Total Net present value of water production in period j with different Interest rates (t = 3%, 1.6% and 12%) (€).

NPVSjt: Total Net present value of approximate soil loss in period j with different Interest rates (t = 3%, 1.6% and 12%) (€).

TH: Total timber production at the end of the planning horizon (m^3).

TG: Total gum arabic at the end of the planning horizon (kg).

TW: Total water production at the end of the planning horizon (m^3).

TNPVS: Total soil loss at the end of the planning horizon (tonnes)

m: Number of stands (i =1 to 100).

n: Silvicultural treatment options (j=1 to 5)

y: The change rate between periods (10%).

t: Interest rate (3%, 1.6%, 12%)

Ti: Area of stand i (ha).

Aj: Optimal periodic area in period j (regulated forest)

Equation 8 appear the objective functions of two different values of the forest. Equations 9, 10, 11, and 12 represent total NPV of timber production, gum arabic production, water production and approximate soil loss in each period. Equations 13, 14, 15 and 16 embody total timber production, gum arabic production, water production and the approximate value of soil loss at the end of the planning horizon. Equation 17 ensures that each stand cannot exceed its area. Equations 18 and 19 represent the NPV of periodic timber (and also possible for gum, water, and soil) flow. Finally, Equation 20 used to ensure that an example of the age class is distributed.

2.3.7. Developing Alternatives

In this thesis six strategies have been developed, three of which are to maximize the production of timber and the other three to maximize gum production (Table 8). Due to their economic and social importance, and because FNC seeks to increase the contribution of the forestry sector to GDP. Values of water production and soil loss are included and used as constraints to the strategies (Table 8).

Table 8. Descriptions of the forest management strategies tested

Strategies	Objective function	Constraints
STR1	Max TH	No constraints
STR2	Max TH	1) The amount of gum production between periods should not exceed 20% 2) In periods 2, 3, 4 and 5 the regeneration area should not exceed 10%
STR3	Max TH	1) The amount of gum production between periods should not exceed 30% 2) SL < 220,000 tonnes (For all periods)
STR4	Max TG	The amount of gum production between periods should not exceed 10%
STR5	Max TG	1) The amount of gum production between periods should not exceed 40% 2) WP > 200,000 m^3 (For all periods) 3) SL < 100,000 tonnes (For all periods)
STR6	Max TG	1) The amount of gum production between periods should not exceed 20% 2) SL < 250,000 tonnes (For all periods)

Note:

STR: Strategies,

TH: Total of timber production (allowable cut) (m^3), TG: Total of gum arabic (kg),

SL: Approximate soil loss (tonnes/ha/year),

WP= Water production value (m^3/ha/year).

3. RESULTS AND DISCUSSION

The timber production outputs of the strategies generated with the help of LINGO program are given in Table 9.

Table 9. Timber outputs of various planning strategies over the planning horizon

Periods	Allowable Cut (timber production) (m^3)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	44,316	44,316	44,316	44,316	23,246	44,316
II	57,231	163,076	57,231	57,231	28,975	57,231
III	70,624	194,293	70,624	291,772	34,960	70,624
IV	83,976	240,179	322,964	330,237	72,036	484,985
V	979,478	349,569	678,279	298,157	436,749	464,902
Total	1,235,628	991,435	1,173,417	1,021,715	595,969	1,122,060
Periods	Thinning Harvest (m^3)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	44,316	44,316	44,316	44,316	23,246	44,316
II	57,231	45,754	57,231	57,231	28,975	57,231
III	70,624	43,120	70,624	46,191	34,960	70,624
IV	83,976	34,879	57,667	27,988	37,776	39,825
V	0	13,262	2,459	10,519	331	4,797
Total	256,147	151,331	232,279	186,245	125,288	216,793
Periods	Final Harvest (m^3)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	0	0	0	0	0	0
II	0	117,321	0	0	0	0
III	0	151,173	0	245,581	0	0
IV	0	205,299	265,297	302,249	34,260	445,160
V	979,478	336,307	675,820	287,637	436,418	460,104
Total	979,478	810,100	941,099	835,467	470,678	905,264

When comparing planning strategies in terms of the amount of timber obtained at the end of the planning horizon, the highest value for timber production was obtained from STR1 (1,235,628 m^3) followed by STR3 with a value of (1,173,417 m^3) (Table 9). Among all strategies used, STR1 can be chosen, because this strategy yielded the highest amount of allowable cut (1,235,628 m^3) at the end of the planning horizon, this strategy yielded as 979,478 m^3 final harvest and 256,147 m^3 thinning harvest. In general, the amount of allowable cut increases over time along the planning horizon for all strategies used (Table 9) (Figure 5).

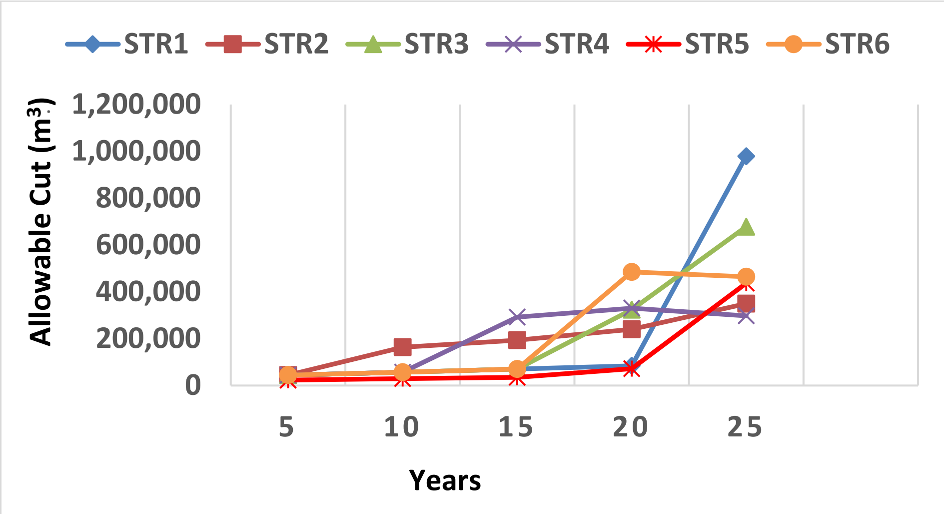

Figure 5. The flow of allowable cut levels

The strategies outputs of the different other ecosystem services generated with the help of LINGO program are given in Table 10.

Table 10. Gum, soil loss and water outputs from strategies over the planning horizon

Periods	Gum production (kg)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	294,680	294,680	294,680	294,680	139,219	294,680
II	319,217	298,813	319,217	319,217	150,889	319,217
III	344,642	296,687	344,642	300,454	161,765	344,642
IV	367,289	283,536	320,327	270,409	166,359	288,470
V	217,344	248,192	224,229	243,368	99,815	230,776
Total	1,543,175	1,421,911	1,503,098	1,428,130	718,048	1,477,789
Periods	Soil loss (tonnes)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	219,708	219,708	219,708	219,708	99,951	219,708
II	219,667	219,692	219,667	219,667	99,935	219,667
III	219,625	219,690	219,625	219,679	99,912	219,625
IV	219,575	219,702	219,646	219,717	99,898	219,683
V	219,791	219,766	219,786	219,772	100,000	219,781
Total	1,098,367	1,098,560	1,098,433	1,098,545	499,696	1,098,466
Periods	Water production (×1000 m^3)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	91,365	91,365	91,365	91,365	41,114	91,365
II	89,397	91,128	89,397	89,397	40,236	89,397
III	87,457	91,388	87,457	91,081	39,359	87,457
IV	85,569	92,420	89,448	93,544	38,993	92,082
V	97,967	95,329	97,365	95,705	44,492	96,793
Total	451,757	461,630	455,032	461,092	204,194	457,095

The strategies that produced the highest amount of gum production are STR1 (1,543,175 kg), STR3 (1,503,098 kg) and STR6 (1,477,789 kg). Among the three strategies (STR4, STR5, and STR6), which developed to maximize gum production, STR6 yielded a higher amount of gum (1,477,789 kg) than STR4 and STR5 (Table 10).

