Cost benefit analysis for *Grevillea robusta* in Ethiopia: linking establishment of a breeding seedling orchard to the economic returns of quality plantings

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WORKING PAPER 6

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CIFOR-ICRAF

Working Paper 6

DOI: 10.17528/cifor-icraf/008579

Pedercini, F., Dawson, I.K., Lillesø, J-P.B., Moestrup, S., Nørgaard, C.T., Abiyu, A., Eshete, G., Jamnadass, R. and Graudal, L. 2022. *Cost benefit analysis for* Grevillea robusta *in Ethiopia: linking establishment of a breeding seedling orchard to the economic returns of quality plantings*. Working Paper No. 6. Bogor, Indonesia: CIFOR; Nairobi, Kenya: World Agroforestry.

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We would like to thank all donors who supported this work through their contributions to the CGIAR Trust Fund: https://www.cgiar.org/funders/

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List of abbreviations and acronyms

AGB	Aboveground biomass
AY	Actual yield
BGB	Belowground biomass
BRA	Branch biomass
BSO	Breeding seedling orchard
CABI	Centre for Agriculture and Bioscience International
CRGE	Climate Resilient Green Economy
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CYG	Closing the yield gap
DBH	Diameter at breast height
EFCCC	Environment, Forest and Climate Change Commission
ETH	Ethiopia
FDRE	Federal Democratic Republic of Ethiopia
GxE	Genotype-by-environment interactions
H	Height
ICRAF	World Agroforestry
ID	Identification
ILO	International Labour Organization
IRR	Internal rate of return
IUCN	International Union for Conservation of Nature
KEN	Kenya
LRO	Landscape Restoration Option
MAI	Mean Annual Increment
masl	metres above sea level
NICFI	Norwegian International Climate and Forest Initiative
NPV	Net present value
NSW	New South Wales
PATSPO	Provision of Adequate Tree Seed Portfolios
PY	Potential yield
QLD	Queensland
RMSE	Root mean square error
RNE	Royal Norwegian Embassy
RWA	Rwanda
SD	Standard deviation
TB	Total biomass
TSC	Tree Seed Centre
UGA	Uganda
UNDP	United Nations Development Program
USD	United States dollar
Vu	Volume under bark

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Acknowledgements

The authors gratefully acknowledge the support of CGIAR funding partners through the CGIAR Research Program on Forests, Trees and Agroforestry (https://www.cgiar.org/funders/). We specifically acknowledge Norway's International Climate and Forest Initiative that supported the writing of this working paper through funding to the Provision of Adequate Tree Seed Portfolios (PATSPO) initiative (http://www.worldagroforestry.org/project/provision-adequate-tree-seed-portfolio-ethiopia) implemented by ICRAF in collaboration with EFCCC and the University of Copenhagen. In addition, our thanks go to Betty Rabar for editorial support in the production of this study.

Abstract

This study was developed in the context of the Provision of Adequate Tree Seed Portfolios (PATSPO) initiative in Ethiopia. PATSPO aims to strengthen the existing tree-seed system by ensuring access to high-quality tree germplasm. Here, we estimate the socioeconomic impact of establishing a breeding seedling orchard (BSO) and distributing quality planting material of the tree *Grevillea robusta* (grevillea) in Ethiopia. Grevillea is a commercially important and popular agroforestry tree species grown in East African smallholder farms. Our study starts by modelling tree growth with a one-parameter regression fitted to literature-sourced growth characteristics. For the purpose of modelling, we identify three 'quality scenarios' (related to the germplasm used) and two 'planting options'. Based on the model's outputs, we investigate the effects of increased tree productivity on farmland economy, on the provision of environmental services, and on the wider forestry sector. Findings are outscaled based on the demand for grevillea planting material in Ethiopia and an assumed reach of PATSPO-derived high-quality germplasm. Our growth models indicated that higher than baseline quality scenarios could produce a significant increase in volume (and biomass productivity). This resulted in several-fold increases in the net present value over the production cycle of agroforestry and woodlot plantings, as well as significant benefits in other economic indicators. At the country scale, our analysis estimated that after 50 years the increase in cumulative net present value of on-farm grevillea plantings should be between Birr 2.7 billion and 1.9 billion when using high-quality germplasm compared to an unimproved germplasm baseline, a significant boost (38 Birr = 1 USD at the time of calculations in 2021). We therefore reveal that establishing a grevillea BSO in Ethiopia could produce significant economic returns for tree growers that are much higher than the initial investment that we determine to be required. Furthermore, using BSO germplasm compared to an unimproved germplasm baseline could over 50 years after the BSO's establishment sequester an extra 1.7 million tonnes of CO2 equivalents annually and achieve an increase in net present value annually of Birr 44 million in roundwood milling into sawnwood. In summary, our current analysis indicated that a focus on grevillea's germplasm quality is predicted to bring significant economic and environmental benefits in Ethiopia. Our approach to estimate the benefits of using quality germplasm in tree planting represents an advance on previous methods and can be widely applied to a broad range of species, production systems and locations.

1 Introduction

Ethiopia is rich in forest ecosystems, with high levels of endemism and significant intra-specific diversity in trees and other organisms (Friis, 1986; Friis et al., 2010; Husen et al., 2012). The conservation of its forest ecosystems is however threatened by intense anthropic pressures such as illegal harvesting, land degradation, soil erosion, overgrazing and forest conversion (Bishaw, 2001; Lanckriet et al., 2015). The root causes of this crisis include the institutional instability of the forestry sector, land tenure insecurity, population growth and widespread poverty (Tadesse et al., 2020). Degraded forest ecosystems are especially found in the Ethiopian highlands, where population density is higher (Yesuf et al., 2005; Lanckriet et al., 2015).

The Ethiopian economy relies heavily on the agricultural sector, which currently employs approximately 66% of the total population (International Labour Organization [ILO], 2020) and, together with forestry, contributes 43% of the country's gross domestic product (FDRE, 2015). Ethiopian farming systems are however largely based on rainfed agriculture (Pistorius et al., 2017) that increases their vulnerability to climate change and ecosystem degradation (FDRE, 2015), making the protection of forest ecosystems more vital. In terms of communities' reliance on forest products, a recent study by UNDP (2017) estimated that around 57 million Ethiopians depend on one or more for their full-time or part-time income. The gross value per household per year of different forest products (e.g., fuelwood, construction wood, traditional medicine, etc.) was estimated at a considerable (for a low-income economy) USD 393 (2015 figures).

Restoring Ethiopia's forest landscapes is necessary to safeguard communities whose livelihoods depend on this natural resource base (Tadesse et al., 2020). In 2011, the Ethiopian government initiated the Climate Resilient Green Economy (CRGE) strategy, a cross-sectoral green growth approach to become a middle-income country with a net-zero increase in greenhouse gas emissions from 2010 levels (FDRE, 2011). One key climate mitigation strategy of the government's plan is to increase forest cover by implementing afforestation, reforestation and sustainable forest management. Tree-planting activities are being carried out to re-green the degraded landscapes of Ethiopia in order to enhance the provision of tree socioecological services. One leading example is in response to the Bonn Challenge, a multilateral initiative to which the government of Ethiopia has pledged 15 million hectares of land to be restored by 2030 (IUCN, 2021).

Access to high quality native and exotic tree seeds and seedlings is essential to support the effective implementation of large-scale tree planting efforts (Dedefo et al., 2017; Sisay et al., 2020). The inadequate quality of tree germplasm currently available in Ethiopia, however, hinders the growth of the forestry sector (World Bank, 2017).

Thanks to a collaboration between the Environment, Forest and Climate Change Commission (EFCCC) of Ethiopia and World Agroforestry (ICRAF), the Provision of Adequate Tree Seeds Portfolio (PATSPO) project was initiated in 2017 to help tackle the country's tree seed and seedling sourcing challenge. PATSPO is funded by the Norwegian International Climate and Forest Initiative (NICFI) through the Royal Norwegian Embassy (RNE) in Ethiopia. It aims to strengthen the existing national tree-seed system by ensuring access to high-quality tree germplasm for a selection of priority tree species that embraces many indigenous species as well as some particularly useful exotic ones. The listing of tree species selected for action by PATSPO was based on a combination of factors, including the demand for planting of the species, their economic value and their ecological roles.

The impact of PATSPO is expected to be outscaled by the restoration efforts currently underway in the country. Tree-planting is a baseline activity linked to several landscape restoration options (LROs), including agroforestry, small-scale plantations (known as woodlots), and commercial plantations. The most suitable LROs depend on a set of landscape-specific variables such as current land cover, farmers' preferences, and land use rights, that define what type of restoration activity can be implemented at a specific location. Most LROs can be implemented by active tree-planting, to remedy the lack of a diverse soil tree seed bank in the majority of degraded locations, or by assisted natural regeneration in less degraded areas. In Ethiopia, most of the needed tree germplasm currently is sourced from poor quality informal sources and private nurseries, with only a small portion coming from government and other improved sources (Lillesø & Derero, 2019). Considering Ethiopia's ambitious restoration targets, the role of PATSPO is key, not only to ensure the provision of quality planting material, higher livelihood benefits for communities and the increased adoption of restorative measures, but also to conserve the country's forest biodiversity, through restoration and substitution of product sources.

PATSPO has commissioned research studies to estimate the ecological and economic benefits of the initiative's implementation. By using economic and ecological indicators, van Schoubroeck et al. (2022) estimate the potential socioecological impact of PATSPO through an ex-ante impact assessment. The study defines a set of hectare-based LROs to investigate their economic feasibility and ecological value. The metrics used in the assessment include net present value, job generation, carbon sequestration and soil conservation. The findings also consider expert knowledge and the available scientific literature. In an earlier study commissioned by PATSPO (Lillesø & Derero, 2019), the tree seed market in Ethiopia was assessed, the most popular tree species identified, and an action framework outlined for upgrading the existing tree seed system nationally.

In the current parallel study to van Schoubroeck et al., we estimate the socioeconomic impact of establishing a breeding seedling orchard (BSO, used to produce high-quality tree seed, further defined below) of the exotic tree species *Grevillea robusta* (grevillea). In our analysis we focus on grevillea rather than a native tree species for two reasons, as outlined below.

First, a bigger data set of higher quality information is available in the scientific literature for grevillea characteristics compared to native tree species in East Africa (as native trees are in general understudied in the region). This means that we are able to establish the relevant parameters for modelling for grevillea more effectively than for other tree species (as we describe below, the model we develop can later be applied to native tree species, when more information on them is available).

Second, soon after its introduction which is believed to have been in the early 1900s (see further information below), grevillea became a popular species to grow in the different countries of East Africa and across sub-Saharan Africa more broadly (Harwood, 1989). Considering Ethiopia specifically, for example, in an internal report of the Addis Ababa National Tree Seed Project which discussed seed supply and demand issues, grevillea was described as the most-demanded exotic tree in the nation by different stakeholders (Hunde et al., 2004). This high demand for grevillea planting material was recently confirmed in the study of Lillesø and Derero (2019) on tree seed markets in Ethiopia. In their survey, grevillea was mentioned by 11% of the nursery growers when asked to list the tree species that "you want to produce but you cannot". Even though in Ethiopia the supply of grevillea seed through formal channels is low compared to demand, around 155 million seeds are sold annually by the country's national Tree Seed Centres (TSCs); and it is ranked sixth in the total number of seeds of particular trees sold (Lillesø & Derero, 2019). More optimal seed supply of grevillea, therefore, has high potential for promoting the future uptake of successful tree planting.

In this study, we explore the cost of BSO establishment for grevillea in the context of the economic benefits to smallholder planters that are gained by using higher quality tree seed. The analysis, apart from being useful for grevillea specifically, provides a model for estimating the impacts of establishing BSOs for other tree species, including for important native trees such as the timbers *Cordia africana* and *Juniperus procera*. It will be possible to better apply our model to these other trees when initial characterization data from the BSOs already established of the species become available in the next few years.

In the current study, we first review the available literature on grevillea to explore its biological characteristics, uses and values. We then use growth data from the literature to model its productivity. Growth models are used to estimate the potential variability in grevillea performance under three different quality scenarios, and including the use of seed from a BSO. We then conduct an economic analysis where potential revenues under two planting options are estimated, with agroforestry and woodlots being the two options chosen. Findings are then outscaled considering the current demand for grevillea planting material nationally and an assumed adoption rate of PATSPO-derived high-quality (BSO) planting material. Anticipated impacts at local and national scales are also quantified, in terms of additional timber production. We conclude by estimating wider societal impacts through carbon sequestration and sawnwood production.

