Master thesis 2021:09

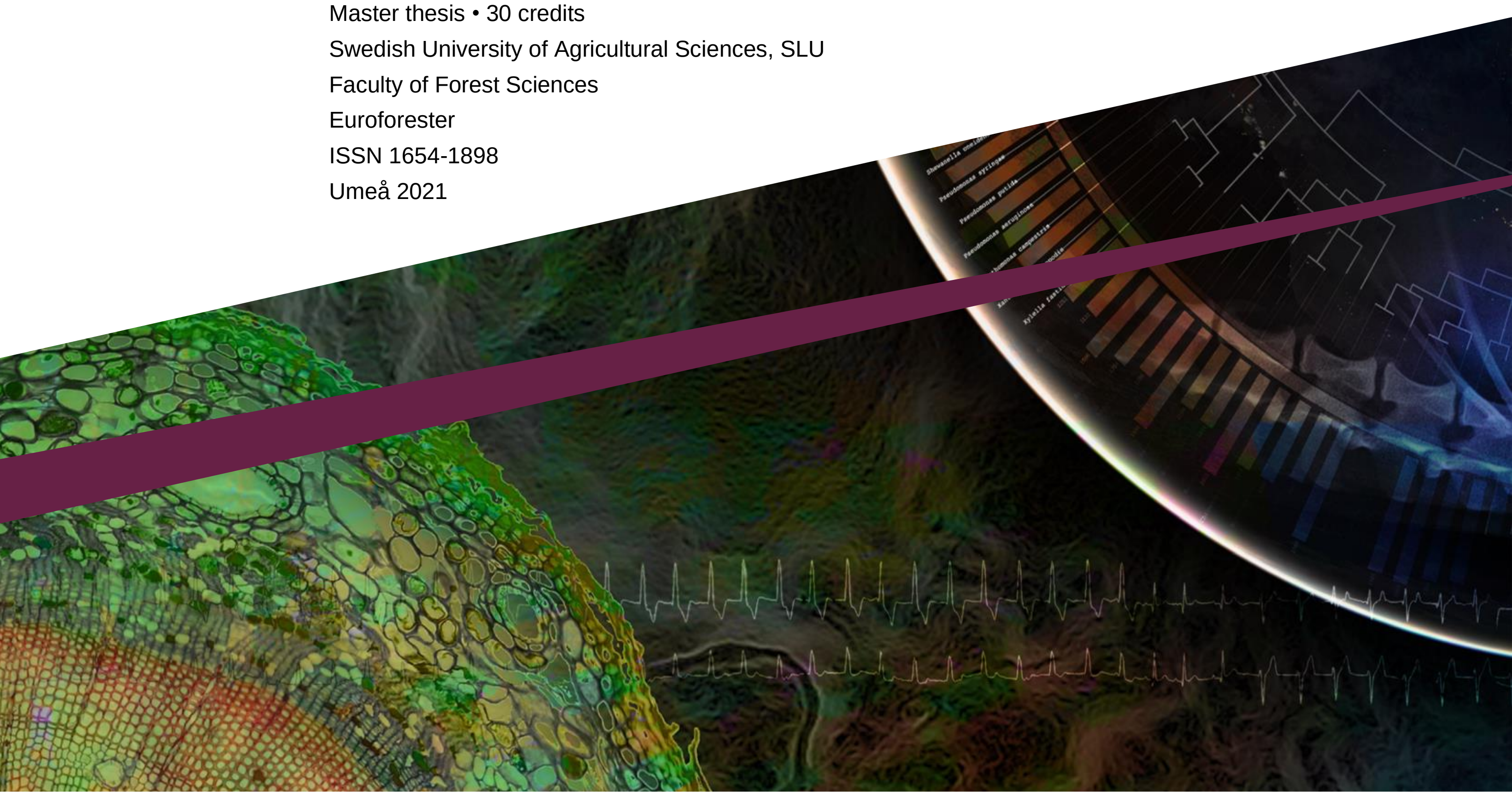
Department of Forest Ecology and Management

Implementation of native tree species in Rwandan forest plantations

– Recommendations for a sustainable sector

Roberto Stelstra

Master thesis • 30 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Forest Sciences
Euroforester
ISSN 1654-1898
Umeå 2021