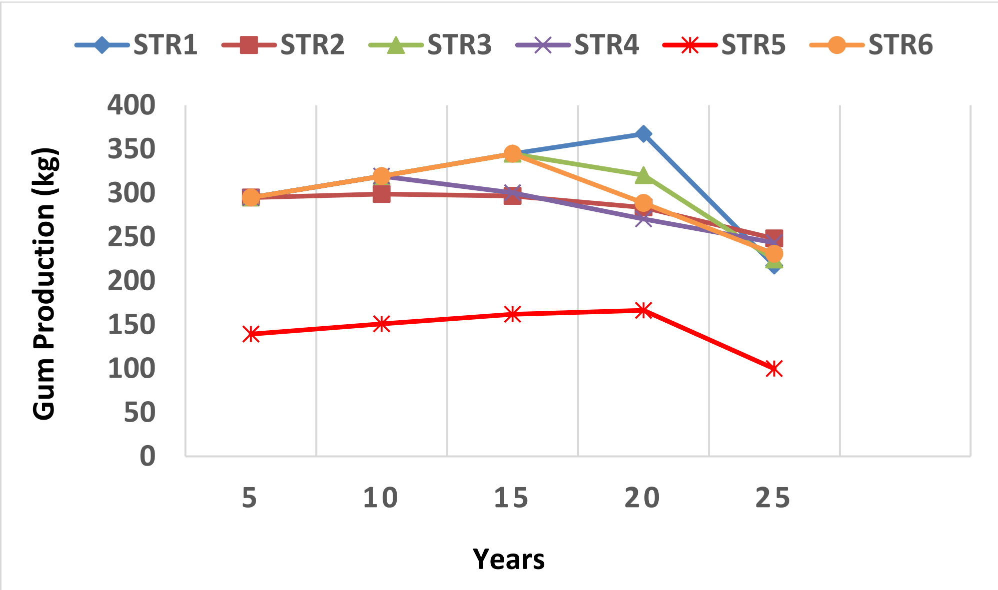

Figure 6. The flow of gum levels

STR5 yielded the lowest soil loss, as (499,696 tonnes). The highest amount of soil loss was produced by STR as (1,098,560 tonnes), followed by STR4 with the amount as 1,098,545 tonnes. (Table 10). Strategies 1, 3 and 4, especially in periods 1 and 2, were involved in producing the same amount of soil loss. It is also noted that these strategies, even during the rest of the periods, produced convergent amounts of soil loss (Figure 7). In general, soil loss in all strategies increases in period 5 due to harvest (Table 10).

Figure 7. The flow of soil loss levels

The strategies that generated the highest amount of water production are STR2 (461.6 million m^3), STR4 (461.0 million m^3) (Table 10). It is observed in all the strategies that water production continues to decline to a certain point, this is because of the large increase in tree diameters at this point, tree diameters were used to calculate water production (Eq.4), after this point it increases and achieves its highest value in period 5 (Figure 8).

Figure 8. The flow of water levels

When compared the strategies in terms of regeneration areas, the largest regeneration area produced by STR1 was observed specifically in period 5, it was 17113.70 ha, followed by STR5 (16,535 ha) in period 5. STR2 except period 1, have regeneration areas in all rest of periods, this is due to the constraints used in this strategy (Table 8). However, these strategies gave the same regeneration area at the end of the planning horizon 17,113 ha (Table 11) (Figure 9). The rotation age is 25 years so in the early periods of planning does not happen regeneration because there is not enough area at the mature age classes (Table 12) (Figure 10).

Table 11. Regeneration areas (ha) according to periods

Periods	Regeneration Areas(ha)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I	0	0	0	0	0	0
II	0	3,188	0	0	0	0
III	0	3,826	0	6,126	0	0
IV	0	4,590	4,918	6,335	578	9,594
V	17,113	5,509	12,195	4,652	16,535	7,519
Total	17,113	17,113	17,113	17,113	17,113	17,113

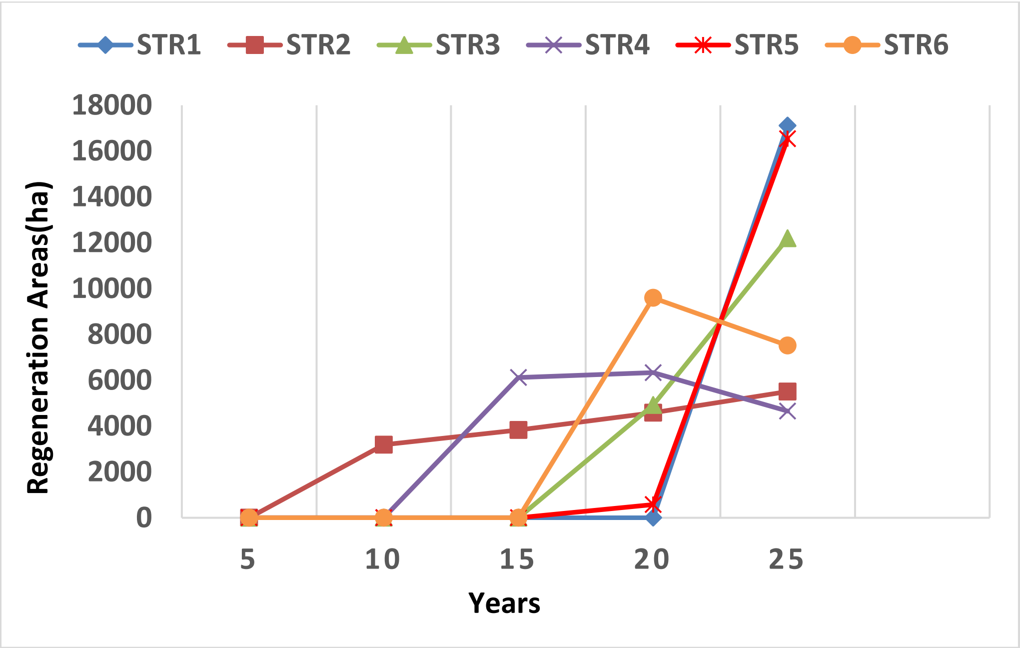

Figure 9. Regeneration areas (ha)

The age class distribution of all strategies at the end of planning horizon that were generated with the help of LINGO program is given in Table 12. Now there is no stand at the age of 25.