2 Grevillea literature review

Below, we compile information from the literature that sets the framework for our current costing analysis.

2.1 Botany, ecology and growth rate

Grevillea robusta Cunn. Ex R. Br. (grevillea) is a fast-growing timber tree native to New South Wales and southern Queensland in Australia, where it is found across a wide range of habitats, from sea level to around 1,100 metres in elevation. In Ethiopia, it performs well in agroclimatic zones at elevations of between 1,500 and 2,700 metres above sea level (masl) (Bekele-Tessema, 2007).

Climate varies widely within the native geographic range, with a rainfall gradient across rugged topography. Generally, conditions are considered suitable when annual rainfall is between 700 and 2,400 mm, with mean annual temperature between 13 and 24°C. However, the species has grown satisfactorily in low-rainfall areas down to 400-600 mm yr-1 in Australia and other countries (Harwood, 1989). Grevillea does not tolerate prolonged seasonal droughts (Harwood & Booth, 1992). Maturity is reached as early as six years after planting.

Grevillea, and most other entries of the Proteaceae family, are able to develop proteoid roots which are thought to increase nutrient uptake when growing in phosphorous-poor soils (Skene et al., 1996). The species has few pests in its natural environment (Harwood, 1990). According to Njuguna (2011), however, in Kenya, grevillea is under serious threat from widespread canker and dieback diseases in some locations. Additionally, grevillea has been observed to host 40 fungal species, which could cause serious disease in other woody and agricultural crops.

Grevillea grows very well in all equatorial highlands where there are two rainy seasons per year (Harwood, 1990). Some growers consider that it does not compete strongly with adjacent crops (see more information below) and hence it is often found integrated in different cropping systems (Owino, 1992; Spiers & Stewart, 1992).

In sites with good climatic and soil conditions, height mean annual increments of 2 m y-1 and diameter at breast height (DBH) increments of 2 cm y-1 are commonly achievable during the first five years of grevillea growth (Harwood & Booth, 1992). Okorio and Peden (1992) recorded that at favourable sites in the East African highlands grevillea also attained similar height and DBH annual increments over the period of growth from five to ten years after planting. On poorer sites at high altitudes (> 2,300 masl) in East Africa, height mean annual increments were lower (Kalinganire, 1996). Growth usually slows between ten and 15 years after planting, except at the most suitable sites (Harwood & Booth, 1992; Okorio & Peden, 1992; Ongugo, 1992; Doran, 1997). An inverse correlation between growth vigour and altitude was found by Okorio and Peden (1992) in the highlands of Uganda. Abebe (1992) found the same relationship in the Ethiopian Highlands. Studies have reported that grevillea trees have a maximum life span of 40 to 50 years before they become senescent (Owino, 1992).

In a mixed species trial involving sixteen high-value rainforest tree species at Mt. Mee in south-eastern Queensland, Australia, grevillea showed the top performance in growth during relatively dry years (Lamb & Borschmann, 1998). At six years of age, the mean height of grevillea trees was 8.9 m and mean

DBH was 16.7 cm. The form factor was 8.6 out of 10, indicating an ideal stem growth and branching pattern. However, the form score was lowered by some individuals that had suffered wind damage. At a sub-humid site with mean annual rainfall of 640 mm in south-eastern New South Wales, Australia, grevillea trees were on average 8.3 m tall with a mean DBH of 13.2 cm after nine years (Clarke et al., 2009).

2.2 Management history

According to Owino (1992), grevillea was first introduced to East Africa in around 1910. Since then, grevillea has grown in its popularity and in its spatial distribution in the region (Ongugo, 1992; Yasu, 1999; Tefera et al., 2001; Muchiri et al., 2002; Muchiri, 2004; Carsan & Holding, 2006; Reyes et al., 2009). It is now commonly found in the central and eastern highlands of Kenya, Ethiopia, Uganda, Tanzania and Rwanda, where it grows vigorously and is often considered as an agroforestry species (Lott et al., 2000a; Ong et al., 2000; Madadi et al., 2009). Overall in Africa, its adoption has been extensive over a large altitudinal range, from 0 to 3,000 masl (Bekele-Tessema, 2007). Grevillea is praised by African farmers for its climatic tolerance (Clarke et al., 2009). Pohjonen (1989) states that grevillea has shown promising performance in a wide range of Ethiopian conditions.

Grevillea is highly popular in Kenya, especially around Mt. Kenya (Castro, 1993; Takaoka, 2008), possibly because it fits pre-existing tree husbandry practices of the Kikuyu community (Castro, 1993). In Tanzania, a study by Yasu (1999) analysed and illustrated the diffusion process of grevillea plantings in the Arusha region and in the wider area of northern-central Tanzania. As early as the 1950s, grevillea was introduced to the Arusha area from around Kilimanjaro by immigrating coffee farmers (Talle, 1990). From the 1970s, the diffusion process and planting intensified due to the usefulness of the timber for on-farm construction, including for homestead building (Yasu, 1999). Grevillea plantings were also used to secure occupancy rights on farms during the confusing situation of Tanzania's villagization program between 1974 and 1981.

Kalinganire (1996) compared the performance of grevillea trees sampled from plantations (33 trees) and farms (34 trees) located in seven different agro-ecological zones in Rwanda. He found that altitude and soil fertility had a major influence on growth, with trees planted at altitudes below 2,300 masl having higher height increments, as did trees in fertile, deep and light soils. His study also showed that larger spacings between trees favoured diameter growth and that trees' mean volumes were higher on farms than in plantations.

The natural regeneration potential of grevillea is limited by the ecological niche it occupies. In its natural range it is an upper-canopy tree (Harwood, 1990). Natural regeneration, which occurs in light-exposed areas, is hindered when its seeds and seedlings are in close competition with other upper-canopy trees (Owino, 1992). A study by Webb et al. (1967) in South Queensland, Australia, observed that grevillea has an allelopathic inhibition mechanism that prevents the under-establishment of its young seedlings. To date, this interaction has not been widely investigated elsewhere, but grevillea has been observed to regenerate badly in some pure plantations in Hawaii (Burns & Honkala, 1990). In favourable conditions, however, grevillea has been observed to become invasive in some settings (Doran, 1997; Marikhele, 2018). In South Africa, Marikhele (2018) found it had colonized 20% of 159 sampled plots of grass and forest vegetation. Despite this, no clear evidence of the species becoming a weed problem in East African natural ecosystems appears to have arisen. From this simple ecological perspective, therefore, there does not appear to be any particular concern with promoting the species in Ethiopia.

2.3 Main uses and farmers' adoption

Grevillea is often cultivated as a source of fuelwood, for timber and poles, and to provide shade and as an ornamental tree. It is popularly used as a source of firewood and charcoal in all of tropical Africa (Poulsen, 1983; Harwood & Getahun, 1990; Muchiri, 2004). The calorific value of the wood is 4,875 kcal kg-1 and it is hard and moderately durable, though susceptible to termite attack. The wood is easy to work by hand and machine (Spiers & Stewart, 1992; Clarke et al., 2009). Though generally not considered suitable for pulp production commercially, the wood produces a short-fibre pulp of acceptable quality (Ghosh, 1972).

In India and Sri Lanka, grevillea is planted as a shade tree for tea and coffee plantations (Figure 1). It is also planted as a shade tree in smallholder farming systems in tropical Africa (Owino, 1992; Kalinganire et al., 1996), specifically in Ethiopian coffee gardens (Negash et al., 2013; Denu et al., 2016). Several studies have observed that grevillea is suitable for intercropping. Bucagu et al. (2013), for example, indicated that grevillea is perceived by farmers to show low tree-crop competition due to its relatively deep roots. Lott et al. (2000b) found that grevillea trees were less competitive than other agroforestry trees commonly planted in farmlands. Conversely, Owino (1992) and Ongugo (1992) state that drops in grevillea use as a shade tree in East Africa over past decades were due to potential negative effects on crop productivity. Smith et al. (1999) observed how four- and six-year-old grevillea trees dominated the root layer when intercropped with maize, with no spatial separation of the rooting zones of the tree and the crop, denoting competition. Management practices affect competition and may partly explain the above contrasting observations. For example, Clarke et al. (2009) reported that grevillea tolerates heavy pruning or pollarding, practices which allows farmers to regulate the amount of competition for light between trees and the adjacent crops. Around Mt. Kenya, grevillea when grown along farmland boundaries is often heavily pollarded (Muchiri, 2004).

Figure 1. A *Grevillea robusta* plantation in Masinagudi, India (Creative Commons Attribution-Share Alike 4.0 International license, "Masinagudi Habitat - Silver Oak *Grevillea robusta* Plantation" by P. Jeganathan).

Grevillea leaves can be used as a soil mulch (Omoro & Nair, 1993; Yobterik et al., 1994) and for livestock bedding (Clarke et al., 2009; Pravalprukskul, 2015). Grevillea mulch can support soil conservation as evidenced by a study conducted in Kenya by Omoro and Nair (1993). They compared the soil balance in a calendar year between a control plot and several other plots where mulches from different agroforestry tree species were applied. The results indicated that grevillea tree leaf mulch lowered soil losses by 75% during heavy rains. Grevillea is also used for soil rehabilitation (Tesfaye et al., 2015).

In a study by Tefera et al. (2001) involving farmer-participatory evaluation of grevillea boundary plantings in Kenya, 66% of those surveyed expressed interest in future grevillea planting. Farmers highlighted fast growth and low competition with crops as primary reasons. In a study about farmers' interests in agroforestry in Rwanda, Bucagu et al. (2013) found that grevillea was the only tree species planted on all surveyed farms, where the most common planting niche for the tree was on boundaries. In a farm tree diversity study in Ethiopia conducted by Duguma and Hager (2010), grevillea was among the five most popular species across the Menagesha Suba area. It was used primarily for construction wood, secondarily for fuelwood, soil erosion control and to form living fences.

As a commercial timber plantation species, grevillea is less attractive than other exotic trees such as eucalypts and pines due to its slower growth and only similar (or poorer) timber quality (Harwood, 1990). It has thus only been planted on smaller areas for this purpose in East Africa (Bekele, 2011).

New uses for grevillea are being described. In Ethiopia, the Dilla University Biology Department demonstrated how its leaves can be used as a substrate for oyster mushroom (*Pleurotus ostreatus*) cultivation. Fruit bodies produced on this substrate were large and abundant. If this technology is feasible in rural areas, it could make an important and sustainable contribution to closing the hunger gap faced by local communities during the dry season (Fekadu, 2014).

2.4 Genetic variation

In the following paragraphs we discuss what is known about intra-specific diversity in grevillea, based on the available literature of provenance and family trials, and from other studies. Some detail is provided as the issue is crucial for the modelling work presented in subsequent sections of this working paper. Main findings relevant to our current study are summarized in Table 1. Importantly, the data show that marked improvements in grevillea performance are possible through appropriate provenance selection, providing a genetic basis for productivity improvements.

In Ethiopia, at Wondo Genet, Sidama Zone, seven provenances of grevillea from Australia and a local landrace[1] were tested in a provenance trial (Hunde et al., 2004). At eight years old, significant differences were found in tree height, with provenance "grevillea" (NSW, Australia) performing best (16.27 m) and "Bottle Creek" (NSW, Australia) next best (15.49 m). Branching patterns between provenances were significantly different. Compared to the top performing Australian provenance, the local landrace "Wondo Genet" demonstrated slower growth (9% less growth in height and DBH).

In a trial established in Rwanda at Ruhande Arboretum, Butare, Mugunga (2009) found significant differences among provenances of grevillea in height and branching pattern. The study confirmed good general stem straightness as indicated by Lamb and Borschmann (1998), indicating that the tree may not require selection to improve this trait. Maximum height in the Rwandan study at 18 years of age was 20.6 m for the Australian provenance "Benarkin", a metre higher than the tested Rwandan landrace "Shyanda, Butare".

[1] We here use the term 'landrace' loosely to refer to genetic material already found growing locally, having been introduced and planted at some earlier stage. We do not intend to convey by the use of the term that the material is necessarily locally adapted for growth and reproduction (although this would be part of the more formal definition of what a 'crop' landrace is).

Also in Rwanda, in a study conducted at Karama and Ruhande, Kalinganire and Hall (1993) found significantly higher values for growth and tree form, and biomass production rates, for natural Australian provenances than for a local landrace. Australian provenances “Imbil”, “Benarkin” and “Glenbar” stood out for their high productivity. The local landrace performed especially poorly in its growth characteristics, with apical and radial growth 30% lower than the mean of all provenances at the Ruhande test site. The authors found that survival rates and tree form were better at the wetter of the two test sites due to lower termite attack.