Implementation of native tree species in Rwandan forest plantations – Recommendations for a sustainable sector

Roberto Stelstra

Supervisor:	Dr. Rosa Goodman, Swedish University of Agricultural Sciences, Forest Ecology & Management
Assistant supervisor:	Dr. Beth Kaplin, University of Rwanda, Biodiversity & Natural Research Management
Examiner:	Dr. Gert Nyberg, Swedish University of Agricultural Sciences, Forest Ecology & Management

Credits:	30 credits
Level:	Second cycle, A2E
Course title:	Masters Thesis in Forestry Science
Course code:	EX0958
Programme/education:	Euroforester Programme
Course coordinating dept:	Department of Forest Ecology & Management
Place of publication:	Umeå
Year of publication:	2021
Part number:	2021:09
ISSN:	1654-1898

Keywords:	Silviculture, Tropical, Mixed plantations, Indigenous species

Swedish University of Agricultural Sciences
Forest Ecology & Management
Tropical Forestry

Publishing and archiving

Approved students' theses at SLU are published electronically. As a student, you have the copyright to your own work and need to approve the electronic publishing. If you check the box for **YES**, the full text (pdf file) and metadata will be visible and searchable online. If you check the box for **NO**, only the metadata and the abstract will be visible and searchable online. Nevertheless, when the document is uploaded it will still be archived as a digital file.

If you are more than one author you all need to agree on a decision. Read about SLU's publishing agreement here: https://www.slu.se/en/subweb/library/publish-and-analyse/register-and-publish/agreement-for-publishing/.

☒ YES, I/we hereby give permission to publish the present thesis in accordance with the SLU agreement regarding the transfer of the right to publish a work.

☐ NO, I/we do not give permission to publish the present work. The work will still be archived and its metadata and abstract will be visible and searchable.

Abstract

The forest plantations in Rwanda have been dominated by monocultures of exotic species, primarily *Eucalyptus* and *Pinus*, for the last 100 years. This type of monoculture leaves the forests vulnerable to disturbances like pests and droughts, and has a negative impact on the species biodiversity in the Rwandan forests. In 2018, the Rwandan Forest Authority released a revised version of their National Forest Policy, in which they recognize the importance of practising a more sustainable form of forestry. Through interviews and literature research this study has aimed to find out which products and traits are sought after in the Rwandese forestry sector, which native species possess these traits and if they could be a competitive alternative to the current exotic species.

I found that timber production still is the main priority in the Rwandan forestry sector, but ecological value, services for local communities and medicinal qualities are also valued. The qualities and traits of eleven potentially useful, native tree species have been analysed and compared. A selection of potentially useful species was made based on their biophysical requirements, their wood quality and the non-timber forest services they could provide. Of these species *Maesopsis eminii*, *Markhamia luta*, *Prunus Africana* and *Milicia excelsa* seem promising alternatives to the established exotic plantation species. Based on those four species a management plan for a mixed-species plantation has been designed, which will be implemented and monitored by the Rwandese forest company SEAL Ltd.

Table of contents

List of tables

List of figures

Abbreviations

DBH	Diameter at Breast Height
DRC	Democratic Republic of the Congo
FRSG	Forestry Research Strategy and Guidelines for Rwanda
IUCN	International Union for Conservation of Nature
LC	Least Concern
MAI	Mean Annual Increment
NFP	National Forest Policy
NTFS	Non Timber Forest Service
RFA	Rwanda Forest Authority
RMA	Rwanda Meteorology Agency
RWFA	Rwanda Water and Forest Authority
SEAL	Sawmill East Africa Limited
SDG	Sustainable Development Goals
SLU	Swedish University of Agricultural Sciences
TSC	Tree Seed Centre
UR	University of Rwanda
VECEA	Vegetation and Climate change in Eastern Africa
WCMC	World Conservation Monitoring Centre

