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Review on the uses, factors, conservation, and restoration measures of *Boswellia papyrifera* trees in Ethiopia and Eritrea: Review

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Abstract. The multipurpose, deciduous tree species *Boswellia papyrifera* grows in a savanna area that stretches eastward from Northern Nigeria to the highlands of Ethiopia and Eritrea. It is a native Ethiopian dryland tree and is well known for producing frankincense, a non-timber forest product. Despite its wide economic, ecological, and social importance, the species is facing serious problems and its area coverage is declining from year to year. Therefore, the objectives of this review paper were investigating some points on the current contribution of the *B. papyrifera* predominated woodlands, its regeneration problems, and future conservation. A series of summaries was prepared for this article's compilation in the form of a critical analysis and discussion, taking into account a variety of perspectives on opposing viewpoints, theories, and methods. Drawing from an extensive collection of literature, the review presents the varieties of ways in which *B. papyrifera* is used, outlines the major factors for its decline, and discusses possible ways of conservation and restoration of the tree's populations. The findings point to uncontrolled tapping of the trees, resulting in their overexploitation, which is being exacerbated by an array of problems with the species regeneration, natural factors such as insects and wind, as well as by climate change. Due to its significance, *B. papyrifera* must be preserved, and the recommended measures include area closures, proper tapping techniques with adequate frequencies, and enrichment planting, supported by rigid regulations.

Keywords: *Boswellia papyrifera*; climate change; frankincense; gum and resin regeneration; restoration.

Introduction

The deciduous tree species *Boswellia papyrifera*, also known as the Sudanese frankincense, grows in a savanna area that stretches eastward from northern Nigeria to the highlands of Ethiopia and Eritrea. The plant is endemic to the Horn of Africa, primarily Ethiopia, Eritrea, and Sudan (Biresaw et al., 2010). It is regarded as a multipurpose tree with substantial ecological and economic benefits (Hassan et al., 2019). Its most well-known product is the valuable oleo-gum resin resin called "frankincense", or olibanum, which is harvested by wounding the bark, a process called tapping (Harrasi et al., 2019; Ogbazghi, 2001; DeCarlo et al., 2019). Due to the papery texture of its bark, the scientific name of the tree translates to "paper-like *Boswellia*". Unfortunately, the plant is endangered by overharvesting and environmental degradation (Harrasi et al., 2019). Furthermore, its population is declining due to grazing and agricultural development (Tadesse, 2020).

According to Abeje et al. (2005), the plant can be found in the *Combretum terminalia* (broad-leaved) deciduous forest and wooded grassland, typically in the 950–1,800 m altitude range on steep rocky slopes, lava flows, or sandy valleys. The species is a versatile deciduous tree that can help reduce desertification and promote economic growth (Mulugeta et al., 2004). Indeed, *Boswellia papyrifera* is the primary commercially significant tree within the Africa's *Boswellia* genus (Anderson, 2012). The many products that *B. papyrifera* offers include poles, lumber, fodder, nectar, and gum, all of which are beneficial for traditional medicine, religious ceremonies, and generating revenue. However, frankincense, a non-timber forest product (NTFP), is the species's most significant and well-known product (Lemenih, 2011). Furthermore, frankincense from *B. papyrifera* is the most traded kind among those harvested from a number of *Boswellia* species. The stem of *B. papyrifera* tree releases a white oleo-gum resin when its bark is cut (Tolera et al., 2013). Frankincense is the term for the globular, pear- or club-shaped tears that form from this emulsion of aromatic oils or resins (Mathe et al., 2004). One to three kilogrammes of frankincense can be harvested from a tree in a year, while the quantity varies depending on the tree's diameter, site productivity, and season (Coppen, 1995). Up until the age of 50–60 years, a tree can still produce resin. Harvested from mature *B. papyrifera* (Del.) Hochst trees in natural woodlands in the Horn of Africa (Tilahun et al., 2011), it is traded globally for the manufacture of incense and perfumes (Mulugeta & Teketay, 2003; Chikamai et al., 2013). The primary producer and world's largest exporter of *B. papyrifera*-derived frankincense is Ethiopia (Abeje et al., 2012).

Boswellia papyrifera flourishes in environments where soil and climate do not provide many opportunities, thereby enabling the productive and economical use of marginal drylands. Therefore, due to the ability to successfully establish and grow under challenging conditions, it is one of the best options to combat desertification, restore degraded drylands, and enable communities in drylands to adapt to potential climate change (Sabo et al., 2022). In Ethiopia, *B. papyrifera* grows on over 1.5 million hectares, mostly on degraded drylands at an altitude between 950 and 1,800 m (Gebrehiwot et al., 2003). Despite its wide economic, ecological, and social importance, the species is facing serious problems and its area coverage is declining from year to year (Ogbazgi, 2001). Moreover, the long-term prospects for a sustained supply of goods and services from the species are disappearing. In fact, *B. papyrifera* species is already listed among endangered species of East Africa that need priority in conservation (Gidey et al., 2020). As a result, the potential range of production from *B. papyrifera* forest communities is significantly diminished, and the species's distribution, abundance, and regeneration status have all been declining in recent years. The absence of the species's natural regeneration and the heightened susceptibility to insects and pests brought on by the over-tapping trend are also serious concerns (Ogbazghi, 2001). Frequent tapping, human-induced fire, overgrazing, and climatic abnormalities are some of the major factors responsible for the degradation of the species and lack of its regeneration (Abeje et al., 2005; Ogbazghi et al., 2006). However, scientific information on natural regeneration and challenges faced by *B. papyrifera*-dominated woodland areas, as well as studies on its ecology and silviculture, is somehow limited (Ogbazghi, 2001; Abeje, 2001). Due to the lack of clear plans and policies for the sustainable development of natural forests in Ethiopia, including *B. papyrifera* stands, there are no clear data concerning the growing stock and the future of *B. papyrifera* stands in Ethiopia. At the same time, the exploitation of frankincense is one of the main sources of income and jobs in Ethiopia's most remote regions, making it a vital source of income for the nation in general and the country's rural residents in particular (Mulugeta et al., 2003).