In Tanzania, Maliondo et al. (1998) tested the growth of seven Australian provenances of grevillea and two Tanzanian landraces (named “Soni” and “Rombo”) at two sites, Kiroka and Mkundi. These sites were 70 km apart and varied for climate, soil and altitude. The best growth was recorded at the Kiroka site, where, at two years old, the mean tree height was 6 m and mean DBH 10 cm. Growth was much poorer at the Mkundi site, where mean height was 3 m and mean DBH 4 cm. The site effect on tree performance was greater than the provenance effect, emphasizing how site quality influences the overall growth rate of grevillea. In relation to site quality, the authors found a small ($0.29 < r < 0.37$) but significant (*p-value* < 0.05) contribution of N and P to DBH and height growth, indicating the importance of soil nutrient availability. Though site quality was more important than provenance in affecting growth, the provenances “Manriver” and “Condondale” from Queensland, Australia still exhibited clear superiority for height and diameter at both sites. The local landraces displayed around 20% slower apical growth than these Australian provenances. At the poor site (Mkundi), despite their relatively slow growth, local landraces were less susceptible to disease and pest attack, which may indicate adaptation to local climatic conditions.

Again in Tanzania, in the Western Usambara Mountains, Madadi et al. (2009) assessed the growth of seven Australian provenances and five Tanzanian landraces of grevillea at the two planting sites of Lushoto and Ubiri. In their study, measurements taken 66 months after planting showed good growth at both sites, with trees 7.8 m in mean height and 8 cm in mean DBH at Lushoto, and 8.0 m in mean height and 7 cm in mean DBH at Ubiri. Overall survival rate was higher at Lushoto (96%, compared to 84% at Ubiri). At both sites, landraces showed poor performance, all scoring below the general mean for apical and radial growth; the five landraces showed, on average, about 25% lower height and DBH growth than the best performing provenance at both sites.

In Australia, a grevillea provenance trial established in the Atherton area of northern Queensland showed significant differences in growth among provenances 40 months after planting, with provenances “Duck Creek” and “Tyalgum” from the lowlands of New South Wales performing better than other provenances (Sun et al., 1995). In another Australian provenance trial of grevillea established in 1995 in Neerdie in south-eastern Queensland, height and DBH measurements 52 months after planting also showed the superiority of the “Duck Creek” provenance (Harwood et al., 2002).

Martins et al. (2004) reported on a grevillea provenance and family trial conducted in the state of Paraná, Brazil in which 60 half-sib families from 18 Australian provenances were tested along with a Brazilian landrace control. The authors calculated cylindric volume gains of 27% and 38% with the selection and clonal propagation of the 200 and 50 best trees, respectively, from the trial (selecting the best 9.5% and 2.4% of trees, respectively), when compared to the local landrace. The best performing families were from the Australian provenances of “Albert River” (from Queensland), “Fine Flower”, “Mann River” and “Duck Creek” (the last three all from New South Wales).

In a second-generation progeny trial established in the same Brazilian state, Martins et al. (2005) reported on potential gains in wood volume. An original first-generation trial was composed of a total of 104 families from 20 different provenances of grevillea. Then, in 2002, 37 genotypes were selected from this trial and utilized as germplasm for the second-generation planting. In this second trial, it was estimated that selecting the 266 best genotypes would produce a genetic gain in over-bark wood volume of 63% over the general mean, while selecting the 50 best genotypes would produce a genetic gain of 115% for the same trait (these selections sampled the best 18% and 3% of trees, respectively).

In addition to exploring phenotypic variation within grevillea, molecular characterisation of genetic variation has been undertaken. Harwood et al. (1992) investigated isozyme variation in provenances sourced from the natural range and in several African landraces. The authors found 15% of genetic variation was attributable to differences among natural provenances, a value typically observed for woody plant species (Hamrick et al., 1992). African grevillea landraces from Burundi, Democratic Republic of the Congo, Kenya and Rwanda showed either very low levels of genetic diversity or allele fixation, which could indicate genetic drift in founder populations. The isozyme patterns observed in broad African materials indicated secondary introductions from within Africa rather than numerous introductions from the native range. Harwood et al. (1992) concluded that "one or a few natural provenances have contributed to the original make-up of many land races [in Africa]", and that "substantial levels of inbreeding, either through self-pollination or through mating among closely related trees, are likely to have occurred [in Africa]".

Somewhat similar isozyme patterns were obtained by Sousa et al. (2018) who compared diversity in five natural populations of grevillea from Australia with a commercial control from Brazil. This control was developed from Australian trees of unknown origin. Evidence of high inbreeding was found in the Brazilian material, which the authors suggested was due to a small number of trees initially being sampled in Brazilian introductions (Shimizu et al., 2002). Sousa et al. (2018) indicated that the limited sampling was responsible for low wood production and the bad stem form of several grevillea plantings in Brazil (due to inbreeding depression effects).

Table 1. Summary of trials and genetic variability studies on grevillea. Entries are organised alphabetically by first author of the study and then date of publication

Authors	Year	Study site	Research Type	Provenances/ sampling structure	Tree age (months)	Main results	Comments
Clarke *et al.*	2009	Australia, NSW	Alley planting on farm	Unknown	108	MAI H = 0.9; MAI DBH = 1.5	Healthy conditions
Harwood *et al.*	1992	Australia and Africa	Genetic variability (isozymes)	19 from Australia and 7 landraces from Africa	-	Genetic variability of African landraces substantially lower than in the natural provenances	The results suggest a single original introduction to the African countries with similar colonial history. In addition, substantial levels of inbreeding appear likely to have occurred in Africa
Harwood *et al.*	2002	Australia, QLD, Needie	Prov. trial	23 from Australia	52	MAI H = 1.7; MAI DBH = 1.8	Provenance differences in growth. “Duck Creek” performed best
Hunde *et al.*	2004	Ethiopia, Wondo Genet	Prov. trial	7 from Australia and 1 landrace from Ethiopia	96	MAI H = 2.7; MAI DBH = 2.1	Provenance differences in height growth. “Grevillea (NSW)” and “Bottle Creek” performed above average. Local landrace showed average growth rate
Kalinganire *et al.*	1996	Rwanda, 7 sites	On farm plantings/ plantation	Unknown	60 to 204	Soil type influences DBH growth. Strong negative correlation between altitude and height growth	Wider spacing favours diameter growth and single tree volume. Plantings should be favoured at altitudes < 2100 m
Kalinganire and Hall	1993	Rwanda, Karama and Ruhande	Prov. trial	7 from Australia and 1 landrace from Rwanda	29	Karama: MAI H = 2; MAI DBH = 1.9 Ruhande: MAI H = 2; MAI DBH = 1.4	Provenance differences in growth characteristics. “Benarkin”, “Imbil” and “Glenbar” performed well. The local provenance performed poorly compared to Australian ones
Lamb and Borschmann	1998	Australia, QLD, Mt. Mee	Mixed species trial	Planting material from SE QLD	72	MAI H = 1.4; MAI DBH = 2.8	Grevillea performed very well compared to other species

Madadi *et al.*.	2009	Tanzania, Usambara Mountains	Prov. trial	7 from Australia and 5 landraces from Tanzania	66	Lushoto: MAI H = 1.4; MAI DBH = 1.5 Ubiri: MAI H = 1.5; MAI DBH = 1.3	No provenance differences in growth. Good growth rate at both sites. The local provenance performed poorly
Maliondo *et al.*	1998	Tanzania, Morogoro	Prov. trial	7 from Australia and 2 landraces from Tanzania	24	Mkundi: MAI H = 1.5 Kiroka: MAI H = 3	Kiroka site characterized by higher amount of rainfall and more fertile soils. Mkundi site drier with sandy soils. Site differences were significant for growth and foliar nutrients. “Manriver” and “Condondale” provenances were superior in growth vigour and foliar nutrient content. Landraces showing below average growth vigour.
Martins *et al.*	2004	Brazil, Paranà, Ponta Grossa	Prov. and family trial	18 from Australia and 1 landrace from Brazil	120	23.3% cylindric volume gain with 200 best trees, 33.3% with 20 best trees	Provenance differences in growth. “Duck Creek”, “Fine Flower”, “Albert R.” and “Mann River” performed best
Martins *et al.*	2005	Brazil, Paranà, Londrina	Second generation progeny trial	37 genotypes from a provenance trial	36	63% cylindric volume gain with 266 best trees, 115% gain with 50 best trees	Second generation trial increases the volume gain over the mean
Mugunga	2009	Rwanda, Butare	Prov. trial	7 from Australia and 1 landrace from Rwanda	216	MAI H = 1.1; MAI DBH = 1.0	Provenance differences in height growth. “Benarkin” performed best. Local landrace still performed relatively well
Sousa *et al.*	2018	Brazil	Genetic variability (isozymes)	5 from Australia and 1 landrace from Brazil	-	Very narrow genetic base of the germplasm introduced to Brazil	High inbreeding in the local landrace may explain the poor stem form and relatively low wood production achieved
Sun *et al.*	1995	Australia, QLD, Atherton area	Prov. trial	12 from QLD and NSW	40	MAI H = 1.7; MAI DBH = 3.1	Provenance differences in growth and morphology. “Duck Creek” and “Tyalgum” performed best

Mean annual increment in height (MAI H) in m y-1; mean annual increment in diameter at breast height (MAI DBH) in cm y^{-1}.

3 Yield modelling

Calibrated by the data revealed by the available scientific literature on grevillea (section 2), we model the potential growth rate of the tree under three 'quality scenarios'. In this section, we explain the methods used for this modelling. Our yield predictions were first computed over a 40-year period, which was then shorten in accordance with the length of an assumed single production cycle for specific grevillea planting options. The analyses we explain below were performed using R statistical software (R Core Team, 2020).

3.1 Introduction to the modelling approach

In our analysis we use a yield model that is based on single-tree growth characteristics, as this is expected to better approximate growth across tree stands established in the various densities and spatial patterns that typify grevillea planting. Earlier studies had also fitted a single-tree model to grevillea growth data from the Kenyan Highlands (Muchiri et al., 2002; Takaoka, 2008) and so our analysis builds on this.

Our resulting fitted model is used to estimate the expected yield of different 'quality scenarios', where this is determined by germplasm quality (G) matched (or not) to site environment (E), factors that may interact (West, 2014). It is beyond the scope of the current study to investigate this interaction (termed GxE), but rather the overall effect is summarized under the 'chapeau' of the quality scenario.

The three quality scenarios we use, which represent a gradation in quality/matching from worst to best, are as follows: first, is the "actual yield" (AY) scenario, which represents the low quality and poorly site-matched germplasm currently available to Ethiopian tree growers. This scenario covers germplasm now distributed through the formal national tree seed market and informal seed sources such as the trees found in farmers' fields from which growers currently directly collect seed; second, is the "closing [the] yield gap" (CYG) scenario, which symbolizes an intermediate stage of germplasm improvement and site matching, achievable by implementing good practices of seed sourcing and considering more carefully the planting location; and third is the "potential yield" (PY) scenario, which represents the use of the highest-yielding available varieties of grevillea, with specific improved genotypes matched carefully to agro-ecological zones.

3.2 Detailed methodology

Data were collected on dynamic single-tree growth characteristics of grevillea specimens from several studies. Target data were tree age, DBH, top height, spacing, and the latitude and longitude coordinates of the planting location. When available, data were also collected on provenance, land use and date of planting. In an attempt to narrow down site condition heterogeneity, a geographic filter was applied to only include planting data from East Africa (see studies listed in Table 1).

Planting site coordinates were linked to a unique ID number (Appendix I). When DBH or height were not reported for specimens, a general DBH-height allometric relationship was utilized to replace missing values. The allometric relationship in equation (1), as it was estimated from tropical forest trees in East Africa (Uganda and Tanazania, see Feldpausch et al., 2011), was fitted to our assembled data, where H is tree height (m) and DBH is diameter at breast height (cm).

$$\ln(H) = 0.6757 + 0.6521 \ln(DBH) \quad (1)$$

When data are limited, as applies in the current case, a one-parameter regression model is relatively straightforward to calibrate (Vanclay, 2009). Though over-simplistic compared to multi-parameter models (Mensah et al., 2018), one-parameter models can still be useful for providing forest stand production estimates (Vanclay, 2009, 2010). Here, we used the steps suggested by Grant et al. (2012), where height and DBH are estimated using equations (2) and (3), respectively:

$$H = \beta_1 (t - 0.5)^{(0.5)} \quad (2)$$

$$DBH = \beta_2 (H - 1.3) / \ln N \quad (3)$$

where t is age (years), H is tree height (m), N is stocking (stems/ha), DBH is diameter (mean DBH over bark, cm) and β_1 and β_2 are the model coefficients. Equation (2) offers a good approximation that allows for robust predictions to be made with few calibration data (Vanclay, 2010). Equation (3) predicts DBH based on tree mean height and initial stocking.