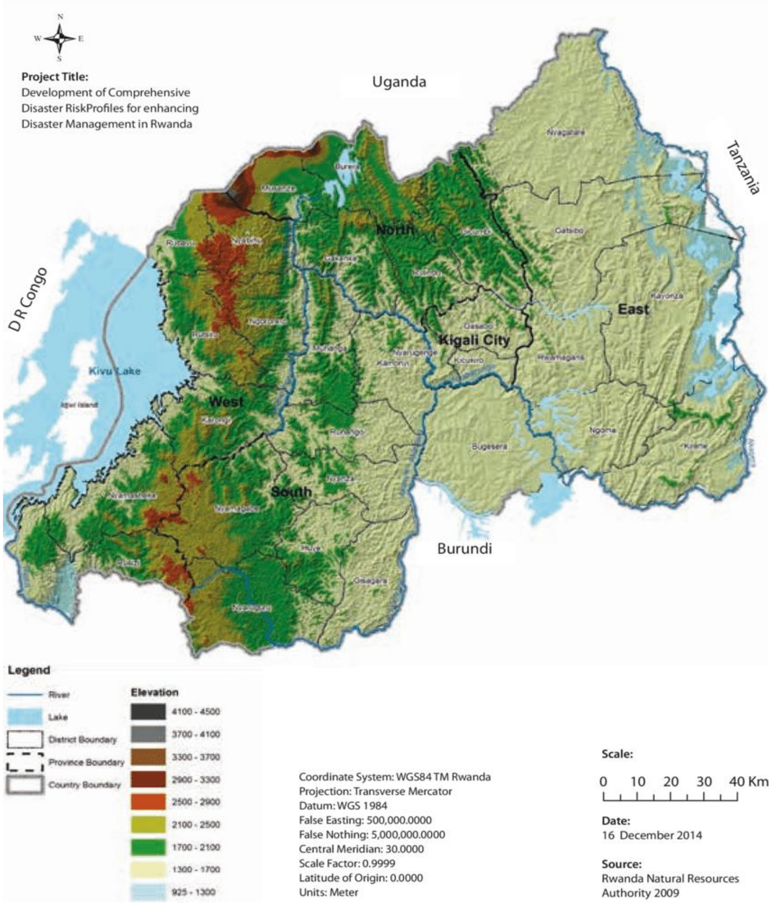
1. Introduction

Rwandan forests are running out of Rwandan tree species. A century of plantation management with exotic species has transformed the landscape and ecosystems completely, which has a negative impact on biodiversity and sustainability of these forests. Large areas of natural forests have been replaced by agricultural plots and single-species, even-aged forest plantations. This study aims to identify native Rwandan tree species that can diversify Rwanda's forest plantations while serving as an economically viable alternative. To do so we need to understand the current situation of Rwanda and its forestry sector first.

1.1. Topography & climate

Rwanda is a relatively small country in Central Africa, located between 1°4' and 2°51' Southern latitude and between 28°45' and 31°15' Eastern longitude (Haggag *et al.*, 2016). It shares its eastern border with Tanzania, its southern border with Burundi, in the west it borders the Democratic Republic of Congo and in the north lies Uganda (Plumtre *et al.*, 2007). Rwanda's landscape is dominated by hills and mountains and its altitudes range from 900 to 4507 masl, which follows a strong East-West gradient (Haggag *et al.*, 2016). In the eastern part of the country the landscape consists of savannah and has an altitude of 1300-1700 meters. Towards the west, the landscape gradually shifts to the mountainous Albertine rift, where Rwanda's highest peaks can be found. This rift is one of Africa's biodiversity hotspots and extends from Lake Tanganyika in the south to 30 km north of Lake Albert (Plumtre *et al*., 2007). It was formed by the diverging movements of the Nubian African Plate and the Somalian African Plate, a process which still causes a lot of volcanic activity in the region. The variability in elevation and bedrock material caused by this process has created a mosaic of different soils, climate types and habitats across Rwanda.

Figure 1 "Elevation map of Rwanda" by Dalena et al., 2015



The climate in Rwanda, due to its proximity to the equator, is tropical (Haggag *et al.*, 2016). However, as a result of Rwanda's topography is there a strong east-west gradient in precipitation as well. In the eastern savannah, the annual precipitation is around 900 mm/ year (Rwanda Meteorology Agency, 2021).

In the Rift region however, the climate is that of a montane tropical forest. It has a wet season extending from September to May, with an average rainfall of over 1500mm/ year (Rwanda Meteorology Agency, 2021). The most intense rain period occurs in September and November, during which months the precipitation will average 10mm/day. There are also two periods of precipitation reduction during this wet season, in late January and late February. In the dry season, in the months from June to August, the precipitation is much lower.