Table 12. Age class distribution at the end of the planning horizon (ha)

Age class	Areas(ha)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
I.	17,113	5509	12,195	4,652	16,535	7,519
II.	0	4,590	4,918	6,335	578	9,594
III.	0	3,826	0	6,126	0	0
IV.	0	3,188	0	0	0	0
Total	17,113	17,113	17,113	17,113	17,113	17,113

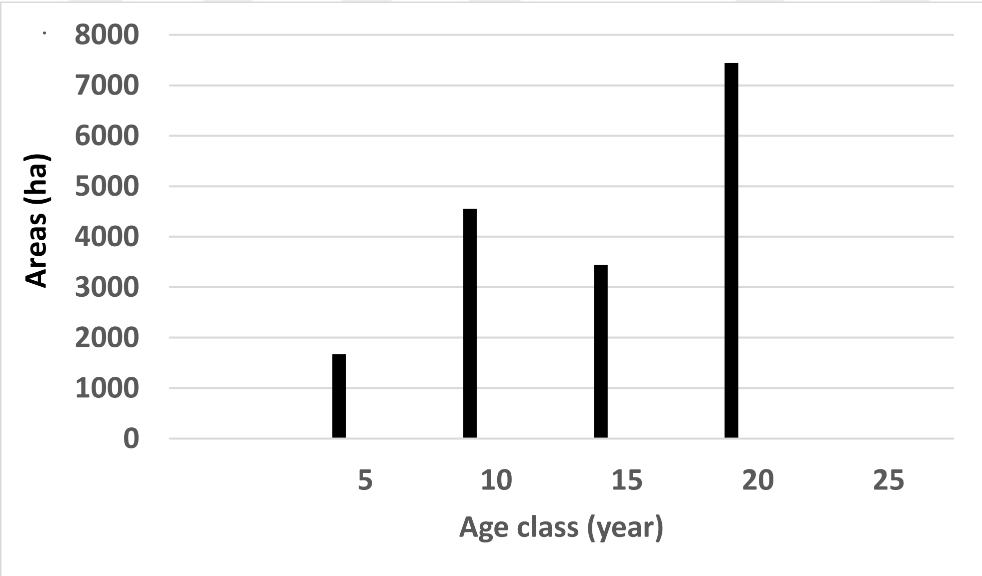

Figure 10. Current age class distribution of Okalma Forest (ha)

Three interest rate 3%, 1.6% (Türker, 2013) (Table 13) (Table 14) respectively and 12% (Ahmed, et al., 2014, URL-2, 2019) (Table 15) have been tried to calculate the net present value.

Table 13. NPV of different planning strategies with using interest rate 3%

Periods	NPV of allowable cut (timber production) (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	123.4	123.4	123.4	123.4	64.8	58.7
2	137.5	391.9	137.5	137.5	69.6	62.9
3	146.4	402.8	146.4	604.8	72.5	65.4
4	150.2	429.5	577.6	590.6	128.8	66.5
5	1,495.4	523.6	1,063.9	444.2	658	646.8
Total	2,053.8	1,871.3	2,048.9	1900.5	993.8	900.4
Periods	NPV of gum production (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	407.5	407.5	407.5	407.5	190.9	171.8
2	383.5	359.1	383.5	383.5	181.3	163.5
3	357.2	307.6	357.3	311.5	167.7	151.2
4	328.4	253.5	286.5	241.8	148.7	138.9
5	167.7	191.5	173	187.8	77	686.7
Total	1,644.5	1,519.2	1,607.9	1,532.2	765.7	6,940.8
Periods	NPV of soil loss (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	306.2	306.0	306.0	306.2	139.2	125.3
2	263.9	264.0	263.9	263.9	120.1	108.1
3	227.6	227.7	227.6	228.1	103.6	93.2
4	196.6	196.7	196.7	197.7	89.3	93.2
5	169.5	169.5	169.6	169.5	77.1	69.4
Total	1,163.9	1,163.9	1,164.1	1,164.2	529.4	476.4
Periods	NPV of water production (million €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	297.0	297.0	297.0	297.0	133.6	120.2
2	250.7	255.5	250.7	250.7	112.8	101.5
3	211.5	221.0	211.5	220.3	95.2	85.6
4	178.5	192.8	186.6	195.2	81.4	72.3
5	176.4	171.9	175.3	173.3	80.0	72.2
Total	1,114.2	1,138.3	1,121.2	1,136.5	503.0	451.8

Table 14. NPV of different planning strategies with using interest rate 1.6%

Periods	NPV of allowable cut (timber production) (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	127.8	127.8	127.8	127.8	67.0	607.1
2	152.4	434.3	152.4	152.4	77.1	697.9
3	173.7	478.1	173.7	717.7	86.0	776.4
4	190.8	545.8	733.9	750.4	163	844.9
5	1,960.1	732.5	1,327.9	624.2	916.7	901.5
Total	2,604.8	2,318.4	2,515.7	2,372.5	1,309.8	3,827.8
Periods	NPV of gum production (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	424.8	424.8	424.8	424.8	200.7	180.9
2	425.1	397.9	425.1	425.1	200.9	181.1
3	423.9	364.9	423.9	369.6	199	179.4
4	417.3	322.1	363.9	307.2	189	176.6
5	228.1	260.5	235.4	255.4	104.9	93.4
Total	1,919.3	1,770.3	1,873.2	1,782.2	894.4	811.5
Periods	NPV of soil loss (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	316.8	316.7	316.7	316.7	144.1	129.7
2	292.4	292.5	292.5	292.5	133.1	119.7
3	272.4	272.5	272.6	272.5	122.9	110.6
4	249.5	249.6	249.6	249.6	113.5	102.1
5	230.7	230.7	230.7	230.7	104.9	944.1
Total	1,361.9	1,362.2	1,362.0	1,362.1	618.6	556.7
Periods	NPV of water production (million €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	307.9	307.9	307.8	307.9	138.3	124.4
2	279.4	284.7	279.4	279.7	125.0	112.5
3	253.6	264.9	253.6	264.0	113.0	101.6
4	231.2	249.8	240.7	252.8	104.1	92.6
5	245	238.5	243.6	239.4	108.9	98.2
Total	1,317.1	1,345.8	1,325.1	1,343.4	589.5	529.3

Table 15. NPV of different planning strategies with using interest rate 12%

Periods	NPV of allowable cut (timber production) (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	100.1	100.1	100.1	100.1	52.5	100.1
2	73.4	209.1	73.4	73.4	37.2	73.4
3	51.4	141.3	51.4	212.3	25.4	51.4
4	34.7	99.2	133.3	136.4	29.8	200.2
5	229.4	81.9	158.9	69.9	102.3	109.1
Total	489.0	631.6	517.1	592.1	247.2	534.2
Periods	NPV of gum production (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	333.1	333.1	333.1	333.1	157.3	333.1
2	204.7	191.6	204.7	204.7	96.8	204.7
3	125.4	107.9	125.4	109.3	58.8	125.3
4	75.8	58.5	66.1	55.8	34.3	59.5
5	25.5	29.1	26.3	28.5	11.7	27.0
Total	764.5	720.2	755.6	731.4	358.9	749.6
Periods	NPV of soil loss (thousand €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	248.2	248.2	248.2	248.2	112.9	248.2
2	141.1	140.8	140.8	140.8	64.0	140
3	80.0	80.1	79.9	80.0	36.0	80.1
4	45.1	45.1	44.9	45.0	20.2	44.9
5	26.4	26.4	26.4	26.0	12.4	26.0
Total	541.1	540.6	540.2	540.0	245.5	539.0
Periods	NPV of water production (million €)					
	Strategies					
	STR1	STR2	STR3	STR4	STR5	STR6
1	241.8	240.8	240.9	240.9	108.4	240.8
2	134.4	137.1	134.4	134.5	60.2	134.4
3	74.2	775.8	74.2	77.3	33.4	74.2
4	44.3	445.2	43.1	45.1	18.8	44.3
5	27.0	260.5	26.6	26.2	18.7	26.5
Total	520.7	1,859.4	519.2	524.0	239.6	520.2

Planning strategies used in terms with each other as regards the total NPV were compared at the end of the planning horizon. With the exception of the NPV of the amount of allowable cut, the total NPV of gum production, water production, and soil loss decreases over time along the planning horizon. In general, positive NPV of all strategies was obtained at the end of the planning horizon.