To estimate single tree biomass, we then applied the allometric equations (4) and (5) (Kuyah et al., 2012a, 2012b):

$$AGB = 0.091\ DBH^{(2.472)} \quad (4)$$

$$BGB = 0.048\ DBH^{(2.303)} \quad (5)$$

where AGB is aboveground biomass (kg) and BGB is belowground biomass (kg). To estimate total under-bark volume (V_u), we applied equation (6) (West, 2009):

$$V_u = 0.3\ DBH^2\ H \quad (6)$$

where V_u is total stem volume (m^3, under-bark). Based on the obtained estimate of stem volume, we calculated bole total dry weight using a wood density value of 610 kg/m^3 (Olale et al., 2019). The biomass proportion allocated to leaves and branches was estimated based on the allometric equations of Owate et al. (2018).

DBH and height models were fitted to data grouped by unique IDs (i.e., locations of sampling sites). Based on single-site model predictions, single-tree mean annual increments in volume (MAI V_u) over a 40-year period were computed. For each site-specific growth model, the MAI V_u general mean (μ) and standard deviation (σ) were estimated. Site-specific MAI V_u values were then grouped into three categories which were used to predict productivity rate corresponding to specific quality scenarios. These were defined using the following criteria:

AY scenario = Sites where MAI $V_u < \mu - \sigma$

CYG scenario = Sites where $\mu - \sigma <$ MAI $V_u < \mu + \sigma$

PY scenario = Sites where MAI $V_u > \mu + \sigma$

Where, as noted earlier, AY = actual yield, CYG = closing yield gap and PY = potential yield. A similar approach was adopted in the study of O'Brien et al. (1995), who also used a single-tree growth model.

4 Growth rates under different quality scenarios

In this section, we show the initial results of our modelling. Profiles of model fit for data segregated by site ID (coloured lines) and for the general pool (no segregation, black line) are illustrated in Figure 2A and 2B, which show predicted growth in tree height and DBH, respectively.

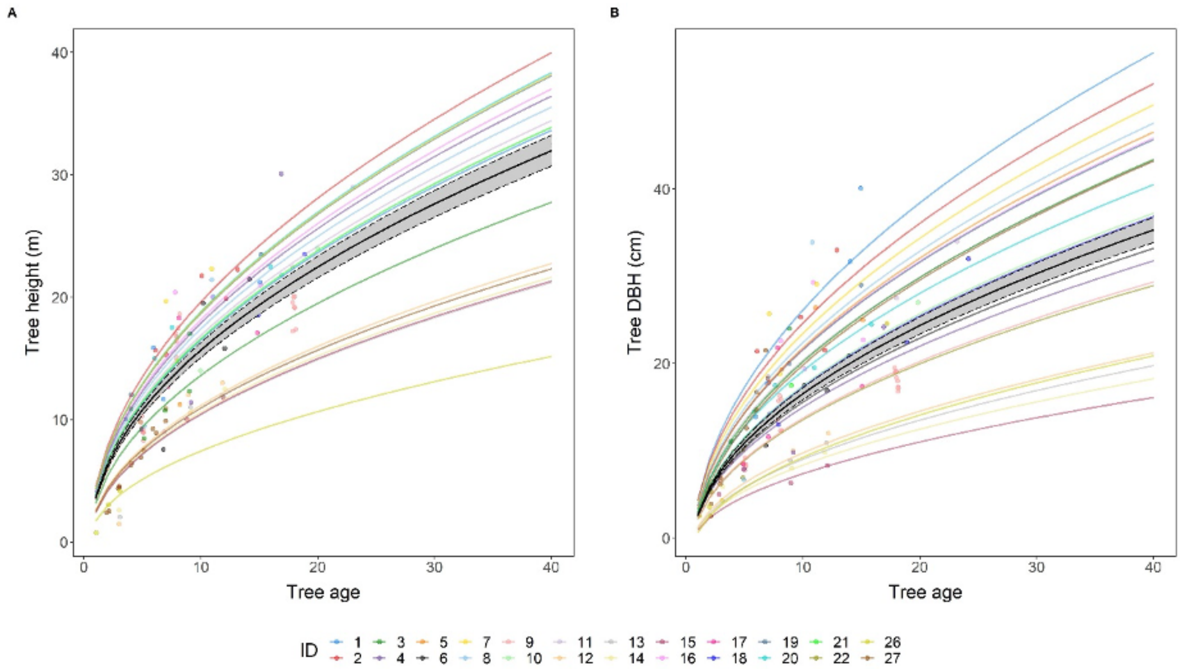

Figure 2. Modelled predicted growth of grevillea for unique IDs (sites, coloured lines) and for the general data pool (black line). Figures A and B show predictions for tree height and DBH, respectively.

At some sites (ID = 2, 4, 7, 8, 16, 19 and 20; see Appendix I), predicted height values were over the limit of 35 m expected for grevillea growth in Ethiopia (Pohjonen, 1989). This is probably due to the lack of entries in our data set for older trees (> 20 years old). For DBH, site predictions ordered differently than those for height, possibly due to different planting densities across sites. The complete dataset used in our modelling can be found in Appendix I.

Overall, the broad spectrum in height and DBH prediction curves that we observed was notable. This may reflect significant between-provenance genetic variation in performance in grevillea, as well as varied site conditions.

For each of the sites shown in Figure 2, the value of MAI V_u was then computed for our data, based on equation (6) applied over a 40-year period. These values were subsequently assigned to one of three categories of quality based on our AY, CYG and PY criteria (as shown in Table 2). Raw data were then assigned to these groupings and modelling using equations (2) and (3) was repeated to show the extent of the growth rate differences among quality scenarios for both tree height and DBH (Figure 3A and 3B, respectively).

Table 2. Sites IDs assigned to three quality scenarios for assessed grevillea plantings

Quality scenario	**Range of MAI Vu**	**IDs**
AY	x < μ - σ	4, 6, 9, 10, 12, 13, 14, 15, 17, 18, 21, 22, 26, 27
CYG	μ - σ < x < μ + σ	3, 5, 11, 16, 20
PY	x > μ + σ	1, 2, 7, 8, 19

See site ID explanations and further information in Appendix I. For assessed plantings overall, mean (μ) MAI V_u was 0.032 m^3 $tree^{-1}$ and the standard deviation (σ) in V_u was 0.019 m^3 $tree^{-1}$.

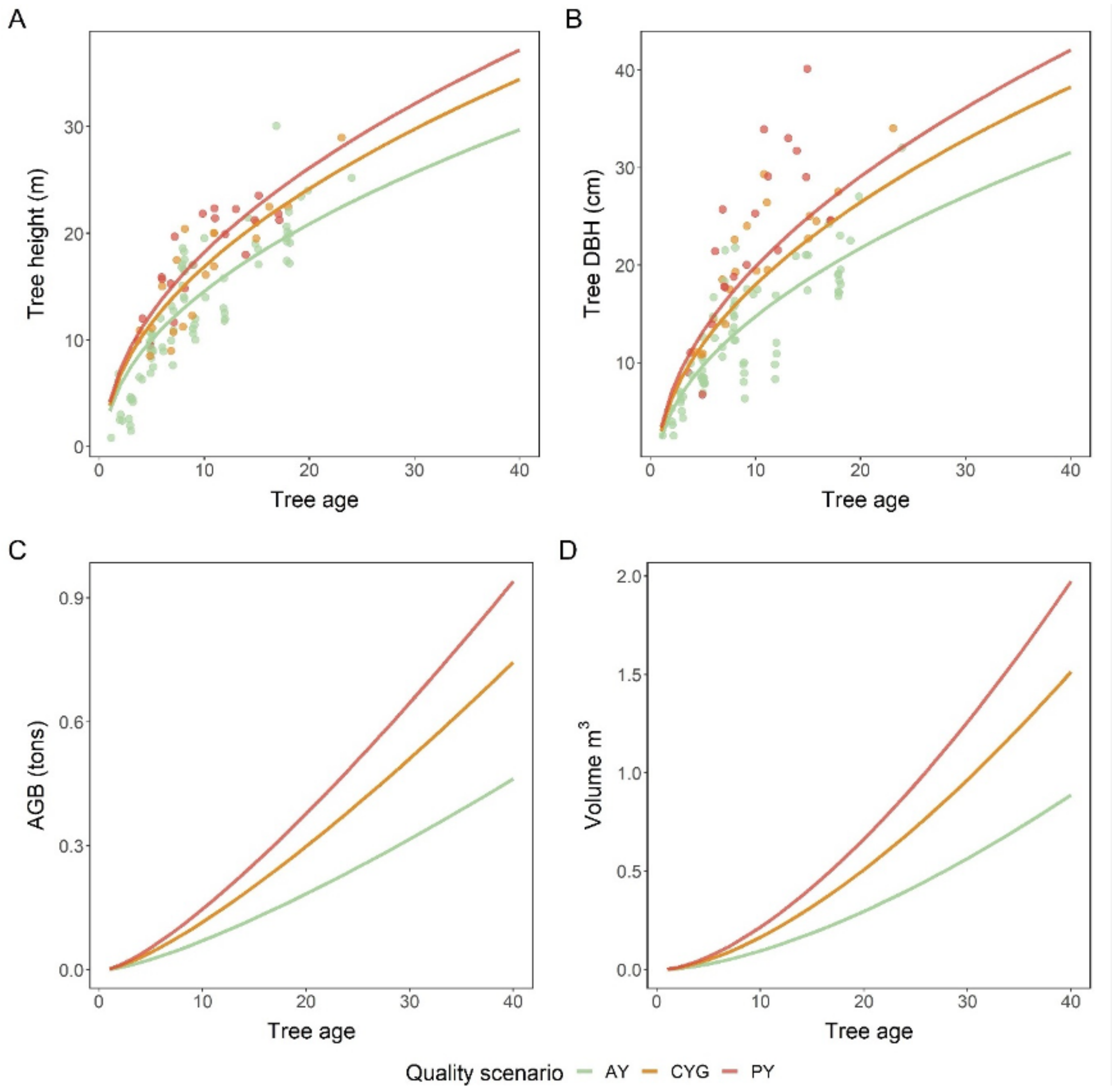

Figure 3. Growth curves of height (A) and DBH (B) fitted to data segregated by three quality scenarios (AY = actual yield, CYG = closing yield gap, PY = potential yield), with derived profiles of aboveground biomass (C, AGB) and under-bark volume (D, V_u).

Based on height and DBH, AGB and V_u profiles were then calculated using equations (4) and (6), respectively (results shown in Figure 3C and 3D, respectively). Although in equation (4) DBH was the only variable included as a predictor, DBH growth was modelled based on the relationship with tree height and planting density as specified by equation (3). Thus, estimates of AGB (Figure 3C) and V_u (Figure 3D) are based on both DBH and H models. The effect of improved apical and radial growth on biomass and volume productivity is expected to intensify with tree age, as is confirmed by our modelling, where curves have not flattened at the 40-year stage.

5 Cost benefit analysis

In this section we describe how we model the economics of grevillea production. We initially illustrate the costs involved in setting up a BSO of grevillea to provide high quality tree seed. We next establish the model framework for exploring the costs and benefits of grevillea production for our two chosen 'production options' of agroforestry and woodlots. Then, we input into our model actual cost and price data from Ethiopia for our three quality scenarios for a one-hectare landholding. We conclude by outscaling findings to the national level, considering the possible capacity and reach of a BSO in providing seed.

5.1 Breeding seedling orchard establishment costs

The establishment of BSOs is a way to provide high quality tree planting material. PATSPO has to date established over 30 BSOs of tree species prioritised by communities, businesses and government in Ethiopia. These BSOs not only produce tree seed *per se*, but they support the selection and evaluation of GxE in tree performance that allow locally-adapted tree seed for growers to be identified. They also act to conserve the tree germplasm (a function that is more important for indigenous trees than for grevillea in Ethiopia).