The objectives of this review paper were considering the major factors related to the decline of the *B. papyrifera* populations in Ethiopia and Eritrea and the species's regeneration problems, and also evaluating the data on its population status and the socioeconomic importance, specifically, to review its distribution and current regeneration status in these countries. Such knowledge helps to understand the scale, relevance and status of associated species and the future impacts of management interventions on *Boswellia* forests. Furthermore, the review and recommendations may assist in the development, sustainable utilization, and conservation of *B. papyrifera* tree species in Ethiopia.

Methodology for the review

A series of summaries was prepared for this article's compilation in the form of a critical analysis and discussion, reflecting a variety of perspectives on opposing viewpoints, theories, and methods. The research goal served as a guide for the synthesis and analysis of the related data and findings from a variety of sources that are connected to the article's theme and logic. By assessing the facts, the review focused on the relationship among the roles, threat, and management of *B. papyifera* trees. Additionally, the review contrasted and compared different perspectives from research papers on the key risks and management strategies for *B. papyifera*. The analysis also pointed out the research gaps that need to be filled in future research. The published research literature from various regions of Ethiopia and Eritrea was systematically searched online. By gathering relevant material from published books, journals, and theses from international scientific databases, the details were obtained.

Background information about *Boswellia papyrifera*

Ecological and climatic description. The indigenous multipurpose tree *B. papyrifera* covers more than 1.5 million hectares in Ethiopia and Eritrea. The ecological distribution of *B. papyrifera* is limited to lowlands that experience hot and dry circumstances. In Ethiopia, it is found in the ecosystem of *Combretum terminalia* woodland. The plant thrives where the yearly temperature is between 25 and 40 °C (with an average temperature of 20 to 27 °C), the elevation range is between 950 and 1,800 meters above sea level, and the annual rainfall is below 900 mm, typically between 100 and 800 millimetres. It grows on degraded sites with sandy river basins, lava flows, steep rocky slopes, and very shallow soils. *Boswellia papyrifera* is also found in *Acacia commiphora* woodlands and has a variety of vegetation relationships (Morka, 2024; Worku et al., 2018). In Eritrea, *B. papyrifera* is mostly found at an altitude between 800 and 1,850 meters above sea level, where the annual rainfall ranges 375 to 700 mm. Its growing season lasts 45 to 100 days (Ogbazghi et al., 2006). Although height, air temperature, and high evapotranspiration, which lower the soil moisture status, had a negative impact on its occurrence, while rainfall and the length of the rainy season had a beneficial impact, the climatic parameters could not be regarded as the only absolute limits (Ogbazghi et al., 2006).

Biological description. Boswellia papyrifera is a member of the Burseraceae family, which includes 17 genera and up to 600 species (Abiyu et al., 2006). There are six species of *Boswellia* in Ethiopia: *Boswellia papyrifera*, *B. neglecta*, *B. microphylla*, *B. ogadensis*, *B. rivae*, and *B. pirrotae*. All known species of *Boswellia* found in Ethiopia, except *B. pirrotae*, are currently harvested for gum-olibanum, with *B. papyrifera* as its main source (Lemenih et al., 2004). *Boswellia papyrifera* trees in the Horn of Africa might grow up to 14–16 m tall and have a maximum diameter at breast height of 51.5 cm. The area is one of the primary locations for the growth of *Boswellia*, and frankincense is commercially extracted there (Abeje et al., 2005). This species is a tiny deciduous tree with a spherical crown, strong branches capped with clusters of leaves, and noticeable vertical resin ducts in the bark.

The tree *B. papyrifera* reproduces sexually and grows back from its seeds naturally (Rijkers et al., 2006). Within the species, seed establishment may vary and seems to be a limiting factor. Insect infestation or a mechanism to improve pollination may cause flower sterility. The fruit set is minimal during open pollination, at roughly 10%. When the embryo reaches maturity, endosperm is absent (Sabo et al., 2022). It has strong, rigid branches with spherical crown leaves and clusters at the tips. The species flowers in October and begins to shed at the beginning of December, while some trees keep their flowers for a considerably longer period of time. It produces leaves during the rainy season, which can occur in April (Tatek et al., 2016). With 11–29 pinnate leaflets, pubescent surfaces, and petioles that are 0.5–4.0 cm long, its leaves are 15–45 cm long. It can yield ten yellow stamens, five petals that are 5–8 mm long, and long red flower stalks that can reach a length of 35 cm. The slash is red-brown and emits a fragrant resin, while the bark is yellowish to pale brown and peels off in huge flakes. Schizogenous oleo-gum-resin pockets can be found in the bark (Dharani, 2011). *Boswellia papyrifera* resin contains resin oil (5–9%), boswellic acids (40–60%), polysaccharides (20–30%), and resin acids (13–17%) (Khan et al., 2016). About 8 to 10 years of age, or when the trunk reaches about 38 cm in diameter at breast height, is when the tree starts to produce resin (Paramanik et al., 2012). Generation length varies by species and is estimated to be 10–15 years for *B. pirottae* and 20–30 years for *B. ovalifoliolata* (Bhakshu et al., 2023). At the same time, *B. papyrifera* can continue producing resin up to the age of 50–60 years. The phonological cycle of the species is mainly controlled by the distribution of precipitation.