Due to its location so close to the equator, the area knows only a small thermal seasonality. The average maximum daily temperature is about 20 C^{o} year-round, and the minimum is around 12 C^{o}. These temperatures show very little variation through-out the year. (Seimon, 2012).

1.2. Native forest

As described in the previous paragraph, the Rwandan ecosystems are heavily influenced by the East-West gradient of its climate and topography and the country knows three major landscape types (see Appendix 1). The savannahs in the East, which are evergreen and semi-evergreen bushlands (Be), according to the classification system as described in *The vegetation of Africa* (White, 1983), are characterised by their drier, park-like landscape. This ecosystem hosts a range of the typical African savannah species, like elephants (*Loxodonta africana*), zebras (*Equus quagga*), African buffalos (*Syncerus caffer*), lions (*Panthera leo*) and leopards (*Panthera pardus*). Especially the large ungulates have a large effect on the flora composition of the ecosystem. Some characteristic tree species of this system are several *Acacia spp.*, *Juniperus procera*, *Olea europaea* and *Osyris lanceolata* (Breugel *et al.*, 2015).

Just east of Kigali the savannah landscape becomes more hilly and shifts to Lake Victoria Transitional Rainforest (Ff; White, 1983). This forest type occurs at altitudes between 1600 and 1900 m in the eastern Kivu-region of the DRC, in Western Rwanda and in Burundi. Characteristic tree species in this ecosystem are *Carapa procera*, *Maesopsis eminii*, *Prunus africana* and *Symphonia globulifera* (Breugel *et al.*, 2015).

On the west-side of Rwanda the landscape is dominated by Afromontane Rainforests (Fa; White, 1983). These forests occur at an altitude of 1200-2500 m and have an annual rainfall of 1250-2500 mm. Almost all species are evergreen in this ecosystem. The forests provide habitat to a range of primates, including the chimpanzee (*Pan troglodytes*), mountain gorillas (*Gorilla beringei beringei*) and colobus monkeys (*Colobus angolensis*). The Afromontane rainforest distinguishes from the West-African rainforests by the presence of conifers and tree ferns in the canopy. Characteristic species include *Podocarpus latifolia, Entandrophragma excelsum*, and *Prunus africana* (Breugel *et al.*, 2015).

1.3. History of Rwandan silviculture[1]

The land which is now known as the Republic of Rwanda has been inhabited by humans for tens of thousands of years. The first inhabitants of this region were hunters and gatherers in the forests that used to cover this land. They lived in small communities with their own political units and hunted both small and large game. Vegeculture was minimally practised in small forest clearings. These hunters and gatherers were eventually joined by an agricultural group. Unlike the hunter-

[1]This history is a simplification of the actual events and will leave out the complicated history between Rwanda's ethnic and social groups, as it is of little relevance for the scope of this study.

gatherers, the new people started clearing the forest in order to establish permanent settlements and agricultural fields where they grew products like sorghum and bananas. The agriculturalists gradually claimed more land and pushed back the hunter-gatherers and became the dominant culture.

During the 15th century, several pastoralist groups migrated into Rwanda, some of which would establish the first kingdoms. In the 19th century these kingdoms merged into what would become the Kingdom of Rwanda, and it covered roughly the same land as now. All these groups of pastoralists and agriculturalists managed the land quite intensively with herding cattle, fields of banana and sorghum (Rennie, 1972).

In 1885, at the Berlin Conference, Rwanda was put under German influence. This was made official in 1897. However, Germany's colonies were split up and divided among other European nations after the defeat of Germany in World War I, and Rwanda was colonized by the Belgians in 1916 (Kamatali, 2014).