In this study, 12% was accepted as an interest rate for Sudan, because it is the most suitable for Sudan (Ahmed et al., 2014). The results to be presented later are the result of using 12% as an interest rate for Sudan.

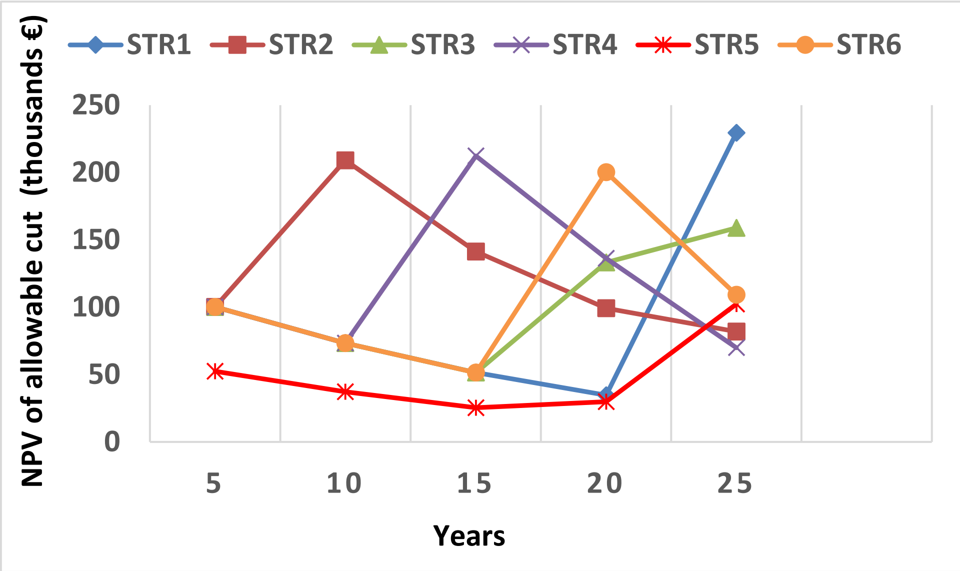

Figure 11. NPV of allowable cut over 25 years

When considering all planning strategies, STR2 gives the highest timber NPV (€ 631.6 thousand) followed by STR4 (€ 592.1 thousand) and finally STR6 with a net present value (€ 534.2 thousand) (Table 15) (Figure 11).

When considering NPV of allowable cut; STR1 resulted in the generated of the highest timber (1,235,628 m^3) (Table 9), because no constraints were imposed on production in that strategy (Table 8). In STR1 while the amount of allowable cut increases over time along the planning horizon (Table 9), the total NPV continues to decline over time to period 4, but in period 5 the total NPV increases and the strategy generated the highest total NPV. This was due to the postponement of the harvest of the largest amount of allowable cut to period 5, where 979,478 m^3 were harvested (Table 9), and the area of 17,113 hectares has been regenerated only in period 5 (Table 11).

When comparing STR1 and STR2, STR1 produced more allowable cut, but STR2 gave a higher NPV (€ 631.6 thousand) than STR1 (€ 489 thousand) (Table 15), because STR2 produced a large amount of allowable cut in the early periods of the planning horizon due to the impact of the constraint imposed on the model in STR2 (in periods 2, 3, 4 and 5 the regeneration area should not exceed 10%), while in STR1 the huge amount of allowable cut was deferred to the period 5 (Table 9). And also STR1 yielded higher amount of allowable cut (1,235,628 m^3) than STR3 (1,173,417 m^3) (Table 9), but STR3 gave more NPV (€ 517.1 thousand) than STR1 (€ 489 thousand) (Table 15) for the same reason mentioned previously, that the STR3 produced a large amount of allowable cut in the early periods of the planning horizon, while in STR1 the large amount of allowable cut was deferred to the period 5 (Table 9).

The age class distribution resulted in an irregular figure of NPV of timber (Figure 11), which did not occur in the forms of other values of forests which were calculated, (Figure 12, Figure 13 and Figure 14). Taking into account the different location and conditions of the forest, this result corresponds to the findings of Keleş et al (2005) and Karahalil et al. (2009). In their studies, that the NPV of timber production takes an irregular form.

Among the three strategies (STR1, STR2, and STR3), which developed to maximize wood production (Table 8), those three strategies have recorded the highest values of soil loss, especially in period1, and over time, soil loss decreases, especially in periods 2 and 3. And the reason for this is to diameters of the trees in period 1 are smaller than diameters of the trees in periods 2 and 3. Thus, basal area values are decreasing in period 1 and increasing in periods 2 and 3. In contrast, when the planning horizon is completed in period 5, the soil loss increases because the value of the basal area becomes zero.

In general, all the strategies that have been developed to maximize timber production have managed to achieve the desired goal, but in varying amounts.

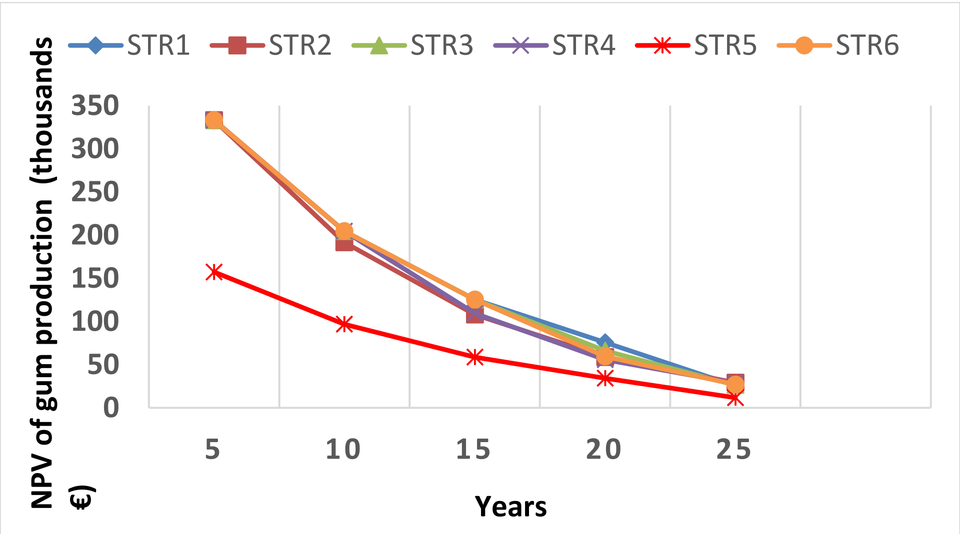

Figure 12. NPV of gum production over 25 years

When considering the NPV of gum production, STR1 generated the highest NPV (€ 764.5 thousand) followed by STR3 (€ 755.6 thousand) and STR6 (€ 749.6 thousand), while STR5 yielded the lowest NPV of gum (€ 358.9 thousand). (Table 15).