Geographical distribution. In Ethiopia, *B. papyrifera* is only found in the dry *Combretum terminalia* broad-leaved deciduous woodlands of dry forests in the north, northwest, and some of the country's largest river gorges in the north (Worku et al., 2018). *Boswellia papyrifera*-dominated woodlands are primarily found in Benishangul-Gumuz, Gambella, Oromiya, Amhara, and Tigray regions, with the tree most extensively used in Tigray (940,000 ha) and Amhara (604,000 ha) (Worku et al., 2018). Available estimates show that approximately 1.7 million hectares of woodlands with *B. papyrifera* as their main species currently occur in three regional states: Amhara, Benishangul-Gumuz, and Tigray. It can be found in drier parts of Africa, from Ethiopia and Eritrea in the east to Nigeria in the west. Ethiopia, Somalia, and Eritrea are where it is most common (Asmamaw et al., 2012). Figure 1 below illustrates the ranges of *Boswellia* species in several nations with varying climatic and geographic conditions.

Population status. The Ethiopian Environmental Protection Authority reports that more than 144,000 hectares of Ethiopian forest are lost each year (WIC, 2002). The primary cause of the rapid depletion and severe degradation of the nation's forest resources is human involvement, mostly for survival and economic purposes. In this context, *B. papyrifera* is no exception. In addition, according to several population assessments of *B. papyrifera* in various geographic locations, the majority of the current population is made up of mature trees. When assessing the condition of tree species in a particular forest region, density and regeneration state are frequently employed indicators (Shahabuddin & Prasad, 2004). The analysis of the population structure of *B. papyrifera* revealed the presence of individualls in smaller diameter classes. Abeje et al. (2005) and Mulugeta et al. (2007) from Metema (Ethiopia), and Kindeya et al. (2003) from Tigray (Ethiopia), and Ogbazghi et al. (2006) and Rijkers et al. (2006) from Eritrea are only a few of the studies that have reported this kind of structure. Nonetheless, in Northern Ethiopia, for example, almost 76% of the current *Boswellia* trees are larger than 30 cm DBH (Kindeya et al., 2002). In all of the aforementioned geographic zones, individuals in the lower diameter classes were underrepresented, while those in the higher diameter classes were overrepresented. Studies observed either none or very few specimens of the lower sizes (seedlings and saplings), suggestsing a severe lack of recruitment through natural regeneration and, consequently, an unstable population of the species (Abeje et al., 2005; Ogbazghi et al., 2006). According to research on *Boswellia* regeneration status thus far, the tree shows poor seedling establishment in its native habitat (Ogbazghi, 2001; Yitebitu, 2002). Moreover, there are factors such as extensive cropping, overgrazing, fire, shifting cultivation, poor resin harvesting techniques, termite infestation, and other insect problems (Tfap 1996; Ogbazghi 2001) (Fig. 2). If the downward pattern persists, there will be no replacements, and the species will probably become extinct after the current old stands are depleted.

Boswellia papyrifera is seen on the map along with the locations of the 23 populations in lowland (red) and highland (blue) locales. Size structures in 3-cm-wide tree diameter classes (minimum diameter, 1 cm) are based on relative abundance (highest class, 1). Size structures reveal that small, juvenile trees (stem diameter <7 cm, grey dashed vertical lines) are frequently absent, possibly as a result of recurrent fires and cattle grazing. Supplementary Table 2 provides site information. Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, The NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and GIS user communities are all credited with creating the Hillshade ecosystem.

Uses of Boswellia papyrifera. From environmental, ecological, social, and religious standpoints, *B. papyrifera* is one of the most significant multipurpose deciduous tree species in Ethiopia and Eritrea. The most important and most traded product of *B. papyrifera* is frankincense, also known as gum olibanum (Coppen, 1995). It has been gathered for a variety of conventional and commercial uses, including liqueurs, detergents, creams, fragrance, medicine, cosmetics, and beverage flavouring (Lemenih & Teketay, 2003). In addition to being employed in the international pharmaceutical, food flavouring, and perfume sectors, frankincense is also chewed, used in coffee ceremonies, and used as traditional medicine by people in Northeast Africa (Ogbazghi et al., 2006). Essential oils derived from *B. papyrifera* gum are utilised in the perfume industry, in the production of paints and varnishes, and as a laxative in the medicinal sector (Ogbazghi, 2001).