Before the Germans and the Belgians arrived, the farmers of Rwanda had a long tradition of small scale silviculture with local shrub and tree species. Around their farms and households they planted species like *Ficus thonningii, Erythrina abyssinica, Markhamia lutea* and *Dracaena afromontana* (RWFA, 2017). These species had many values; they provided fodder, food, medicine and fuelwood, among other products. Around 1900, Belgian missionaries brought in exotic species of which they knew were fast-growing (RFA, 2021). They introduced *Eucalyptus spp.* and *Grevillea robusta* from Australia and *Cupressus lusitanica* from Central America, of which especially *Eucalyptus* was used a lot (Ndayambaje, 2013). The Belgians needed large quantities of timber to build churches, bridges and houses (RFA, 2021). They also needed more fuelwood and wanted to reduce soil erosion on mountaintop areas (Amsallem *et al.*, 2002). A large scale reforestation project with the exotic species was started, with as goal to establish 1 ha of woodlots per 100 inhabitants. These stands were primarily planted on land previously cleared by farmers for agriculture (Ndayambaje, 2013). These efforts continued until 1948.

In 1962 Rwanda regained its independence. By 1967, roughly 20,000 ha of exotic stands had been established, of which the majority were *Eucalyptus*. This year marked the beginning of true forestry in Rwanda. With funding from Switzerland, the Kibuye Pilot Forestry Project (PPF) was launched. This project managed to reforest 5500 ha of land in a ten year time span (Ndayambaje, 2013; Amsallem *et al.*, 2002). In 1975, the reforestation of Rwanda was given a new stimulus. In order to achieve the large-scale reforestation plans, the Rwandan government introduced the national holiday 'Umuganda' (National Arbor Day). Every year on the last Saturday of October, the whole country is mobilized to plant new trees (Amsallem *et al.*, 2002). This policy, in combination with the running projects, resulted in an increase in the plantation area from 25,500 ha in 1975 to

247,500 ha in 1989 (Ndayambaje, 2013; RWFA, 2017). The species supplied by the government were the same species that the Belgian colonizers introduced, especially *Eucalyptus spp.* As this species requires almost no silvicultural knowledge to manage (for firewood), it was ideal to supply to famers. (Ndayambaje, 2013).

What happened in the period from 1990 to 1994 is somewhat unclear. According to Amsallem (2002), the expansion of the plantation area continued slowly for a couple more years, until it came to a complete halt in 1994 due to the Rwandan Civil War and the genocide that followed. According to Ndayambaje (2013) , 15,000 ha of plantations were destroyed during this war by illegal logging, agricultural expansion and for the establishment of refugee camps for returning civilians . Although uncertain to which extend, it is obvious that the Civil War had a large impact on Rwanda's forests.

In the post-war period from 1995 to 1999, reforestation efforts were slowly started again. In 1999, the government decided to distribute free *Eucalyptus* saplings to farmers to speed up the efforts. In recent years, a couple major projects (Rwanda Forest Management Project (PAFOR) in 2002, Rwanda Reforestation Support Programme (PAREF) in 2008) have contributed to afforestation as well, along with the first National Forest Policy in 2003 and the new version in 2010 (Nduwamungu, 2011).

While there have been many, often successful, efforts to increase Rwanda's plantation area over the last century, there has been a vast decline in natural forests as well. In the period between 1960 and 2007, the area decreased by 64%. The main drivers for this decline are illegal forest extraction, artisanal mining activities, urbanization and the related infrastructure development and agricultural expansion (RWFA, 2017).

1.3.1. Mixed forest plantations

Even-aged monoculture plantations have dominated plantation forestry worldwide for a long time and still continue to do so, but the interest for mixed-species plantations is growing fast. This trend has only recently gained some momentum, so for now there is limited understanding about the dynamics and mechanisms of mixed-species plantations, and even less about those with (African) tropical species. There is no fixed definition of mixed-species forestry. Mixed-species stands usually consists of 2-4 species, although more complex systems are possible. The system can either be a even-aged system or an un-even aged system (Liu *et al.*, 2018).

Whichever complexity is being used, it is evident that there are a great deal of advantages to this system as opposed to monocultures. The mix of species in this type of plantations creates more ecological niches and can thus sustain a larger species richness in its system. This creates a more valuable matrix between the areas with natural forests and can have a positive effect to the productivity of the surrounding lands. For example, by using native, flowering species, many pollinating insects, like honeybees, will be supported. These species are also vital for successful agriculture, and mixed plantations are more resilient to pests and abiotic disturbances, such as droughts and storms. Moreover, if an uneven-aged system is used, the stand can be harvested without having to risk soil erosion, which is a big advantage in hilly or mountainous areas. Another benefit to the soil is the lower risk of nutrient depletion. As different species require different ratios of nutrients, the use of resources in a mixed system will be maximized, which could lead to a higher productivity of the site (Liu *et al.*, 2018).