Although STR1 aims to maximize wood production, it generated the highest amount (1,543,175 kg) and the highest NPV of gum Arabic (€ 764.5 thousand). The reason for this is the model let a huge amount of allowable cut to period 5, and no treatment was carried out on trees in the first four periods of the rotation age (Table 9), which means, the model let the trees growing, and thus increased their diameters, which are used to calculating gum production in the equation 5, which reflected positively on the production of gum Arabic. STR4, STR5 and STR6, which were also intended to maximize the production of gum were compared. The highest NPV was obtained from STR6 (€ 749.6 thousand) (Table 10). The reason for that is being the constraint imposed on the model that was the amount of gum production between periods should not exceed 20% (Table 8). This led to generate the higher amount of gum in the early periods of the planning horizon. And the lowest NPV was obtained from STR5 as (€ 358.9 thousand) (Table 10), the reason for this is due to one of the constraints imposed on the model that was the amount of gum production between periods should not exceed 40% (Table 8), which negatively reflected on the production of gum.

When considering all planning strategies it is noted that gum arabic production continues to increase to a specific point and then starts to decrease to its lowest value in period 5 (Table 10). There are two reasons for this, the first is that there is an inverse relationship between the production of gum and the production of timber, which achieves its highest value in period 5, the period during which the production of gum reaches its lowest value. The second reason is that gum production from trees decreases when trees ages are between 20 and 25 years (Mohammed, 2017). (Figure 6). The total NPV of gum production decreases over time along the planning horizon and takes the inverse J shape (Figure 12). The reason for that is the production of gum is in large quantities in the early periods of the planning horizon (Table 10). In all strategies the total NPV of gum arabic is higher than its counterpart in the timber production, so the focus on gum production is feasible, especially with the increasing global demand for gum arabic (IFAD, 2009; Abdel Nour, 2013; FMI, 2019), and gum arabic has achieved significant returns when exporting, it was reached more than 84 million $ in some years (World Bank, 2012; SCA, 2018). When comparing strategies aimed to maximize the production of gum arabic with strategies for maximizing timber production, it was found that gum strategies generated less soil loss (Table 10).

Figure 13. NPV of soil loss over 25 years

STR5 recorded the lowest NPV of soil production (€ 245.5 thousand) followed by STR6 (€ 539 thousand) and STR4 (€ 540 thousand) (Table 15) (Figure 13).

When considering soil loss; STR5 yielded the lowest amount (499,696 tonnes) and the reason for that is the inclusion of less than 100,000 tonnes of soil loss as a binding constraint to the model in STR5 that had a positive impact on the reducing minimal soil loss, this has contributed to reducing soil loss. As the soil continues to be eroded with water and wind unchecked, much of the land will be lost. For example, in the region of El-Suki (which is 10 kilometres away from the study area) alone, it lost more than 50,000 tonnes/year due to the erosion by water (Anonymous, 2006). Therefore, the use of Strategy 5 would reduce soil loss and contribute to avoiding erosion.

Among the six strategies were used, STR2 resulted in the highest amount of soil loss (1,098,560 tonnes), due to the impact of the constraint imposed on the model in STR2 that was (in periods 2, 3, 4 and 5 the regeneration area should not exceed 10%), this led to an increase in the harvest in these periods, and thus decreased the values of the basal area that used to calculate soil loss values (Equation. 2). This finding is consistent with the findings of Keleş et al. (2005) and Karahalil et al. (2009) in their studies, it was the lower the basal area, the greater the loss of soil. Note that for all strategies, the decrease in the rate of soil loss is very little, because the diameters of the trees are very small, which effects on the basal area.

In general, strategies that aimed to maximize gum production (STR4, STR5, and STR6), produced lowest amount of soil loss, due to increased basal area values, and strategies, which aimed to maximize timber production, produced highest amount soil loss.

Figure 14. NPV of water production over 25 years

When NPV of water production is taken into account, STR2 gave the highest NPV as (€ 1,859.4 million) followed by STR1 (€ 520.7 million), and the lowest NPV of water production was obtained from STR5 as (€ 239.6 million). The NPVs of water production was the greatest values in this thesis.

When considering water production; STR2 that used to maximize timber production, this strategy generated a higher amount of water production (461,6 thousand m^3) than other strategies. Because of the constraint that was used in this strategy (in periods 2, 3, 4 and 5 the regeneration area should not exceed 10%), this limits fluctuations in harvests, all that led to increasing in amount and NPV of water production in STR2. Note that the NPV of water production in all strategies takes the inverse J shape, except in Strategy 2 it takes an irregular shape (Figure 14), due to the huge increase in the amount of cutting (Table 9). That means, the greater the production of wood, the greater the production of water. When consideration of STR4 and STR6, they produced almost identical quantities of water production (Table 10), but STR4 yielded higher NPV (€ 524 million) than STR6 (€ 520.2 million) at the end of the planning horizon, that was because, the impact of the constraint imposed on the model in STR6 that was (the loss of soil should be less than 250,000 tonnes for all periods), thus, the model tried to ensure less soil loss, which negatively affected on the NPN of water production. This result is consistent with the findings of Karahalil et al. (2009) and Keleş et al. (2005) in their study, taking into account the different locations and conditions of the forest, they mentioned that reduced soil loss values negative affects water production.

STR5 produced the lowest NPV of water production (€ 239.6 million), due to the constraints imposed on the model (for all periods water production must be > 200,000 m^3 and soil loss must be < 100,000 tonnes), and also objective of STR5 to maximize gum arabic production, this requires increasing the diameters of the trees (Table 8), all this has negatively affected water production values and NPV of water production.

As expected, strategies aimed at increasing wood production increased water production, and strategies aimed at increasing gum production produced less amount water production. In general, positive NPV of all strategies was obtained at the end of the planning horizon.

4. CONCLUSIONS AND SUGGESTIONS

At the end of the study, this thesis was able to achieve the goals set by the researcher in advance. With the help of linear programming, the four forest values (gum production, water production, soil conservation as well as timber production) were integrated into a single plan using different strategies. Each strategy was compared (for 5 periods) as well as comparison of planning strategies with each other based on net present value. The most appropriate strategy has been identified which is consistent with the capabilities of the forest enterprise. Gum production values (which has great attention local and international) were quantified and a comparison was made between strategies aimed at maximizing gum production and strategies aimed at maximizing the production of timber, based on the NPV of each strategy.

Among of all strategies, the researcher recommends choosing STR2 because it achieves a balance between maximizing gum arabic production, maximizing timber production, maximizing water production and reducing soil loss.

In the plan developed for the management of the Okalma Forest, approximately 50 ha regenerate annually, but if the STR2 developed in this research is selected, in the first 5 years only 5,509 ha will be renewed. Once the planning horizon is complete, the all forest area will be regenerate (17,113 ha). The amount of allowable cut of the current plan is (236,357 m^3), but if the STR2 developed in this research is chosen, it produces 991,435 m^3 of the amount of allowable cut, and also STR2 gives 151,331 m^3 as a thinning harvest, which can provide revenue to meet the expenses of management of forest. And also the amount of gum arabic production of the current plan is about 514,795 kg, but if the STR2 that developed in this research is chosen, 1,421,911 kg of gum arabic will be obtained.