Here, we outline the costs of establishing a BSO for grevillea based on PATSPO's practical experiences. We illustrate the total costs involved up to a full year after BSO establishment in Figure 4, using a 'tree-map' where the area sizes are proportional to the costs of particular activities. Further data, summarized by the main activities with their costs, are provided in Appendix II.

Figure 4 shows that post (initial)-establishment activities such as watering, and fencing to protect the BSO, took up more than half of the total budget, at 30% and 29% of the total, respectively. The next highest expenditure was linked to nursery operations (19%). Initial field establishment costs such as planting and site clearance were only a low proportion of the total expenditure (6%).

The data revealed that the total expense of BSO establishment was approximately 470,000 Ethiopian Birr for a single hectare stand containing 2,500 grevillea seedlings at initial establishment. This is equivalent to around USD 12,300 when applying a conversion rate for Ethiopian Birr to USD of 38:1, the rate prevailing in 2021 when price data were collected.

5.2 Model framework for measuring incomes from agroforestry and woodlots

To assess the potential income to growers from grevillea plantings, we chose 'agroforestry' and 'woodlots' as the two most suited production options. These options are valid for a variety of farming systems in which grevillea is planted by Ethiopian smallholders (the same options would also be relevant more widely in East Africa and through the tropics). As noted in our literature review (section 2), grevillea planted in East Africa is often found in agroforestry situations such as live fences and as shade trees. Grevillea is also widely established in the region in small woodlots (and these are expected to be primary sources of timber supply in Ethiopia going forward; FDRE, 2017).

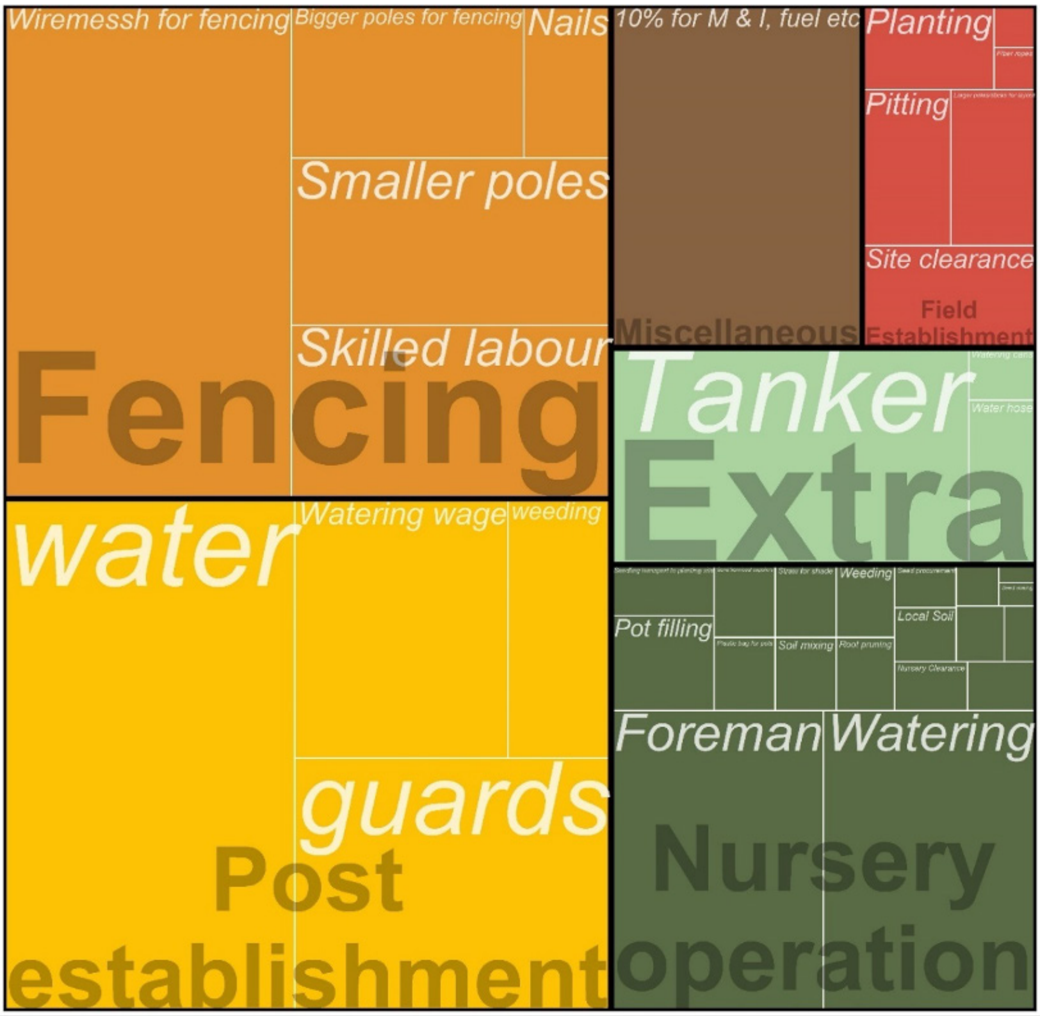

Figure 4. A tree-map where BSO establishment costs are represented. Different squares are proportional in area to specific costs

The parameters we use for modelling in agroforestry and woodlot situations are summarized in Table 3 and the paragraphs below. In each case, we considered a landholding of one hectare for modelling purposes.

In an agroforestry system, we expect grevillea to be planted at a low density integrated with crops. We therefore set this option to have 60 trees planted for a one hectare area overall, a value typical of studies that have researched East African smallholders' agroforestry practices (Yasu, 1999; Muchiri et al., 2002; Carsan & Holding, 2006). We assume an actual spacing of 4 m by 4 m between planted trees, which means that they only occur on about 10% of our modelled land area (they are aggregated into this smaller area with crops between them). This spacing would be typical for grevillea established in an agroforestry system (Edo et al., 2017). (The setting out of this spacing is important because the overall performance of the trees in our model is spacing sensitive.)

In the case of the smallholder woodlot option, where grevillea is commonly planted to produce poles and construction wood (Pravalprukskul, 2015), we expect a high density of planting. We therefore set this option to have 1,100 trees planted initially for a one hectare area overall, a value approximating that seen by observers in practice (Pohjonen, 1989; Matthies & Karimov, 2014). We assume an actual spacing of 2 m by 2 m between planted trees, which means that they occur on 44% of our modelled land area (where they are aggregated on land assigned solely for wood production). This proportion of a landholding covered by a woodlot would be typical of smallholder practice in the Ethiopian highlands

(Matthies & Karimov, 2014). We then assume that half of these trees will be thinned seven years after planting (Pohjonen, 1989).

For both planting options, we set the seedling mortality rate after initial field planting at 20%, with lost seedlings being replaced in the second year. This mortality value is chosen as conservative for modelling purposes (Reyes et al., 2009; Marikhele, 2018). Further tree mortality after the initial establishment stage was not considered in our current model, as evidence suggests it should be low (Muchiri et al., 2002). Harvesting schemes were set differently for each planting option based on information sourced from Pohjonen (1989), Muchiri et al. (2002) and Matthies and Karimov (2014).

Table 3. Assumptions used for different planting options when estimating contribution margins

Assumptions	**Agroforestry**	**Woodlot**
Trees/ha	60	1,100
Landholding occupied by planting option (% of 1 ha)	10%	44%
Spacing (m)	4 x 4	2 x 2
Seedling mortality (%)	0.20	0.20
Pruning	50% of annual biomass allocated to branches when tree age > 3 yrs	50% of annual biomass allocated to branches between years 4 and 8
Harvesting	1st harvest: when DBH ~26 cm (30 trees) 2nd harvest: when DBH ~32 cm (30 trees)	1st harvest: year 7 (550 trees) 2nd harvest: when DBH ~ 26 cm (550 trees)

Assumptions on trees per hectare at different ages, and for spacing and mortality, based on the studies of Pohjonen (1989); Muchiri et al. (2002); Matthies and Karimov (2014).

Our cost-benefit analysis involved calculation of the net present value (NPV), the internal rate of return (IRR) and the equal annuity cashflow (EAC) of agroforestry and woodlot planting options, considering productivity under appropriate planting densities and single production cycle lengths, and taking account of different quality scenarios. The application of different single production cycle lengths is based on the threshold size for DBH being reached at different times based on the quality scenario. The application of different single production cycle lengths does not compromise our overall comparisons as EAC allows us to compare the financial efficiency of projects with different lifespans. The formulae used to calculate NPV, IRR and EAC are shown in equations (7), (8) and (9):

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t} \tag{7}$$

$$0 = NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+IRR)^t} \tag{8}$$

$$EAC = \frac{i \cdot NPV}{1 - (1 + i)^{-t}} \tag{9}$$

where t is the number of years after planting, n is the number of years after planting of the last harvest, i is the discount rate (set to 10% in this analysis) and CF_t is the contribution margin or net cash flow in year t. The cumulative NPV was also calculated to estimate the year after planting when landowners would start to achieve a positive overall NPV.

Cost-benefit analysis was performed using the *jrvFinance* (Varma, 2019) and *FinCal* packages (Fan, 2016) of R.

5.3 Inputting cost and price data into the model

Information on labour and other production costs, and wood prices, are needed as inputs for model application. We take these from the literature and from local knowledge gained by the PATSPO initiative.

For the labour costs of managing smallholders' grevillea plantings, estimates were founded on Nigussie et al. (2020) who studied costs for eucalyptus woodlots in the Ethiopian highlands. The labour cost of harvesting was based on a price of 1.3 Birr tree^{-1} for trees less than 26 cm DBH and 2.7 Birr tree^{-1} for larger trees. The cost for a round of pruning was set at 0.7 Birr tree^{-1}. The establishment costs for trees were based on calculations made for the establishment of BSOs (see earlier). The price for grevillea seedlings was set to 4.6 Birr each for the AY (lowest) and CYG (intermediate) quality scenarios. A premium of 50% was applied to seedlings of the (highest) PY quality scenario. Fuller data on costings are provided in Appendix II.

On-farm wood prices were sourced from a farm survey undertaken during the fieldwork conducted in support of the ex-ante impact assessment of PATSPO of van Schoubroeck et al. (2022). We applied a price of 1.4 Birr kg^{-1} for air-dried wood of a DBH below 26 cm and 2.8 Birr kg^{-1} for harvested logs with a DBH greater than 26 cm. This means that the wood of thinned out grevillea trees in the woodlot production option was valued at 1.4 Birr kg^{-1}, since it is assumed that at this stage the trees will not have reached a DBH of 26 cm. Pruned branches, which will most likely be used by farmers directly for domestic fuelwood supply (Dessie, 2011), were assigned a replacement cost of 1 Birr kg^{-1}. According to the investigations of the PATSPO team, wood prices are expected to increase by roughly 20% in real terms over the next decade in Ethiopia (Moestrup, unpublished observations). We applied this rate of increase across our entire modelled time period to both timber and fuelwood production.

Using these model inputs, the fixed and variable costs of the establishment and management of smallholders' agroforestry plantings and woodlots, based on a one-hectare total landholding, were calculated as time-series vectors. A summary of the net costs for planting options and quality scenarios, by establishment and management activity, and across an entire single production cycle, is provided in Table 4. Further information is given in the paragraphs below. A detailed time-series of expenses is given in Appendix II.

Our analysis showed that the woodlot planting option required much higher initial investment than the agroforestry option (total values of at least 25,000 Birr and around 2,000 Birr for the two options, respectively). This was due especially to the greater costs of the seedlings and for the tending of trees for the woodlot option (for which many more trees are planted). The differences in the total investment cost between the three quality scenarios for either planting option were relatively small. This difference was greatest for the woodlot planting option for the PY scenario compared to the other quality scenarios, because of the large number of more expensive seedlings used for the woodlot PY scenario.

Specifically for the agroforestry planting option, the pruning costs diminished as the quality scenario improves from AY to CYG to PY. This was due to the shortening of the production period in our model that is associated with higher germplasm productivity (i.e., the single production cycle length is shortest for the PY quality scenario, intermediate for the CYG scenario, and longest for the AY scenario). For woodlots, pruning costs were in our model the same across quality scenarios.