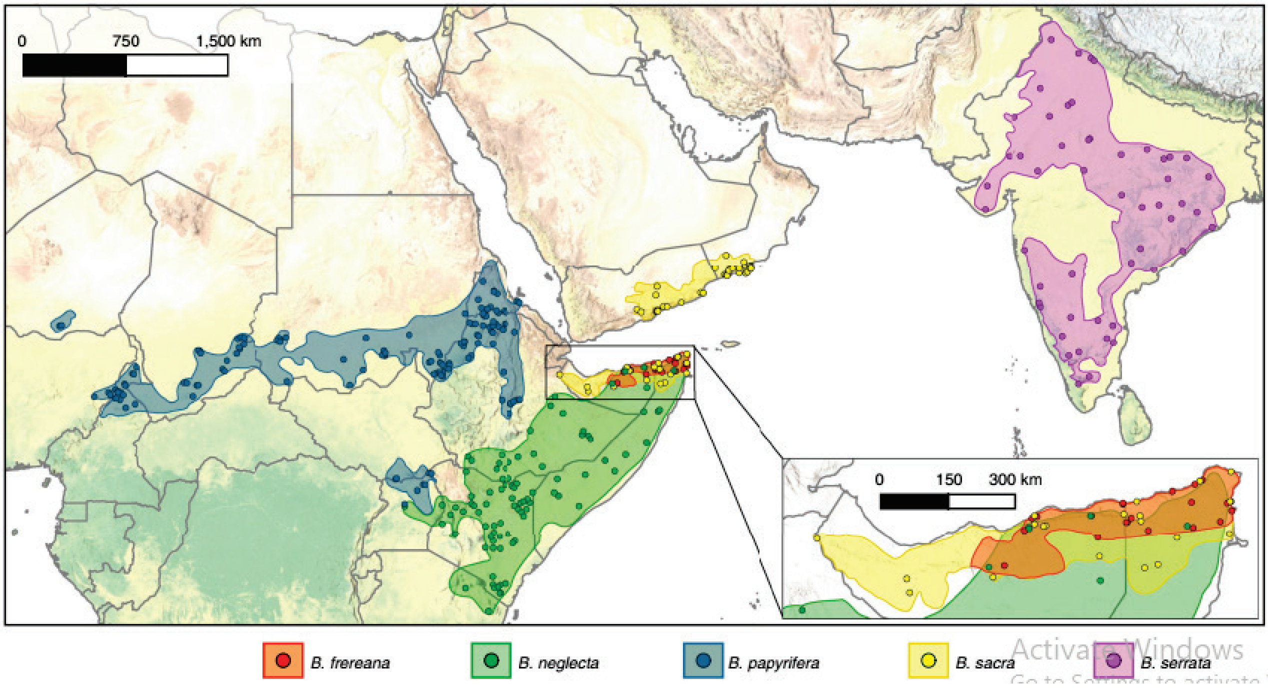

Fig. 1. Distribution *Boswellia papyrifera* tree species around the world (Bongers et al., 2019)

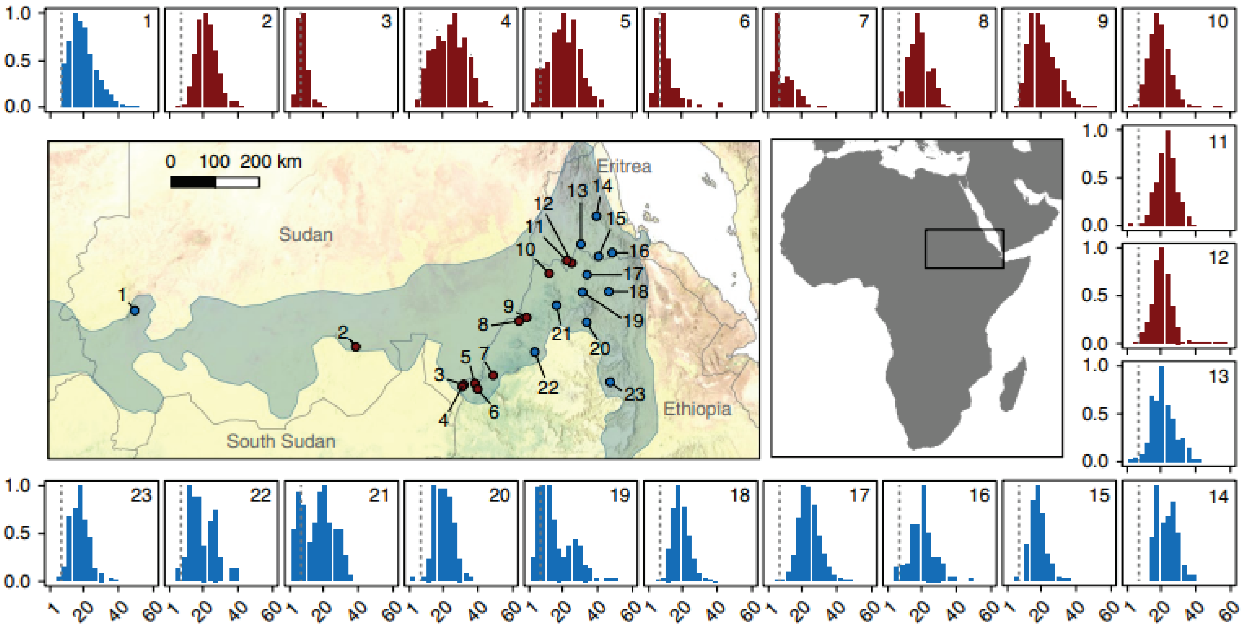

Fig. 2. Distribution and size structures of *Boswellia papyrifera* populations

Despite its many uses, *B. papyrifera* has not yet been cultivated and gum is collected in woods, from trees that grow naturally (Ogbazghi et al., 2006). Gum collecting and commercialisation remain concessionaires' sole rights since the implementation of the concession system in Ethiopia and Eritrea (Tadesse et al., 2020; Lemenih & Kassa, 2011). *Boswellia papyrifera* is essential for a variety of products and services, such as gum, nectar, fodder, lumber, and poles, among others, that are necessary for traditional medicine, revenue production, religious rites, cultural behaviours, and more, as confirmed by Abeje et al. (2012). The numerous uses of *B. papyrifera* and its products, especially frankincense, in the fields of the ecology, economy, climatic conditions, socioeconomics, and religion are thoroughly examined in this section.

A. Environmental, ecological, and climate uses. The leaves and seeds of *B. papyrifera* are highly valued as dry-season feed for camels and other livestock, and almost every part of the tree serves a specific purpose (Gebrehiwot et al., 2003). The fragrant flowers that emerge as the tree sheds its leaves are important sources of nectar for honey bees. Due to its ability to thrive in arid climates and moisture- and nutrient-deficient soils, *B. papyrifera* is among the top candidates for combating desertification, restoring degraded drylands and strengthening their resilience and adaptation, and also for mitigation of climate change in dryland communities (Ogbazghi et al., 2006; Worku & Bantihun, 2018; Lemenih & Teketay, 2004; Abeje et al., 2012). *Boswellia papyrifera* survives in harsh ecological and climatic conditions, thereby enabling drylands to be utilized economically by offering opportunities for production (Abeje et al., 2012). The tree grows in rocky and dry areas where other trees usually fail, including on steep slope gradients reaching 40%, and this ability helps to improve degraded areas and provides economic and social benefits by providing plant cover, biomass, shade, and soil protection (Gebrehiwot et al., 2003).