The results of this study are consistent with previous studies and emphasize modeling ability to optimize forest management plans because of their ability to provide alternatives to planning and thus help to make an appropriate decision, which would maintain a balanced supply of ecosystem resources.

After the results reached in this thesis were discussed, the researcher recommends the following:

Future studies should be conducted using the same data that was used in this thesis, but using other economic valuation methods which Bettinger et al (2017) mentioned in their study (e.g. Prices and Costs, Internal Rate of Return, Benefit/Cost Ratio, Equal Annual Equivalent, Soil Expectation Value, Forest Taxation and finally Environmental and Social Evaluation of Natural Resources). Two methods of economic valuation of ecosystem services can be used and compared to each other.

In this study, the equations used to calculate the amount of water production, and also to calculate soil loss are equations developed in Turkey. It is consequently strongly recommended that to develop a water production equation for Sudan, and also to develop a soil loss equation for Sudan, based on universal soil loss equation. It is also recommended that a yield table should be developed for *Acacia seyal*.

Modeling should be included in forest management plans in Sudan, because there is always a problem facing forest management is the difficulty of determining the objective of afforestation, by modeling it is possible to distinguish between different objectives.

5. REFERENCES

Abdel Nour, H. O., 2013. Gum Arabic in Sudan: Production and socio-economic aspects. Medicinal, Culinary and Aromatic Plants in the Near East, Proceedings of the International Expert Meeting organized by the Forest Products Division. FAO Forestry Department and the FAO Regional Office for the Near East. Cairo, Egypt.

Abdelmagid, A., 2014. Book review: Gum Arabic in the Sudan. Sudan Vision. (Unpub–lished).

Abubakr, A., Salih. M., Elagib, N., Tjernström, M., Zhang, Q., 2018. Characterization of the Sahelian-Sudan rainfall based on observations and regional climate models. Atmospheric Research. Volume 202, Pages 202-218.

Adam, Y. O., 2016. Gum Arabic Value chain analysis in East Darfur, Sudan. Technical Report. UN environment.

Ahmed, A. E., Elhadi, H. M., Adam, Y.O. and Eisa, M. A., 2014. Payment for Environmental Services (PES): A mechanism for adopting the agroforestry farming system among gum Arabic producers in Sudan, International Journal of Development and Sustainability, Vol. 3 No. 5, pp 1099-1112.

Ahmed, M. E., 2006. The Socio-Economic Role of in Sustainable Development of Rule Area in the Gum Belt of Sudan. Institut für International Forst- und Holzwirtschft, Technische Universität Dresden, Tharandt, Germany.

Anand, S. V., 2013. Global Environmental Issues. 2: 632 doi: 10.4172/scientificreports.632.

Anonymous, 2006. Soil Conservation and Land Use in the Sudan. Sudan Silva, 19, pp. 34-38.

Badi, S. A., 2016. A ten-year plan for the management of the Okalma forest. Sudan. University of Khartoum Dspace. Undergraduate Dissertations. Faculty of Forestry. Batch 20.

Bettinger, P., Boston, K., Sirsy, J. P., Grebner, D., L., 2017. Forest Management and Planning, Academic Press, ISBN: 978-0-12-809476-1, 346 p.

CBOS, 2019. Exchange rates 14.02.2019. Khartoum: Central Bank of Sudan CBOS. https://cbos.gov.sd/en.

CFI, 2019. Net Present Value (NPV). Corporate Finance Institute. London. https://corporatefinanceinstitute.com/resources/knowledge/valuation/net-present-value-npv/

Chisholm, R. A., 2010. Trade-offs between ecosystem services: Water and carbon in a a biodiversity hotspot.

CIA, 2010. Central Intelligence Agency. Library: The World Factbook - Sudan. Overview.

CIA, 2017. Central Intelligence Agency. Library: The World Factbook - Sudan. Economy.Overview.

Couteaudier, T. Y., 2007. Export Marketing of Sudanese Gum Arabic Export Marketing of Sudanese Gum Arabic, Report Number: 41099. Volume No: 1. Pages 1–45. Multi Donor Trust Fund-National, Technical Secretariat. The World Bank - Khartoum.

Daily, G., Polasky, S., Goldstein, J., Kareiva, P., Mooney, H., Pejchar, L., Ricketts, T., Salzman, J. and Shallenberger, R., 2009. Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment, 7(1), pp.21--28.

De Groot, R., Alkemade, R., Braat, L., Hein, L. and Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity, 7(3), pp.260--272.

Değermenci, A. S. 2018. Meşcerelerin gençleştirme ve bakım düzeninin su miktar ve kalitesi açısından optimize edilmesi. Doktora Tezi, Düzce Üniversitesi, Fen Bilimleri. 166 s.

Egoh, B., Evangelia, G., Drakou, A., Martha, B., Dunbar, Maes, J., Louise, W., 2012. Publications Office of the European Union2012 –111 pp. –21.0 x 29.7 cm EUR – Scientific and Technical Research series –ISSN 1831-9424(online)ISBN 978-92-79-25821-3(pdf)doi:10.2788/41823.

Elagib, N. A., Martin, G., 2000. Climate impacts of environmental degradation in Sudan. GeoJournal, Vol. 50, No. 4 (2000), pp. 311-327 Published by: Springer Stable URL: http://www.jstor.org/stable/41147481 Accessed: 15-07-2016 16:21 UTC.

Elmqvist, B., Olsson, L., Elamin, E. M., 2005. A traditional agroforestry system under threat: an analysis of the gum arabic market and cultivation in the Sudan. Article in Agroforestry Systems, DOI 10.1007/s10457-004-2371-3.

EPA, 2017. United States Environmental Protection Agency. Environmental Topics- Water Topics.

European Commission, 2014. Mapping and Assessment of Ecosystems and their Services. Indicators for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020. ISBN 978-92-79-36161-6. Technical Report - 2014 – 080.

FAO, 1995. Report of the FAO Expert Consultation on Harmonization of Criteria and Indicators for Sustainable Forest Management.13-16 November 1995. Rome-Italy.

FAO, 1999. Gum arabic in Sudan: production and socio-economic aspects. www.fao.org/docrep/X5402e/X5402e12.htm.

FAO, 2000. Practical guidelines for the assessment and measurement of criteria and indicators for sustainable forest management in dry-zone Africa. Rome-Italy.

FAO, 2014. Non-wood forest products. Food and Agriculture Organization of the United Nations.

FAO, 2015. Food and Agriculture Organization of the United Nations. Global Forest Resources Assessment 2015: How Are the World's Forests Changing? Second edition. Rome, Italy (ISBN 978-92-5-109283-5).

Felipe-Lucia MR, Soliveres S, Penone C, Manning P, van der Plas F, Boch S, Prati D, Ammer, C, et al., 2018._Multiple forest attributes underpin the supply of multiple ecosystem services. Nature Communications, Doi: 10.1038/S41467-018-07082-4.

FMI, 2019. Gum Arabic Market: Global Industry Analysis and Opportunity Assessment 2015-2025.Future-market-insights https://www.futuremarketinsights.com/reports/gum-arabic-market.

FNC, 2015. Workshop on the project of wood belts. Forestry National Corporation. Gedaref -Sudan.

FNC, 2017. Workshop-Gum Arabic production. Forestry National Corporation Khartoum - Sudan.

FNC, 2018. State of Forests Report, pp 20-23. Forestry National Corporation, Khartoum - Sudan.