Table 4. Summary of costs over a single cycle of production for grevillea planting options and quality scenarios

Planting option	Quality scenario	Production cycle (years)	Cost category (costs in Birr)					
			Harvest	*Pruning*	*Seedlings*	*Tending*	*Weeding*	*TOTAL*
Agrofor-estry	AY	36	160	1,080	330	644	192	2,406
	CYG	25	160	700	330	644	192	2,026
	PY	21	160	580	494	644	192	2,070
Woodlot	AY	34	2,200	3,300	6,039	11,814	1,690	25,042
	CYG	24	2,200	3,300	6,039	11,814	1,690	25,042
	PY	20	2,200	3,300	9,058	11,814	1,690	28,062

Costs are divided into main categories. Quality scenarios: AY = actual yield, CYG = closing yield gap, PY = potential yield.

Adding in these price data to our model, we next generated net revenues as time-series vectors while adopting a discount rate of 10% for NPV calculations, a rate set based on previous studies in Ethiopia (Duguma, 2013; Matthies & Karimov, 2014; van Schoubroeck et al., 2022). The IRR was also calculated to obtain the discount rate at which NPV is equal to zero, and the EAC was computed to estimate the annual rate of return that will be earned with the investment. A summary of the results of these calculations over an entire single production cycle for planting options and quality scenarios is given in Table 5 and further information is provided in the paragraphs below.

This analysis showed six important features. First, NPVs were higher for the woodlot planting option than for agroforestry for the two higher quality scenarios (NPVs approximately double), though for the AY scenario the opposite situation was observed. Second, quality scenario had a major impact on the overall magnitude of NPV with both planting options. Thus, for the agroforestry planting option, a roughly 2-fold NPV increase was observed when moving from the AY to CYG scenario, and the same magnitude of increase again was seen when moving from the CYG to PY scenario. In the case of the woodlot planting option, the equivalent figures were an around 20-fold increase followed by a 1.6-fold increase. A focus on quality in germplasm provision is thus indicated to bring major NPV benefits for both planting options.

The third important feature evident in Table 5 is the difference in IRR between planting options. Comparing planting options for each quality scenario, the IRR was always higher for the agroforestry option. For agroforestry, the IRR ranged from 17% through 24% to 30% for the AY, CYG and PY scenarios, respectively, whereas for woodlots the equivalent figures for the quality scenarios were 10%, 16% and 18%, respectively. The lower IRR values for woodlots reflect the higher investments they require and indicate that agroforestry can be described as a safer investment option. The fourth important feature is also reflected in the above IRR values that indicated that IRR was higher for both planting options the greater the quality scenario, again emphasizing the importance of focusing on quality in germplasm provision.

The fifth important feature detected was the difference in EAC between planting options. EACs were higher for woodlots (approximately three to four times higher) apart from the AY scenario where the reverse situation applied. Sixth and finally, our results indicated that quality scenarios had a significant effect on absolute EACs within both planting options (mirroring the situation with NPV values as described above).

Table 5. Summary of NPV, IRR and EAC values over a single cycle of production for grevillea planting options and quality scenarios

Planting option	Quality scenario	Production cycle (years)	NPV (in Birr)	IRR	EAC (in Birr)
Agroforestry	AY	36	3,896	17%	403
	CYG	25	9,144	24%	1,007
	PY	21	18,461	30%	2,135
Woodlot	AY	34	1,756	10%	183
	CYG	24	39,587	16%	4,406
	PY	20	61,593	18%	7,235

Discount rate of 10% applied for NPV calculations. Quality scenarios: AY = actual yield, CYG = closing yield gap, PY = potential yield.

In summary, our current analysis indicated that a focus on germplasm quality is predicted to bring significant benefits for growers in profitability and investment safety for both agroforestry and woodlot plantings of grevillea, considered over a complete single production cycle.

Our NPV values were somewhat lower than those revealed by other work on the economic feasibility of agroforestry practices and woodlots in the Ethiopian highlands (Duguma, 2013; Matthies & Karimov, 2014), possibly because of the higher labour costs we assumed in our study. Elsewhere in East Africa, most farmers in the Tanzanian Southern Highlands dedicated fewer than 10 days per hectare over the whole production period to the management of trees on their land (Arvola et al., 2019), which is also lower than the time allocation we assume. Although our model carries relatively high costs, it may also support higher timber quality and hence improved prices. We have not factored this point into our current analysis.

In a further analysis of NPVs for our two production options and three quality scenarios, we explored year-on-year trends in the cumulative values of calculations. These are depicted in Figure 5. The graphs show that planting options have rather different profiles, as summarised in the paragraphs below.

For agroforestry, the cumulative NPV became positive earlier after planting than for woodlots, at the time of first timber harvest (which is 24 years for the AY quality scenario, 17 years for the CYG scenario and 14 years for the PY scenario). Before this time, fuelwood harvest had slowly contributed to paying back the initial investment for the agroforestry option. For this planting option, the last timber harvest, that came in years 36, 25 and 21 for the AY, CYG and PY scenarios, respectively, resulted in a jump in NPV.

In the case of woodlots, the cumulative NPV remained negative until the final year of the production cycle (year 35, 24 and 20 for the AY, CYG and PY scenarios, respectively), when a large jump in NPV is observed. This reflects the greater investments required for woodlots than for agroforestry planting. Before the final year, the harvested wood from thinned woodlot trees (thinnings harvested in year seven) contributed only partially to pay back initial investments, as wood volumes and hence values were relatively low for these early growth stage trees. For the PY scenario, however, the wood harvested from thinning contributed to pay back half of the initial investment.

Figure 5. Cumulative NPV (Birr ha^{-1}) for grevillea for the planting options of agroforestry and woodlots and three quality scenarios. Note the difference in x-axis scaling between quality scenarios, reflecting the different lengths of a single production cycle (long, intermediate and short for AY, CYG and PY, respectively).

5.4 Outscaling breeding seedling orchard impact

To scale our calculations to the national level, we considered how much seed a grevillea BSO could produce. At year seven when trees reach biological maturity, a one-hectare BSO is designed to contain a total of 625 trees (thinned from an initial 2,500 trees to remove 1,875 of the specimens showing average or below average growth performance, corresponding to a selection intensity of 75%). At this stage, we assume for current modelling an average seed yield of 400 g tree^{-1} y^{-1}, which based on a value of 121,500 seeds kg^{-1} corresponds to approximately 48,600 seeds from each tree in the BSO. Although we expect seed production to be positively correlated with tree size (Moles et al., 2004), for current modelling purposes we kept a constant value for all future years as our estimate of average production (i.e., we apply a constant value from biological maturity in year 7 to senescence in year 50). We also assume that 20% of the BSO seed will be lost due to damage and impurity, a further 25% will not germinate, and a further 30% will be lost during the raising of seedlings in nurseries prior to field planting. Taking these factors together, this means that only 42% of the BSO seed will be converted to seedlings actually available for field planting. Under these assumptions, the estimated number of seedlings available for planting annually from a one-hectare grevillea BSO from year seven onwards is approximately 12.8 million.

The above value of 12.8 million seedlings being available annually from the grevillea BSO compares to a best estimate of the annual demand for grevillea seedlings in Ethiopia of approximately 125 million (Lillesø and Derero (2019); note that this equates to about 300 million seed if applying the same conversion value of seed to seedlings as used above). This means that the grevillea BSO could in theory meet approximately 10% of Ethiopia's current demand for grevillea seed/seedlings. For current modelling purposes we however assume it can meet 5% operationally (i.e., supply 6.3 million seedlings for planting), due to delivery system constraints and inertia. In our modelling we keep this proportion constant across years, as we do the projected absolute annual demand for seedlings. Assuming that half of the BSO-sourced grevillea seedlings are planted in the agroforestry production option and half as woodlots, this equates to 43,000 ha of 'improved' agroforestry and 2,400 ha of 'improved' woodlots being established annually.

To outscale BSO impact it is necessary to equate the seed it produces to our three quality scenarios. As a minimum, the seed should align with the CYG scenario and in the best case with the PY scenario. For current purposes, we modelled the cumulative NPV difference for Ethiopia as a whole between each of these two scenarios and the business-as-usual AY scenario, and expressed the results graphically over a 50-year timescale (Figure 6). We also modelled a midpoint between CYG and PY scenarios compared to AY.

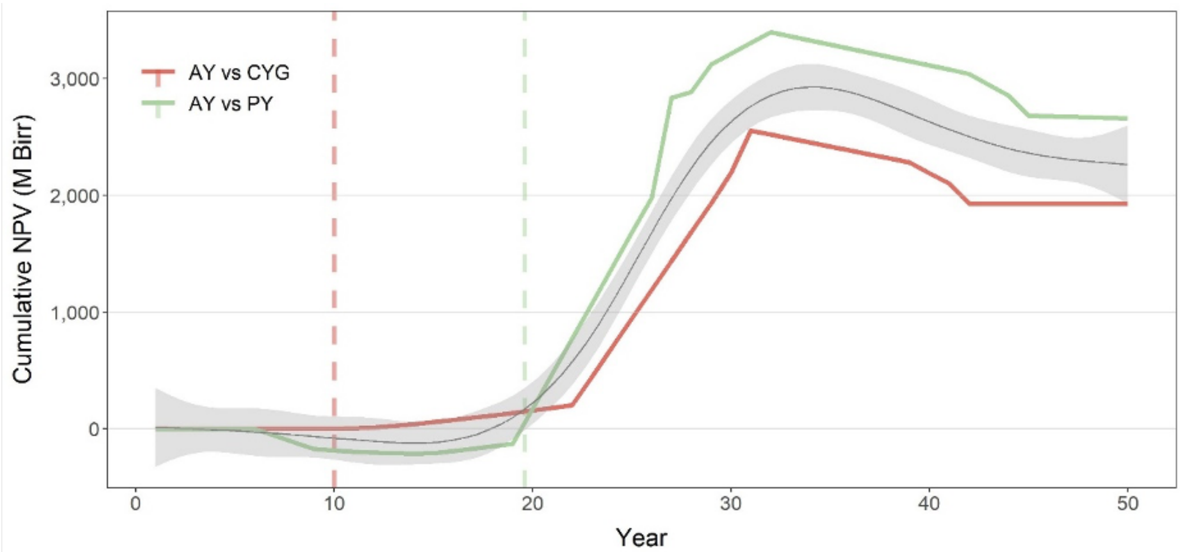

Figure 6. The difference in cumulative NPV nationally between each of the CYG and PY quality scenarios and the business-as-usual AY scenario, based on the establishment of a grevillea BSO in year 1. The vertical lines indicate when the cumulative NPV shifts from negative to positive for both comparisons. The grey profile corresponds to an average level of tree improvement between CYG and PY scenarios.

Figure 6 shows that the break-even point from BSO planting is expected to be reached at years 10 and 19 for the CYG and PY quality scenarios, respectively. This lag reflects the time that is needed for the BSO to biologically mature, and for the agroforestry and woodlot trees established from these seeds to begin production. In subsequent years, significant NPV benefits are achieved through using BSO germplasm compared to business-as-usual planting material. After 50 years, the increase in cumulative NPV of the PY compared to AY quality scenario is Birr 2.7 billion, with the value being 1.9 billion for the CYG versus AY quality scenario.

6 Further information on production and economics

In this section we make a further examination of the outputs of our modelling based on roundwood and sawnwood production, and relate these to environmental service provision (carbon sequestration) and additional economic benefits.

6.1 Roundwood production and carbon sequestration

Here, we take a closer look at the roundwood production projections of our model at one-hectare landholding and country scales. At the landholding level we consider our three quality scenarios for the two production options of agroforestry and woodlots (Table 6). At the national scale, we explore the benefits from BSO planting based on the equating of BSO seed to the PY quality scenario, and consider climate mitigation effects.

In Table 6 and Figure 7, data on mean annual increment in total biomass (MAI TB), under-bark volume (MAI V_u) and branch biomass (MAI BRA) are summarised. These data, which are consistent with previously published productivity rates (Pohjonen, 1989; Burns & Honkala, 1990; Muchiri et al., 2002; Bekele, 2011; CABI, 2020), indicate the significant benefits that are achieved from CYG and PY quality scenarios compared to the AY baseline (e.g., 73% and 84% for MAI V_u and MAI BRA, respectively, for the woodlot production option with the PY quality scenario). The last figure of 84% for branch biomass improvement indicates the fuelwood benefits of the higher quality scenarios, which could substantially support meeting rural households' energy requirements in Ethiopia (Yigezu & Jawo, 2020).

Based on the assumptions for national scaling from a BSO given in section 5.4, the increased biomass production derived from the replacement of AY grevillea plantings with PY plantings would result in the sequestration of an additional 1.7 million tonnes of CO2 equivalents annually at a country level, averaged over the 50-year modelled period. Our rough estimate would also suggest that using BSO (PY scenario) grevillea seed rather than AY seed would satisfy an extra 4% of the country's roundwood demand by 2040, based on current estimates of requirements (World Bank, 2017).