B. Socioeconomic uses. Boswellia papyrifera and other gum- and resin-producing trees, such as *Acacia*, *Boswellia*, and *Commiphora* species, have real and potential socioeconomic and environmental significance for local communities and merchants, as they provide a large number of job opportunities (Gebrehiwot et al., 2003; Abeje et al., 2005; Gidey et al., 2020), and because gum and resin or incense products are sold for cash income on both domestic and foreign markets (Getahun and Kebede, 2020). The gum known as frankincense, or olibanum, is used for commercial purposes, while the wood stem of *B. papyrifera* is used for poles and lumber in Ethiopia and Eritrea, its leaves for fodder, and its flowers for beekeeping (Gebrehiwot et al., 2003; Ogbazghi et al., 2006). According to Gebrehiwot et al. (2003), the stem, leaves, and seeds of *B. papyrifera* are highly valuable as feed for livestock, including goats, camels, and other. The light and rather soft stem wood of *B. papyrifera* is used for plywood, picture frames, veneers, matchboxes, pencils, and furniture (Gebrehiwot et al., 2003; Zinaw, 2012). Rural populations use *B. papyrifera* wood for poles and timber (Ogbazghi, 2001). *Boswellia papyrifera* pink-scented flowers are used by honeybees for pollen and nectar, especially during the extended flowering season from October to February, which is ideal for starting a bee colony (Gebrehiwot et al., 2003). According to Gebrehiwot et al. (2003), honey from *B. papyrifera* growing regions is often of high quality.

Both male and female rural farmers can find off-farm work options by collecting the resin (Gebrehiwot et al., 2003; Alemu et al., 2015; Worku & Bantihun, 2018; Lambrecht & Mahrt, 2022). For example, in Northern Ethiopia, women also help in sorting and grading frankincense, whereas men are primarily responsible for tapping and collecting it (Gebrehiwot et al., 2003; Alemu et al., 2015). A taper can earn 100–150 USD by collecting 1,000–1,500 kg of frankincense, while women can make an average of 160 USD during ten months of off-farm work (Aregawi, 1997; Gebrehiwot et al., 2003).

C. Religious and medicinal uses. Boswellia papyrifera is said to be the source of the ancient frankincense, which has been used for millennia in a variety of religious rituals. Its scent is thought to improve meditation and spiritual experiences (Ogbazghi et al., 2006; Fatima et al., 2024). From ancient Egypt (3000 BC) to the present day (Fatima et al., 2024), frankincense resin has been used extensively for burning incense, for example in church ceremonies and religious practices around the world (Demissew, 1993; Coppen, 1995; Göttsch, 1986). The Romans and Greeks, respectively, connected frankincense with sacrifice in the second and sixth centuries BC (Göttsch, 1986). Since the Kingdom of Aksum in 500 BC (Goldschmidt, 1970) to the current day in the Orthodox Church (Göttsch, 1986), incense has been utilised for religious ceremonies. According to the Bible, frankincense is a holy substance that is offered to God in worship (Exodus 30:34) and was one of the three gifts that the Three Wise Kings (Magi) gave to the baby Jesus (Matthew 2:11). In order to provide a pleasant scent that represented the prayers of the peoples ascending to God, it was frequently burned during church, tabernacle, or temple sacrifices and ceremonies (Revelation 8:4). The tradition of burning incense (frankincense or hardened resin) in churches dates back to the early days of Christianity and is still performed in the largest and oldest Orthodox and Catholic churches in the world (Gebrehiwot et al., 2003). For example, it is estimated that over 2 million kilogrammes of frankincense are used annually by more than 15,000 Ethiopian churches, or 150 kg each church annually (Gebrehiwot et al., 2003; Worku et al., 2011). In Ethiopia (Gebrehiwot et al., 2003; Eshete et al., 2012; Wyk, 2015) and Eritrea (Girmai et al., 2016), *B. papyrifera* is also utilised in traditional medicine. Frankincense leaves and roots, and bark, are utilised as traditional remedies for a variety of ailments (Ogbazghi, 2001). According to Gebrehiwot et al. (2003), *B. papyrifera* is used for stimulation, its roots and leaves are used to treat lymphadenopathy or swollen lymph nodes; its resin is used as a febrifuge; its bark treats stomach problems and quenches thirst when chewed, and when burned it repels mosquitoes in the tropics.

Major factors for the decline of *Boswellia papyrifera*

Expansion of farming system in the woodland. Environmental concerns have been raised due to the decline in *B. papyrifera* populations in Eastern Africa (Marshall, 1998; Woldesilassie, 2001). There is strong evidence that populations of *B. papyrifera* in Ethiopia (Abrham et al., 2010; Bantihum & Azene, 2018), Sudan (Abrham et al., 2010; Paramanik et al., 2012; Gessmalla et al., 2015), and Eritrea (Ogbazghi et al., 2006) have been declining in recent decades. It is believed that immigration, both sponsored (resettlement) and spontaneous (Kindeya, 2003; Mulugeta et al., 2007), as well as the ongoing flow of immigrants from the country's highlands, are the main causes of the degradation of the woodlands dominated by *Boswellia*. The presence of extensive woods, with rich soil and ideal climate for growing cash crops like cotton and sesame, is what drives these influxes. In addition, because *Boswellia* forests offer the possibility of higher economic returns from future land use alternatives, farmers have favoured land inside the forest. Thousands of immigrants from all across the country, particularly from the surrounding highlands, have been drawn to these opportunities. Immigrants have a propensity to cultivate larger areas, and there seems to have been extensive land grabbing in the area (Dejene et al., 2010). Such utilization of the land resources drives clearing of the woods and their conversion to other land uses. Groenendijk et al. (2012) predict that if harvesting continues at its current pace, the yield of *B. papyrifera* in Ethiopia will drop by 50% over the next 15 years, and the population as a whole would decline by 90% over the following 50 years. In fact, over 177,438 hectares of *B. papyrifera* woods have been lost in Northern Ethiopia over the past 20 years. For comparison, in the late 1970s, *B. papyrifera* covered over 510,000 hectares of land in Tigray alone (Kindeya et al., 2003).