GAC, 2017. Gum Arabic Company. Gum Arabic Production Report. Page 4.

Ge Sun, Steven, G. McNulty, Jennifer Moore., 2019. Modeling the Potential Effects of Forest Management and Climate Change on Water Yield across the Southeastern U.S. Available: https://www.researchgate.net/publication/253969918.

Glyn, O., Takashi, O., Kazunari, U., 2008. The regulatory and scientific approach to defining Gum Arabic (*Acacia senegal* and *Acacia seyal*) as a dietary. Food Hydrocolloids, 22: 24-35.

Guo, Z., Xiao, X. and Li, D., 2000. An assessment of ecosystem services: water flow regulation and hydroelectric power production. Ecological Applications, 10(3), 2000, pp. 925–936.

Guo, Z., Xiao, X., Gan, Y.and Zheng., Y., 2001. Ecosystem functions, services and their values – a case study in Xingshan County of China. Ecological Economics 38 (2001) 141–154.

Guo, H., Wang, B., Ma, X., Zhao, G., Li S., 2008. Evaluation of ecosystem services of Chinese pine forests in China. Science in China, Series C: Life Sciences, 51(7), 662–670.

Gül. A. U., 1998. Performing functional planning using linear programming in forest management. Individual research, Trabzon.

Gül, A.U., 2002. Linear programming model for functional planning in: Proceedings of the Symposium on the New Concepts and Targets in Forest Management Planning, Faculty of Forestry of Istanbul University, Turkey, pp. 56-66.

Hassan, R., Hertzler, G., Benhin, J. K.A., 2009. Depletion of forest resources in Sudan: Intervention options for optimal control. Science. Volume 37, Issue 4, April 2009, Pages 1195-1203.

HCENR, 2014. Sudan. Fifth National Report to the Convention on Biological Diversity (CBD). The Higher Council for Environment and Natural Resources.

Hermann, A., Schleifer, S, and Wrbka, T., 2011. The Concept of Ecosystem Services Regarding Landscape Research: A Review, Living Rev. Landscape Res., 5, (2011), 1. [Online Article]: cited.

Holzman, D. C., 2012. Accounting for Nature's Benefits: The Dollar Value of Ecosystem Services. Environ Health Perspect. Vol .120 (4): pp 52–57.

Ibrahim, A. M., and Osman, M. E., 2001. Report of the meeting of the network for natural gums and resins in Africa (NGARA). In: Chikamai B.N., Mbiru S.S. and Casadei E. (Eds), Gums and Resins production in Sudan. Kenya College of Communications Technology, Nairobi, pp. 43–49.

IEC, 2019. Prices of services. Investment Encouragement Commission, Page 2.Sudan.

IFAD, 2009. Revitalizing the Sudan Gum Arabic Production and Marketing Project. International Fund for Agricultural Development, Department of Dairy and Food Science and Technology, Egerton University.

Joseph, B, and Keith, G., 2003. Decision Methods for Forest Resource Management. Chapter 2., Principles of Linear Programming: Formulations . Library of Congress Catalog Card Number: 2002117166. International Standard Book Number: 0-12-141360-8.

Karahalil, U., 2003. Modelling Soil Conservation and Timber Production Values Using Linear Programming (A case study in Karanlıkdere Planning Unit). Master Thesis, Karadeniz Technical University Graduate School of Natural and Applied Sciences, Trabzon, 84 pp.

Karahalil, U., 2009. Preparing Forest Management Plans for Forested Protected Areas (A Case Study in Köprülü Canyon National Park), PhD Thesis, Karadeniz Technical University, 172 p.

Karahalil, U., Başkent. E.Z., Köse, S., 2009. Integrating soil conservation , water production and timber production values in forest management planning using linear programming, *4*(11), 1241–1250.

Kaya, A., Bettinger. P., Boston. K., Akbulut. R., Uçar. Z., Siry. J., Merry. K., Cieszewski. C., 2016. Optimisation in Forest Management. Current Forestry Reports , March 2016, Volume 2, Issue 1, pp 1–17.

Keleş, S., 2003. Ormanların Su ve Odun Üretimi Fonksiyonlarının Doğrusal Programlama Tekniği İle Optimizasyonu (Karanlıkdere Planlama Birimi Örneği), Karadeniz Teknik Üniversitesi Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, Trabzon.

Keleş, S., 2018. An Assessment of Hydrological Functions of Forest Ecosystems to Support Sustainable Forest Management, Journal of Sustainable Forestry. ISSN: 1054-9811.

Keleş, S., Karahalil, U., Köse, S., 2005. Ormanların Toprak Koruma ve Su Üretimi Fonksiyonlarının Odun Üretimi İle Birlikte Planlanması (Karanlıkdere Orman Planlama Birimi Örneği). KTÜ, Orman Fakültesi, Orman Mühendisliği Bölümü, Trabzon. KSU Journal of Science and Engineering 8(1).

Kenter, J. O., Reed, M. S., Fazey, I., 2016. The Deliberative Value Formation Model. Ecosystem Services. Volume 21, Part B, Pages 194-207.

Kuhlman, T., 2014. Estimating the costs and benefits of soil conservation. https://www.researchgate.net/publication/40106363.

LINGO, 2006. www.lindo.com. Release (10)29 Nov 10.Chicago.IL 60622.

LINDO, 2017. Examining the Solution Report. LINGO 17 Online User's Manual.https://www.lindo.com/doc/online_help/lingo17_0/index.html?examining_the_solution.htm.

Marlise. S., Grenha, A., 2015. Polysaccharide nanoparticles for protein and Peptide delivery: exploring less-known materials. Advances in Protein Chemistry and Structural Biology. Volume 98, 2015, Pages 223-261.

Masiero, M., Pettenella, D., Boscolo, M., Barua, S.K, Animon, I. Matta, J.R., 2019. Valuing forest ecosystem services: a training manual for planners and project developers. Forestry Working Paper No. 11. Rome, FAO. 216 pp. Licence: CC BY-NC-SA 3.0 IGO.

MEA, 2005. Living beyondour means: Natural assets and human well-being. Retrieved from. http:www.millenniumassessment.org/en/Reports.aspx. Millennium Ecosystem Assessment. Volume 1.

Mesbah, L. A., 2014. Ecosystem Services for a Sustainable, Energy Policy, Vol. 2, No.3.

Mısır, M. 2001. Çok amaçlı orman amenajman planlarının coğrafi bilgi sistemlerine dayalı olarak amaç programlama yöntemiyle düzenlenmesi (ormanüstü planlama birimi örneği ile). Doktora Tezi, Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Tez No: 106506. 144 s.

Mısır, N., Mısır, M., Karahalil, U., and Yavuz, H., 2007. Characterization of soil erosion and its implication to forest management. J. Environ. Biol.28 (2), 185-191 (2007).ISSN: 0254-8704.

Mohammed, A. M. E., 2017. Estimation of the Active Components in Gum Arabic Collected from Western Sudan. International Journal of Science and Research (IJSR). Volume 6 Issue 3. Paper ID: ART20171695.

Mohammed, H. M., 2012. The State of Forest Genetic Resources in Sudan. Forest situation after separation. Report. pp 20-24.

Mohammed, M.H., and Rohle, H., 2011. Gum Talha from Acacia seyal Del. Variety Seyal in South Kordofan, Sudan. Research Journal of Forestry, 5: 17-26.