Table 6. Summary of mean annual increments over a single cycle of production for grevillea planting options and quality scenarios

Planting option	**Quality scenario**	**MAI TB** (t^{-1} ha^{-1} y^{-1})	**MAI V_u** (m^3 ha^{-1} y^{-1})	**MAI BRA** (t^{-1} ha^{-1} y^{-1})
Agroforestry	AY	0.9	1.1	0.1
	CYG	1.2 (44%)	1.6 (38%)	0.2 (44%)
	PY	1.4 (70%)	1.8 (60%)	0.2 (69%)
Woodlot	AY	6.5	9.7	0.9
	CYG	9.7 (49%)	13.9 (43%)	1.4 (50%)
	PY	11.9 (82%)	16.8 (73%)	1.7 (84%)

Mean annual increment (MAI) data are reported for total biomass (TB), under-bark volume (V_u) and branch biomass (BRA). In brackets the percentage increase from the AY baseline quality scenario is given for CYG and PY scenarios

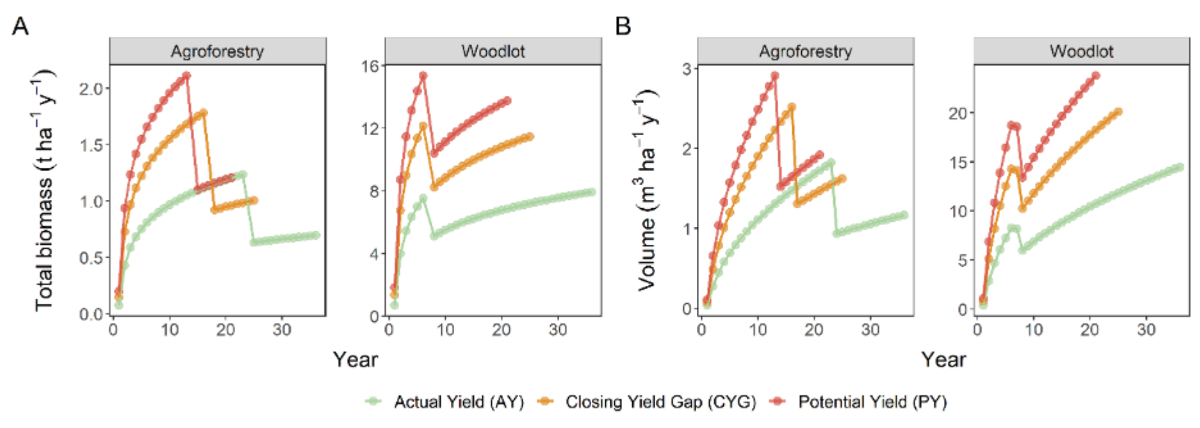

Figure 7. Mean Annual Increment for AGB (t ha^{-1} y^{-1}) and V_u (m^3 $ha^{-1}y^{-1}$) over time for grevillea production for agroforestry and woodlot planting options and three quality scenarios. The y-axis reflects one production cycle which varies in length for the quality scenario.

6.2 Sawnwood production and incomes

Here, we take a closer look at the value of sawnwood production for timber enterprises at the country scale, based on a baseline quality scenario compared to PY scenario trees raised from BSO seed. The price of timber sold by timber enterprises is often much higher than that received by growers (Nawir et al., 2007), so it is important to take this into consideration when considering the overall impact of germplasm quality improvement for the national economy.

Based on the assumptions for national scaling from a BSO given in section 5.4, the increased NPV of sawnwood derived from the replacement of AY grevillea plantings with PY plantings is estimated to be Birr 44 million annually. Over a 50-year period, PY plantings would generate an increase in sawnwood value of Birr 2.2 billion in total over AY plantings.

These estimates were based on a log recovery rate of 36% from roundwood to sawnwood volume (Abebe & Holm, 2003) and a price based on an import cost of sawnwood of 455 USD per m^3 (Girma, 2021). Only harvested timber with DBH > 26 cm was included in the analysis. We did not include the cost of processing logs in our estimation.

Our rough estimate would suggest that using BSO seed rather than AY seed of grevillea would bring significant benefits to timber enterprises.

7 Synthesis

In this working paper we have set out an approach to evaluate the benefits that can be achieved with using higher quality tree germplasm in smallholder tree plantings in Ethiopia. Our approach takes the case of grevillea, planted in agroforestry and woodlot production options, as its example. It systematically applies a series of steps to measure impacts, from growth modelling using a one-parameter regression of three different quality scenarios, through the parameterization of two planting options at a one-hectare scale, to outscaling findings nationally. Anticipated impacts at landholding and national scales were quantified in terms of additional timber production, carbon sequestration and sawnwood production. Our approach to estimate the benefits of using quality germplasm in tree planting provides some advances on previous methods (e.g. Kjaer & Foster, 1996; Marcu et al., 2020). It investigates the effects of improved germplasm on both profitability and environmental services, at both local and national scales, and can be applied when there is limited primary data. Our modelling shows that the returns on investment in using higher quality grevillea seed provided by a BSO should be considerable in terms of the extra value of wood from agroforestry and woodlot plantings, in the additional tonnes of CO2 equivalents sequestered, and in the superior returns on sawnwood production.

In our analysis we have modelled the benefits of using improved germplasm for grevillea planting in Ethiopia because more growth data are available for the species in East Africa than for most other tree species planted in the region. Grevillea is an exotic tree species to Ethiopia and arguably more interesting would be to model the benefits of using improved germplasm for native trees, as these are more important for achieving broader forest landscape restoration targets. With the basic model now developed for grevillea, it can be applied to native tree species in the future. This will become more relevant as more data on native tree species performance become available for East Africa. New sources of information are the BSOs that were recently established by the PATSPO initiative in Ethiopia for a range of indigenous timbers including the priority species *Cordia africana* and *Juniperus procera*. Data collected from these BSOs in the next few years will support modelling. Our current study indicates the clear benefits that should materialise from PATSPO's work to establish these BSOs to provide improved tree seed.

The benefits and costings laid out in the current study should only be considered as preliminary. This is for a range of reasons. For example, in our analysis we did not model the extra costs that would be involved in delivering BSO seed to smallholders, compared to them accessing business-as-usual seed from existing farmland trees as is common current practice. Improving smallholder growers' access to BSO germplasm involves considerable investments in the broader tree seed system, in terms of infrastructure and capacity development. (Note that the PATSPO initiative also takes on these additional roles, beyond producing BSO seed.) For growers, improving production is also not only about receiving improved tree seed inputs. For example, business loans may be required to support initial tree establishment before the financial and other benefits outlined in our modelling can be achieved. Our yield modelling approach for grevillea also has shortcomings due to the lack of extensive primary data on the tree's performance across Ethiopia's different agro-ecological zones. Our estimates of downstream timber value were also based only on very limited data.

Nevertheless, our analysis represents a useful starting point for future work that will address data gaps. Important information on grevillea growth will come from PATSPO establishment of BSOs of the species in Ethiopia, while farm surveys will be conducted in the country's highland regions to collect data on tree management strategies, timber and fuelwood prices, labour costs and market access.

Equally, our study also represents a springboard for germplasm supply modelling for other tree species and production systems outside Ethiopia.

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Appendices

Appendix I

Complete data for single tree growth characteristics

ID	Age	DBH	H	Country	Lat	Lon	Lon	Land use	Density	Reference
1	6	13.9	15.9	RWA	-2.43	28.93	28.93	Agroforestry	250	Kalinganire (1996)
1	7	17.7	11.7	RWA	-2.43	28.93	28.93	Agroforestry	250	Kalinganire (1996)
1	14	31.7	18	RWA	-2.43	28.93	28.93	Agroforestry	250	Kalinganire (1996)
1	15	40.1	21.2	RWA	-2.43	28.93	28.93	Agroforestry	250	Kalinganire (1996)
2	6	21.4	15.7	RWA	-1.72	29.26	29.26	Agroforestry	250	Kalinganire (1996)
2	7	17.8	15.3	RWA	-1.72	29.26	29.26	Agroforestry	250	Kalinganire (1996)
2	10	25.3	21.8	RWA	-1.72	29.26	29.26	Agroforestry	250	Kalinganire (1996)
2	12	21.5	19.9	RWA	-1.72	29.26	29.26	Agroforestry	250	Kalinganire (1996)
2	13	33	22.3	RWA	-1.72	29.26	29.26	Agroforestry	250	Kalinganire (1996)
3	4	11.1	10.9	RWA	-1.61	29.33	29.33	Agroforestry	250	Kalinganire (1996)
3	5	10.9	8.5	RWA	-1.61	29.33	29.33	Agroforestry	250	Kalinganire (1996)
3	7	13.9	10.7	RWA	-1.61	29.33	29.33	Agroforestry	250	Kalinganire (1996)
3	9	24	12.3	RWA	-1.61	29.33	29.33	Agroforestry	250	Kalinganire (1996)
4	5	7.9	9.2	RWA	-1.61	29.33	29.33	Woodlot	775	Kalinganire (1996)
4	7	14.2	13.2	RWA	-1.61	29.33	29.33	Woodlot	775	Kalinganire (1996)
4	9	9.8	11.4	RWA	-1.61	29.33	29.33	Woodlot	775	Kalinganire (1996)
4	17	24.2	30.1	RWA	-1.61	29.33	29.33	Woodlot	775	Kalinganire (1996)

5	8	19.3	11.2	RWA	-2.25	29.34	29.34	Agroforestry	250	Kalinganire (1996)
5	11	26.4	16.9	RWA	-2.25	29.34	29.34	Agroforestry	250	Kalinganire (1996)
5	15	25	19.5	RWA	-2.25	29.34	29.34	Agroforestry	250	Kalinganire (1996)
6	7	10.6	7.6	RWA	-2.25	29.34	29.34	Woodlot	775	Kalinganire (1996)
6	10	17.5	19.5	RWA	-2.25	29.34	29.34	Woodlot	775	Kalinganire (1996)
6	12	16.9	15.8	RWA	-2.25	29.34	29.34	Woodlot	775	Kalinganire (1996)
6	14	20.9	21.5	RWA	-2.25	29.34	29.34	Woodlot	775	Kalinganire (1996)
7	7	25.7	19.7	RWA	-2.59	29.41	29.41	Agroforestry	250	Kalinganire (1996)
7	8	18.8	14.8	RWA	-2.59	29.41	29.41	Agroforestry	250	Kalinganire (1996)
7	11	29.1	22.3	RWA	-2.59	29.41	29.41	Agroforestry	250	Kalinganire (1996)
7	17	24.6	21.2	RWA	-2.59	29.41	29.41	Agroforestry	250	Kalinganire (1996)
8	5	6.7	9.5	RWA	-2.59	29.41	29.41	Woodlot	775	Kalinganire (1996)
8	11	33.9	21.4	RWA	-2.59	29.41	29.41	Woodlot	775	Kalinganire (1996)
8	17	24.5	21.8	RWA	-2.59	29.41	29.41	Woodlot	775	Kalinganire (1996)
9	5	8.4	9.3	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	9.2	9.8	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	8.2	8.9	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	7.8	9	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	7.9	9	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	7.9	8.3	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	8.5	9.3	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	5	8.4	10.3	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	15.9	18.6	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	16.3	17.5	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	15.7	16.8	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	14.9	16.6	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	14.7	15.1	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)