Extensive tapping and overexploitation. According to Ebuen (2016), the population declines observed after several years of monitoring in various countries where the bulk of *Boswellia* is found were caused by improper tapping techniques, which lead to trees being overtapped and overharvested year-round (Hassan, 2012). According to numerous studies, the trees are being overharvested in Ethiopia and Eritrea to satisfy the global demand for *B. papyrifera* (Abrham et al., 2010; Mengistu, 2011). Moreover, the Boswellia trees are also being overharvested in other countries, for example, Djibouti (Abdoul et al. 2012). Inappropriate tapping techniques could involve girdling the tree with cuts that are too long or too deep. According to Rijkers et al. (2006), tapping decreases the seed viability and yield of *B. papyrifera*. This tree is negatively impacted by tapping in a number of ways. Nonviable seeds are produced as a result of intensive tapping. At the same time, the absence of juvenile and sapling size classes is a characteristic of overharvested populations. Poor regeneration is indicated by the high mortality rate of mature trees and the scarcity of young trees and saplings in populations throughout the ranges of this species (Ogbazghi et al., 2006). According to Ogbazghi (2001), the germination rates for seeds from the tapped stands in Eritrea are low, equaling 14% and 16%, as compared with 80% from the untapped stands. Excessive tapping has produced seeds that are not viable or lack embryos, which has resulted in a very low recruitment of seedlings. The resin flows continuously when tapping is done during the wet season. According to reports, the resin that has accumulated on the stems can air dry, leaving the plants vulnerable to fire (Abeje, 2002). Compared with healthy trees, overtapped trees have a decreased pollination rate (16%) (Rijkers et al., 2006). Sunnichan et al. (2005) discovered that tapped trees had less fruit set. Poor harvesting practices are a substantial factor of the species decline (Oqbazghi, 2001; Abdoul et al., 2012), and therefore tree tapping and collection techniques need to be updated for long-term tree protection (Hassan, 2012). Tests of germination using temperature and water availability combinations revealed that germination would not be an issue if it were required for planting or research. Research has demonstrated that *B. papyrifera* has few or no issues with dormancy (Tilahun & Legesse, 1999).

Overgrazing. The natural regeneration of *B. papyrifera* has been harmed by uncontrolled overgrazing. Goats and other livestock are reported to have a strong preference for *B. papyrifera* seeds and seedlings. In addition, cattle caretakers defoliate the leaves for fodder when the rains begin, while goats and cattle consume the bark during the dry season. Animals that browse and graze enjoy the succulent stem of *B. papyrifera* seedlings. Furthermore, *Boswellia* is susceptible to grazing and trampling because of its extremely sluggish germination (Ogbazghi, 2001). When *B. papyrifera* seedlings are grazed, all of their aboveground vegetative portions are completely removed, making survival challenging. The fact that saplings have a greater survival rate than juveniles suggests that livestock generally has a more detrimental influence on juveniles. According to several studies, seedling establishment was superior in the fenced or enclosed experimental plots compared with the areas that were openly grazed. For example, seedlings in Eritrea reached a maximum height of only 15 cm and a basal diameter of 1.5 cm in just three years (Ogbazghi, 2001). The chance of being eaten, stomped underfoot, or harmed is increased by this prolonged juvenile stage. Fire is another risk in this regard, as it can kill the majority of seedlings. Other risks include the use of wood for fuel (Abeje, 2002). Another concern is the ability of grazing to alter a vegetation's floristic makeup. Thus, it is clear that protection from a variety of biotic disturbances, such as livestock grazing, has increased the number of seedlings in area closures.

Insect infestation. A serious threat to *Boswellia* tree species is insects (Ogbazghi, 2001; Abdoul et al., 2012). Termites are a regular and widespread issue in the region (Gebremedhin, 1997; Kineya et al., 2003). In addition, numerous beetle species that burrow into living trees can attack this plant. Furthermore, Abeje (2002) found that an unidentified worm caused more damage to the tapped trees in Gondar than to the uncapped stands. According to research on seed quality assessment, insects attacked roughly 18% of the seeds in Ethiopia and between 20% and 25% of the seeds in Eritrea (Ogbazghi, 2001). Insects that consume wood weaken trees, making them more vulnerable to disease and causing the high adult mortality rates seen in *Boswellia* populations (Groenendijk et al., 2012). In three populations in Sudan, over half of the seeds produced were infected and therefore not viable. Based on the viability analysis of the seeds gathered at the research locations, a significant portion of the seeds are lost due to sterility or insect damage (Tayeb & Adam, 2008). While the insects harming *Boswellia* trees in Ethiopia lack research, at least three tree-burrowing beetles, including *Sphenoptera chalcichroa*, are found in Oman. Their larvae burrow beneath the bark and bore into the trunks of living trees, while their eggs are laid in the bark wounds. Bugs or other creatures raise seedling mortality. The damaged twigs and debarked stems provide the beetles with a place to lay their eggs and allow them to hatch (Negussie, 2008). The combined effect of termites and beetles will accelerate the demise and fall of these trees when they begin to dry up.

Wind. Another element that can harm *Boswellia* trees is wind. *Boswellia papyrifera* tree stands frequently experience wind-induced uprooting since the plants have shallow roots that do not extend far into the ground. All of these causes have contributed to the unregulated conversion and uncontrolled use of forests dominated by *B. papyrifera*, which has caused widespread deforestation and degradation. Therefore, these issues need to be addressed in order to rehabilitate damaged *Boswellia* sites and ensure sustained production of the species in Ethiopia.