Morri, E., Pruscini, F., Scolozzi, R., Santolini, R., 2014. A forest ecosystem services evaluation at the river basin scale: Supply and demand between coastal areas and upstream lands (Italy). Ecological Indicators 37, 210–219.

NGWA, 2018. Information on Earth's water, National Groundwater Association. Westerville, OH 43081. United States

Okada, T., Mito, Y., Iseri E, Takahashi, T., Sugano, T., Akiyama, Y.B, Watanabe, K., Tanaya, T., Sugino, H., Tokunaga, K., Kubo, T., Kuwae, T., 2019. Method for the quantitative evaluation of ecosystem services in coastal regions. PeerJ 6:e6234 DOI 10.7717/peerj.6234.

Omer, A. M., 2018. Agricultural Residues for Future Energy Option in Sudan: An Analysis. Ann Adv Chem. 2018; 2: 017-031.

Roussel S., 2019. Ecosystem Services. In: Marciano A., Ramello G.B. (eds) Encyclopedia of Law and Economics. Springer, New York, NY. DOI: https://doi.org/10.1007/978-1-4614-7753-2_711.

Rover, T. De, Persson, T., 2014. The Concept of Ecosystem Services. Integrating the concept of ecosystem services on the environmental impact assessment of the Bunge Quarry. Master Thesis, Uppsala University, Sustainable Management (MSc), 7 pp.

SCA, 2018. Sudanese Customs Authority. Report. Part 3, pp 3-6.

Sharma, C. M, Gairola, S., 2009. Why the Conservation of Forest Soil and Water is Necessary? Academia Arena, 1(6):15-20. (ISSN 1553-992X). Department of Botany, HNB Garhwal University, P.O. Box No. 51, Srinagar Garhwal-246 174, Uttarakhand India.

Sinnar State, 2019. The crop market -Monthly report. Page 2.

Sirelkhatem, R, Gaali, E. E., 2009._Phylogenic analysis in *Acacia senegal* using AFLP molecular markers across the Gum Arabic Belt in Sudan. African Journal of Biotechnology Vol. 8 (19), pp. 4817-4823.

Stolton, S, and Dudley, N., 2007. Managing forests for cleaner water for urban populations. Forests and water. Food and Agriculture Organization of the United Nations. Unasylva No. 229. Vol. 58, 2007/4.

Sulieman, M. S., 1996. Changing forest management strategies in Sudan, a challenge for forestry educational systems. Wageningen Agricultural University. ISBN 90-5485-495-2, pp 6-11.

Tarig, E. M, Maruod, E. M, Manal, A. K, Ahmed, M. E, Moayad, B. Z., 2014. Competitiveness of Gum Arabic Marketing System at Elobeid Crops Market, North Kordofan State, Sudan. World Journal of Agricultural Research, vol. 2, no. 5: 252-256. Doi: 10.12691/wjar-2-5-9.

Thakur, B. K., Gupta, V., 2015. Groundwater Arsenic Contamination in Bihar: Causes, Issues and Challenges. Manthan: Journal of Commerce and Management, Volume: 2, ISSUE 1.DOI:10.17492.ISSN 2347-44440.

Türker, M. F., 2013. Ormancılık İşletme Ekonomisi.Güncellenmiş ve Genişletilmiş.2.Baskı. Trabzon. Pages 172-173.

United Nations, 2019. Energy Statistics Database (Fuelwood)–Sudan. Versionv0.14.6Beta.http://data.un.org/Data.aspxd=EDATA&f=cmID%3AFW%3BtrID%3A1231. Statistics Division.

University of Khartoum, 2016. A ten-year plan for the management of the Okalma forest. Database of the Faculty of Forestry, University of Khartoum-Sudan.

URL-1,.https://www.nation.co.ke/business/seedsofgold/2301238-3934070-jspe7v/index.html. 19th May, 2019.

URL-2, https://thewaterproject.org/water-crisis/water-in-crisis-sudan .Water in Crisis–Sudan. The Water Project.. 17th May 2019.

URL-3, https://tradingeconomics.com/sudan/interest-rate. From the trading economics website. 20th April, 2019.

USGS, 2016. The World's Water. The United States Geological Survey. Reston, Virginia, United States.

Wainwright, J. and Mulligan, M., 2004. Environmental Modelling: Modelling in Forest Management. ISBNs: 0-471-49617-0 (HB); 0-471-49618-9 (PB).

Wangai, P., Burkhard, B., Mueller, F., 2016. A review of studies on ecosystem services in Africa. International Journal of Sustainable Built Environment (2016). IJSBE 136No, of Pages 21.

WEF, 2018. World Economic Forum; Author: Anna Swaithes, Head of Water and Food Security Policy,SABMiller.https://www.weforum.org/agenda/2018/03/food-security-s-social-network.

Weintraub, A., Romero, C., 2006. Operations research models and the management of agricultural and forestry resources: a review and comparison. Interfaces 36 (5), 446457.

William, A. L., 1984. Introduction to Forest Resource Management. Chapter 11 pp 203-205: Basic Linear Programming Concepts. Krieger Publishing Company, 1984 - Technology & Engineering - 298 pages.

World Bank, 2012. The World Bank. Revitalizing the Sudan Gum Arabic Production and Marketing Project. Implementation Status and Results Report. Report No: ISR8088. November 2, 2012.

World Bank, 2016. The World Bank. Revitalizing the Sudan Gum Arabic Production and Marketing Project. Implementation Status and Results Report (COFN-C1320 and TF-94764). Report No: ICR00003537. Agricultural Global Practice. AFCE2. Africa Region.

Yolasığmaz, H. A. 2004. Orman Ekosistem Amenajmanı Kavramı ve Türkiye'de uygulaması: Artvin merkez planlama birimi örneği. Doktora Tezi, Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, 229 s.

Zainal, A. and Isa, M., 1990. The Application of Linear Programming For Forest Land Use and Timber Management Planning With Watershed Considerations In Terengganu, Peninsular Malaysia. Masters of Forestry (Hydrology) (MF), Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis, Oregon, 97331 United States of America. May 18th. 1990.

Zengin, H., 2009. Orman Kaynaklarından Fonksiyonel Yaklaşma İle Çok Amaçlı Faydalanmanın Optimizasyonu. Doktora Tezi, İstanbul Üniversitesi, Fen Bilimleri Enstitüsü, İstanbul.Türkiye. 214 s.

Zengin, H., Bozali, N., Asan, Ü, Destan, S., Değirmenci, A. S., 2011. Ekosistem Tabanlı Fonksiyonel Planlamada Tamsayılı Programlama ile Optimizasyon. 1. Ulusal Akdeniz Orman ve Çevre Sempozyumu, 26-28 Ekim 2011, Kahramanmaraş.

CURRICULUM VITAE

Elharith HAGR was born on January 1, 1992, in Gedaref District of Sudan. After completing primary and secondary education, HAGR enrolled for Bachelor of Science degree in Faculty of Forestry of the University of Khartoum. He worked as a trainer for the Ministry of Agriculture and Forestry of Gedaref state in Sudan, and later as a teaching assistant for one year at the University of Gezira before getting a scholarship from Presidency for Turks Abroad and Related Communities (YTB) to study for his Master of Science degree in Forestry Engineering at Karadeniz Technical University in Turkey. HAGR speaks the English language, Turkish language as well as his mother tongue, which is Arabic.