9	8	13.6	17.1	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	12.3	13.8	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	8	12.3	16.4	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	19.1	20	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	19.5	20.1	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	17.3	19.2	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	17.2	17.2	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	18	17.4	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	16.8	20.6	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	18.4	19.6	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
9	18	19	19.1	RWA	-2.55	29.77	29.77	Woodlot	1,600	Mugunga (2009)
10	10	17	14	UGA	-1.08	29.87	29.87	Woodlot	1,372	Okorio and Peden (1992)
10	15	21	19	UGA	-1.08	29.87	29.87	Woodlot	1,372	Okorio and Peden (1992)
10	20	27	24	UGA	-1.08	29.87	29.87	Woodlot	1,372	Okorio and Peden (1992)
11	7	18.5	9	UGA	-1.25	29.98	29.98	Woodlot	1,372	Okorio and Peden (1992)
11	18	27.5	22.5	UGA	-1.25	29.98	29.98	Woodlot	1,372	Okorio and Peden (1992)
11	23	34	29	UGA	-1.25	29.98	29.98	Woodlot	1,372	Okorio and Peden (1992)
12	3	7	1.5	RWA	-2.23	30.11	30.11	Woodlot	1,111	Habiyambere and Musabimana (1992)
12	9	10	12	RWA	-2.23	30.11	30.11	Woodlot	1,111	Habiyambere and Musabimana (1992)
12	12	12	13	RWA	-2.23	30.11	30.11	Woodlot	1,111	Habiyambere and Musabimana (1992)
13	3	6.5	2	RWA	-2.23	30.11	30.11	Woodlot	1,600	Habiyambere and Musabimana (1992)
13	9	8.9	11	RWA	-2.23	30.11	30.11	Woodlot	1,600	Habiyambere and Musabimana (1992)
13	12	10.9	12	RWA	-2.23	30.11	30.11	Woodlot	1,600	Habiyambere and Musabimana (1992)
14	3	5.9	2.6	RWA	-2.23	30.11	30.11	Woodlot	2,500	Habiyambere and Musabimana (1992)
14	9	8	10.6	RWA	-2.23	30.11	30.11	Woodlot	2,500	Habiyambere and Musabimana (1992)
14	12	9.8	12.5	RWA	-2.23	30.11	30.11	Woodlot	2,500	Habiyambere and Musabimana (1992)
15	3	5	4.5	RWA	-2.23	30.11	30.11	Woodlot	4,444	Habiyambere and Musabimana (1992)

15	9	6.3	10	RWA	-2.23	30.11	30.11	Woodlot	4,444	Habiyambere and Musabimana (1992)
15	12	8.3	11.8	RWA	-2.23	30.11	30.11	Woodlot	4,444	Habiyambere and Musabimana (1992)
16	5	10.8	11.1	RWA	-2	30.16	30.16	Agroforestry	250	Kalinganire (1996)
16	8	22.6	20.4	RWA	-2	30.16	30.16	Agroforestry	250	Kalinganire (1996)
16	10	19.4	16.1	RWA	-2	30.16	30.16	Agroforestry	250	Kalinganire (1996)
16	11	29.3	20	RWA	-2	30.16	30.16	Agroforestry	250	Kalinganire (1996)
16	15	22.7	21	RWA	-2	30.16	30.16	Agroforestry	250	Kalinganire (1996)
17	5	8.5	10.5	RWA	-2	30.16	30.16	Woodlot	775	Kalinganire (1996)
17	7	11.6	12.7	RWA	-2	30.16	30.16	Woodlot	775	Kalinganire (1996)
17	8	21.8	18.3	RWA	-2	30.16	30.16	Woodlot	775	Kalinganire (1996)
17	15	17.4	17.1	RWA	-2	30.16	30.16	Woodlot	775	Kalinganire (1996)
18	8	13	14	UGA	0.7	30.55	30.55	Woodlot	1,736	Okorio and Peden (1992)
18	15	21	18.5	UGA	0.7	30.55	30.55	Woodlot	1,736	Okorio and Peden (1992)
18	19	22.5	23.5	UGA	0.7	30.55	30.55	Woodlot	1,736	Okorio and Peden (1992)
18	24	32	25.2	UGA	0.7	30.55	30.55	Woodlot	1,736	Okorio and Peden (1992)
19	3.5	9	10	UGA	0.58	31.42	31.42	Woodlot	1,768	Okorio and Peden (1992)
19	4	11	12	UGA	0.58	31.42	31.42	Woodlot	1,768	Okorio and Peden (1992)
19	9	20	17	UGA	0.58	31.42	31.42	Woodlot	1,768	Okorio and Peden (1992)
19	15	29	23.5	UGA	0.58	31.42	31.42	Woodlot	1,768	Okorio and Peden (1992)
20	6	14.5	15	UGA	0.42	32.92	32.92	Woodlot	1,276	Okorio and Peden (1992)
20	7.5	17.5	17.5	UGA	0.42	32.92	32.92	Woodlot	1,276	Okorio and Peden (1992)
20	11	19.5	20	UGA	0.42	32.92	32.92	Woodlot	1,276	Okorio and Peden (1992)
20	16	24.5	22.5	UGA	0.42	32.92	32.92	Woodlot	1,276	Okorio and Peden (1992)
21	6	12.5	12	UGA	0.43	33.17	33.17	Woodlot	3,086	Okorio and Peden (1992)
21	9	17.5	17	UGA	0.43	33.17	33.17	Woodlot	3,086	Okorio and Peden (1992)
21	18	23	22	UGA	0.43	33.17	33.17	Woodlot	3,086	Okorio and Peden (1992)
22	2	5.3	6	KEN	-0.04	34.12	34.12	Agroforestry	10,000	Otieno (1992)

22	2	5.3	6.8	KEN	-0.04	34.12	34.12	Woodlot	10,000	Otieno (1992)
22	5	10.1	10.7	KEN	-0.04	34.12	34.12	Agroforestry	10,000	Otieno (1992)
22	5	6.9	9.8	KEN	-0.04	34.12	34.12	Woodlot	10,000	Otieno (1992)
26	1	2.5	0.8	ETH	7	35.92	35.92	Agroforestry	2,500	Yakob Edo (2017)
26	2	3.6	3.03	ETH	7	35.92	35.92	Agroforestry	2,500	Yakob Edo (2017)
26	3	4.3	4.16	ETH	7	35.92	35.92	Agroforestry	2,500	Yakob Edo (2017)
27	2	2.5	2.4	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	2	3.9	2.5	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	3	6.2	4.4	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	3	6.8	4.6	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	4	8.7	6.3	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	4	9.9	6.5	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	5	10.5	6.9	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	5	12.6	7.5	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	6	14.7	8.9	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	6	16.7	9.3	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	7	18.3	9.9	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)
27	7	21.5	10.9	KEN	-1.02	36.05	36.05	Agroforestry	1,600	Kiriinya (1994)

Unique IDs, alpha-3 country codes and latitude (lat) and longitude (lon) are linked to each specific observation. Tree phenotypical data collected are tree age (years), tree top height (m) and tree diameter at breast height (DBH, cm). Initial planting density per hectare and main land use are also sourced information.

Appendix II

For both agroforestry and woodlot planting options, only 'field establishment' activities were included as the initial cost stage (year 1). A proportional cost per tree was derived from original BSO field establishment costs per ha by dividing by the number of trees planted (for the BSO this was 2,500 ha^{-1}). The cost per tree was then multiplied by the number of trees for each planting scenario. The original data were obtained from PATSPO staff and referred to management activities up to one year after planting the BSO. Variable planting option costs through the production cycle were estimated based on the available literature (Pohjonen, 1989; Bekele, 2011; Matthies & Karimov, 2014), plus using a salary rate of 80 Birr/person-day of work (Nigussie et al., 2020). Below, the establishment costs of BSOs and planting options are explained in detail. This begins with a table summarising the activities and sub-activities needed to establish a grevillea BSO in Ethiopia, according to PATSO staff.

Summary of activities and sub-activities with related total costs for establishing a grevillea BSO in Ethiopia (2,500 trees, 1 hectare)

Activity	Sub-activities	Cost (Birr)	% of total costs
Field establishment	Site clearance, fibre ropes, larger poles/sticks for layout, wage for layout preparation, pitting, planting	26,850	5.7
Miscellaneous	10% for measurement and inventory, fuel, etc.	38,755	8.3
Nursery operation	Seed procurement, nursery clearance, lumber for nursery beds, plastic bag for pots, forest soil from local suppliers for potting up, sand from local suppliers, straw for shade, soil mixing, pot filling, seed sowing, seedling shed construction, seedling transplanting/singling, watering, weeding, root pruning, foreman, seedling packing before establishment, seedling transport to planting site	85,540	18.3
Fencing	Wire mesh for fencing, bigger poles for fencing, smaller poles, skilled labour, nails	135,000	28.9
Post-establishment (initial costs)	Guards, water, watering wage, weeding	140,160	30.0
Extra	Watering cans, water hose, tanker	41,600	8.9

The costs cover a period of up to one year after planting.

Considering now our two planting options, the costs are explained below in the further table. The annual land tax was set at 160 Birr/ha. Establishment and weeding costs were sourced from BSO costs (above). For both agroforestry and woodlot planting options, timber harvest is not included as a labour cost, since farmers commonly sell timber as standing trees (to local saw-millers). Fuelwood harvest (50% pruning of total branch biomass produced per year) is calculated using a rate of 0.5 Birr per tree, based on Nigussie et al. (2020). The same rate is used for the thinning of woodlots. Harvesting of fuelwood is considered as an activity which is ongoing yearly from year 4 until the end of the production cycle. Establishment costs include the value of seedlings. The cost of seedlings is set at 4.6 Birr/unit except for high-yielding varieties (PY) which are valued at 6.9 Birr/unit. The establishment costs during the second year are related to the re-planting of dead seedlings (for 20% of seedlings).

Table of cost flow related to management activity for each grevillea planting option

Scenario	Activity	Year 1	Year 2	Years 3 - 5	Years 6 – 10	Years 11 - n
Agrofor-estry	Tending	644	-	-	-	-
	Timber Harvest	-	-	-	-	80 (harvest I and II)
	Fuelwood labour	-	-	40 (year 4+)	40	40 (20 after harvest I)
	Seedlings	AY & CYG = 275 PY = 412	AY & CYG = 55 PY = 78	-	-	-
	Weeding	192	-	-	-	-
Woodlot	Tending	11,814	-	-	-	-
	Timber	-	-	-	733 (year 7)	1,467 (har-vest II)
	Fuelwood labour	-	-	733 (year > 3)	733 (up to year 9)	-
	Seedlings	AY & CYG = 5,033 PY = 7,549	AY & CYG = 1,006 PY = 1,510	-	-	-
	Weeding	845	-	-	-	-

All costs in the above table are in Birr and the single production cycle is divided into sub-periods to simplify the table layout, with n being the last harvest year. When a cost figure is not repeated throughout the sub-period indicated in the column header, years are specified in brackets. Harvest I and harvest II refer to the year when the DBH threshold is reached and trees are harvested. The year number is variable because productivity rates are different depending on the quality scenario.

DOI: 10.17528/cifor-icraf/008579

CIFOR-ICRAF *Working Papers* contain preliminary research results on tropical forest issues that need to be published in a timely manner to inform and promote discussion. This content has been internally reviewed.

This study was developed in the context of the Provision of Adequate Tree Seed Portfolios (PATSPO) initiative in Ethiopia. PATSPO aims to strengthen the existing tree-seed system by ensuring access to high-quality tree germplasm. Here, we estimate the socioeconomic impact of establishing a breeding seedling orchard (BSO) and distributing quality planting material of the tree *Grevillea robusta* (grevillea) in Ethiopia. Grevillea is a commercially important and popular agroforestry tree species grown in East African smallholder farms. Our study starts by modelling tree growth with a one-parameter regression fitted to literature-sourced growth characteristics. For the purpose of modelling, we identify three 'quality scenarios' (related to the germplasm used) and two 'planting options'. Based on the model's outputs, we investigate the effects of increased tree productivity on farmland economy, on the provision of environmental services, and on the wider forestry sector. Findings are outscaled based on the demand for grevillea planting material in Ethiopia and an assumed reach of PATSPO-derived high-quality germplasm. Our growth models indicated that higher than baseline quality scenarios could produce a significant increase in volume (and biomass productivity). This resulted in several-fold increases in the net present value over the production cycle of agroforestry and woodlot plantings, as well as significant benefits in other economic indicators. At the country scale, our analysis estimated that after 50 years the increase in cumulative net present value of on-farm grevillea plantings should be between Birr 2.7 billion and 1.9 billion when using high-quality germplasm compared to an unimproved germplasm baseline, a significant boost (38 Birr = 1 USD at the time of calculations in 2021). We therefore reveal that establishing a grevillea BSO in Ethiopia could produce significant economic returns for tree growers that are much higher than the initial investment that we determine to be required. Furthermore, using BSO germplasm compared to an unimproved germplasm baseline could over 50 years after the BSO's establishment sequester an extra 1.7 million tonnes of CO2 equivalents annually and achieve an increase in net present value annually of Birr 44 million in roundwood milling into sawnwood. In summary, our current analysis indicated that a focus on grevillea's germplasm quality is predicted to bring significant economic and environmental benefits in Ethiopia. Our approach to estimate the benefits of using quality germplasm in tree planting represents an advance on previous methods and can be widely applied to a broad range of species, production systems and locations.

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