Climate change. The *B. papyrifera* tree population and growth have declined due to climate change, primarily because of factors such as increased drought conditions, decreased precipitation trends, high rainfall variability, and extreme temperatures in its already arid native habitats. This could result in a decrease in the amount of frankincense resin available. In addition, human pressure and environmental degradation, which are the primary causes of the rapid reduction in *B. papyrifera* trees (Lemenih et al., 2014; Gidey et al., 2020), can be made worse by climate change and increasingly frequent extreme climate events (Madera et al., 2024). These consequences also endanger the livelihoods of people that depend on frankincense production (Madera et al., 2024), with some studies even predicting that up to half of frankincense production may shrink within the next 20 years (Tolera et al., 2013; Lemenih et al., 2014). In tropical woodland systems, *B. papyrifera* trees adapt differently to local climatic conditions; however, climate change may alter the leaf-bearing season, which could impact resin yield and crown carbon acquisition (Mengistu et al., 2012). The January–March tapping season in Ethiopia yields the largest harvest of frankincense (Abeje et al., 2012; Cherenet et al., 2020). These yields can be affected by variations in rainfall between and within years and shifts in seasonal rainfall patterns such as earlier or later onset and cessation. Additionally, changing the tapping season may influence yield outcomes. The most prevalent drought conditions in recent years have been reported as a result of extremely low March–May rainfall in the majority of East African countries (Taye & Dyer, 2024), including Eritrea and Ethiopia, which have been experiencing a notable increase in drought conditions (Mera, 2018; Measho et al., 2019; Mulualem et al., 2024). Variability in rainfall and warming temperatures may lead to more frequent and severe droughts, which might impede the trees' capacity to produce resin, resulting in stunted growth and death. Accordingly, the amount and quality of frankincense resin that the trees produce can be greatly decreased by drought stress. As climate zones change, *B. papyrifera* optimal habitat distribution may also vary, which could result in a population decline in regions that are currently prospering. The environmental services that *B. papyrifera* offers, such as soil stabilisation, carbon sequestration, and biodiversity support, will also be disrupted. Another serious concern for the health and regeneration of *B. papyrifera* is that climate change could foster the development of pests and diseases. All these changes, driven by global warming, may result in significant price increases, as *B. papyrifera* populations will be declining.

Conservation and restoration measures for *Boswellia papyrifera*

The protection of *B. papyrifera* forests will be based on their biological and economic functions. Due to a number of interconnected issues, *B. papyrifera* has been declining in various locations. It has been over ten years since its seedlings were last observed. The regeneration of the woodland and the growth of saplings are the initial functions of the alternatives for sustainable ecological restoration that are taken into consideration. Stakeholders agreed that the alternative's beneficial ecological responsibilities would enhance the livelihoods of the stands, and therefore the production of frankincense from the woodland over time in a sustainable manner. These approaches were cited as successful strategies for the long-term preservation of degraded forests in other countries. Compared with the woodlands under nonexclosures with a continuous tapping history, the *B. papyrifera* woodlands in exclosures with a slight tapping resting period (5–10 years) produced more foliage, fruits, and viable seeds, had a stable population structure, higher regeneration, and frankincense yield, and expirienced fewer pest and fire attacks (Gebrehiwot et al., 2003; Rijkers et al., 2006; Negussie et al., 2008, 2018; Tilahun et al., 2011; Abeje et al., 2012; Alemu et al., 2012). In order to achieve this, various alternative livelihood sources need to be introduced to the woodland, including gathering non-timber forest products (NTFP) such as grass, dead wood, honey, and medicinal plants. It has been recognised that these alternate forms of income help preserve dryland forests (Lemenih & Kassa, 2011; Tadesse et al., 2020). According to many studies (Abiyu et al., 2006; Ogbazghi et al., 2006; Abeje et al., 2011; Tolera et al., 2013; Lemenih et al., 2014; Negussie et al., 2018), these are necessary for the sustainable conservation of *B. papyrifera* woodlands. Incorporating various stakeholders with conflicting interests is also necessary to conserve *B. papyrifera* woodlands in a sustainable manner in terms of ecological, economic, and biological criteria (Abiyu et al., 2010; Lemenih & Kassa, 2011; Tilahun et al., 2011; Mekonnen et al., 2013; Derero et al., 2018; Negussie et al., 2018; Bongers et al., 2019). Free grazing and excessive tapping (without resting period for frankincense production) were also taken into consideration as the main hazards to the development of the alternatives as a result of these activities. Additionally, comparable processes were used to create the standards by which the alternatives were judged. While the frankincense companies wish to preserve the woodland for frankincense production, the local community needs to use it as extra pastures for animal grazing. Following recommendations from the literature, the options were developed, stakeholders made statements, and their representatives were democratically chosen. The economic factors were examined, such as their involvement in maximising livelihoods through the sustainable production of frankincense. The alternatives' functions in reducing pest attacks on the woodland were also taken into account according to the biological criteria.

Adult trees in *B. papyrifera* populations throughout the species's range in Ethiopia and Eretria still exhibit high levels of genetic diversity. The majority of the current *B. papyrifera* populations are now smaller, geographically dispersed, and do not have recruitment of new tree generations, so the demographic threats should not be disregarded (Abeje et al., 2011; Groenendijk et al., 2012; Tolera et al., 2013). The majority of existing variation should be preserved through sampling for conservation and *in situ* management of genetic resources. While maintaining within-population diversity, sizable core populations should be conserved, which will not lose variety as a result of genetic drift, and conserving among-population diversity should concentrate on maintaining the most genetically different populations (Namkoong, 1988). Because damaged adult *B. papyrifera* populations under human-influenced landscapes nevertheless retain genetic diversity comparable to that of the once-continuous forests, their conservation importance should not be undervalued. To ensure that genetic diversity is preserved for future generations, active enrichment planting is necessary for the *in situ* or *circa situm* (conservation in human-influenced landscapes) management of such depleted populations. This includes planting new trees in areas between existing populations, as well as within existing populations to replace dying old trees. The population in Afar may merit special attention for conservation efforts due to its geographic isolation, population decline, and the capacity to thrive in hard climatic conditions, even though very limited genetic data has been collected thus far. It is unknown how the region's changing climate, including rising temperatures and decreasing and erratic rainfall (Joanne et al., 2005), may affect the species's population dynamics, including regeneration, population growth, and ecological range shift. Climate change trends, however, are predicted to cause dryness to spread in desert regions like Afar Bir Hale, raising the possibility of population decline and eventual local extinction. The preservation of this population *ex situ* in laboratory and field gene banks is therefore highly recommended, in addition to the more popular *in situ* conservation. Establishing proof-of-concept trial plantations in each of the four locations is necessary to preserve all local and regional genetic variation *ex situ* and to use these as source populations for upcoming breeding programs, as indicated by the strong correlation between the genetic clustering and highly varied environmental conditions. People must act quickly if they continue to value frankincense as a commodity for both domestic and international markets. In the context of Ethiopia and Eritrea, the following pertinent conservation and restoration methods should be applied correctly.

Area closure to facilitate natural regeneration. From ecological and commercial standpoints, *B. papyrifera* has enormous potential. But because of both natural and man-made influences, its population is in a catastrophic state of degeneration. In order to restore these forests, it should be a priority to provide protection for *B. papyrifera* seedlings that have been regenerated. Degraded woods that include *B. papyrifera* are subject to two significant demands: prompt environmental restoration and the timely supply of tree products. Small seedlings and new regenerations of *B. papyrifera* are negatively impacted by excessive grazing. It makes survival difficult by destroying all aboveground vegetative portions. Although the benefits of encouraging natural regeneration through confined spaces are widely acknowledged, additional factors that affect *B. papyrifera* natural regeneration must be addressed (Kineya et al., 2002; Moges & Kindu, 2006). The primary tasks to be carried out are plantations and area closures in order to recover the rapidly declining *B. papyrifera* population. Environmental restoration has benefited from recent initiatives to use closed areas in dry deciduous woods (Kineya et al., 2003). *Boswellia papyrifera* seedlings, sprouts, and saplings require protection because they are vulnerable to fire, browsing, and trampling. Seedling mortality during the dry season significantly reduces the potential of natural regeneration for *B. papyrifera* woodlands, despite the fact that those enclosure practices can reduce soil degradation, free trees and seedlings from browsing pressure, and are thus crucial for forest rehabilitation (Ogbazghi et al., 2001). Therefore, area closures and plantations are the primary means of reversing the rapid decline in the *B. papyrifera* population.

Proper tapping frequency and tapping intensity. Adult trees have been harmed by improper tapping because it exposes them to worms, fire, and other threats (Abeje, 2002). Moreover, an intensive tapping system has a negative impact on seed output. Given the socioeconomic circumstances associated with the species, a total ban on tapping would be impractical. To prevent harm to the biology of the *B. papyrifera* trees and the nearby seedlings during incense harvesting, the current conventional tapping methods must be modified (Kineya et al., 2003). For example, less strenuous technique include incorporating rest periods and lowering the number of tapping points per tree and the frequency of tapping every season. According to Mulugeta & Hailemaryam (2009), market connections may also provide farmers with an economic incentive to maintain the environmental benefits provided by woodlands and manage dry forests sustainably. Successful frankincense-based company development at the local level also requires building stronger local institutions where the community takes the initiative and creating long-lasting market connections. Furthermore, to reduce harm to trees and seedlings during incense harvesting, stringent regulations and law enforcement measures are required (Sintayehu et al., 2020).

Enrichment planting to support natural regeneration. According to Tatek (2008), enrichment planting should be used in conjunction with area closure. However, to date, it has not received much attention. Additional silvicultural work is required to support plantings. As mentioned previously, *B. papyrifera* is especially vulnerable at young stages. Accordingly, it is necessary to look into the particular needs of *B. papyrifera* seedlings with regard to seed collection, nursery life span, planting time, and post-planting care (Gebrehiwot et al., 2002). *Boswellia papyrifera* seedlings are being raised by several nurseries in Ethiopia for enrichment planting. However, there has not been much success. In Northern Ethiopia, for instance, only 4.5% of nursery-raised seedlings planted in the field in 1999 and 8.7% in 2000 have survived (Kindeya et al., 2002). Eritrea also reported a similar low survival rate (Woldesellasie, 2001). A significant contributing factor is the lack of understanding about the species's silviculture, including when to collect seeds, how to nurse them, where to plant them, and how to care for them after planting. Although establishment and growth statistics are not yet available, *Boswellia* is now being planted in areas by a number of governmental and non-governmental sectors (Toussaint, 2005). Therefore, to aid in rehabilitation, careful attention must be paid to artificial regeneration through enrichment planting or seed addition. Lastly, to preserve the seed vitality in *Boswellia* forests, especially in Northern Ethiopia, resin overexploitation must be prevented (Rijkers et al., 2006).

Conclusion

The species *B. papyrifera* is crucial to the ecological and economic health of dryland regions around the world. From the small community to the national level, it has a variety of socioeconomic, environmental, traditional, and household significances. However, based on the findings shown here, the forest region of *B. papyrifera* is dealing with a number of issues, and the trees' survival is in jeopardy. Numerous natural and man-made factors are contributing to the species's rapid population decline. The indicators unequivocally demonstrate the high incidence of tree loss and vegetation deterioration in the locations. In addition to naturally occurring conditions, human-induced pressures cause the habitat of *Boswellia* to rapidly disappear. Therefore, for the benefit of the local national communities, efforts should be made to conserve, restore, and produce *Boswellia* resources in a sustainable manner. In the regions of the nation where *B. papyrifera* is grown, silvicultural research on alternate propagation techniques, seed collection, nursery procedures, selecting suitable planting locations, and post-planting care should be enhanced. For example, lowering tapping intensity and permitting rest periods should be put into practice. Robust regulations and law enforcement measures should be implemented to lessen the harm that resin harvesting causes to trees and seedlings. Furthermore, to encourage natural regeneration, area enclosure techniques involving enrichment planting must be reinforced. Lastly, the restoration of Ethiopia's *Boswellia* woodland should start right away with the provision of management treatments for regenerated seedlings and the previously closed regions.

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