However, this is not always the case. Under certain circumstances the productivity and soil fertility can decrease due to asymmetrical competition. It is hard to predict in which cases this will become a problem due to the limited research to mixed plantations. In any case is it important to select species with compatible growth rates to avoid suppression by the fast-growing species (Forrester *et al.*, 2005). Another disadvantage compared to monocultures is the complexity of the system. The reason that monocultures are so successful and popular is that they are simple and efficient, which lowers the production costs. A mixed stand will require more labour-costs in planting, maintenance and harvesting, and it will be more difficult to use specialized tools in the processing stage (Liu *et al.*, 2018). As a consequence the end-product could be more expensive.

Although asymmetrical competition can be an issue when done wrong, combining species with complementary traits is the key to a more productive mixed stand. Combinations of shade-tolerant and sun-loving species, pioneer and climax species, species with different canopy heights and structures, etc., can increase the production levels by reducing competition for resources.

Currently, one of the biggest challenges for mixed-species forestry is the limited scientific knowledge about the individual species and the mechanisms in which they respond to each other on a stand level, which makes site matching and species matching complicated. The other big challenge is the stigma around this system. Many foresters are convinced that high yields are not possible with this system (Liu *et al.*, 2018).

The opportunity for Rwanda lies in the current small scale of their industry. As the sector is still developing rapidly and is not yet optimized for even-aged monoculture production, there are still options to experiment with other forestry systems.

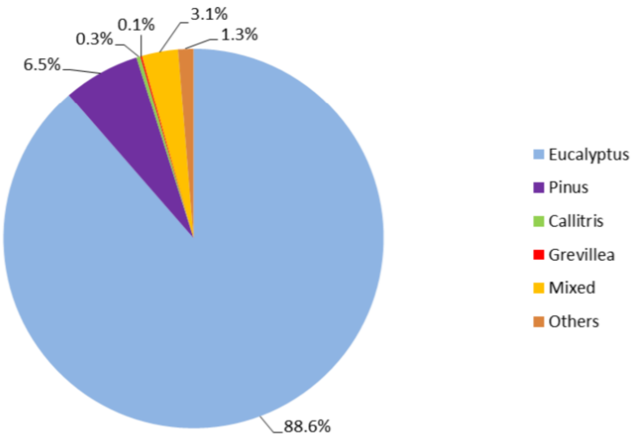
1.4. Problem description

The events of the past century have left their marks on the Rwandan landscape. The state coordinated reforestation efforts have been successful in increasing tree cover, and the current forest cover in Rwanda is now 30.4%[2] (Ministry of Environment, 2019).

However, this same reforestation policy has leaned heavily on exotic species. In 2008, 89.3% of all plantation area consisted of *Eucalyptus spp.* and 6.2% *Pinus spp*. The most planted native species was *Maesopsis eminii*, with an area coverage of less than 0.001% (4 ha) (Nduwamungu *et al*., 2013; **Fout! Verwijzingsbron niet gevonden.**).

In addition to this low variability in forestry plantations, the natural forests have suffered a 45.3% decline in area between 1984 and 2015 to 235,192 ha. The remaining natural forests are heavily fragmented and scattered through an agricultural landscape. The largest remaining areas in 2015 were Nyungwe National Park (rainforest), Volcanoes National Park (rainforest) and Akagera National Park (savannah shrublands) (RWFA, 2017). The rest of the natural forests are minor national parks and forests, sometimes as small as 6 ha.

Figure 2 "Plantation species composition in Rwanda."



This combination of declination of natural forests and the planted exotic stands have diminished the biodiversity in Rwanda's forest ecosystems.

Another issue with Rwandan forestry is the low production levels of the forest plantations. The average standing volume of plantation stands in the country is 50 m^3/ha (FRSG; Ministry of Environment, 2019) with an annual increment of less than 8 m^3/ha/y (RWFA, 2017). These levels are very low, especially considering the tropical climate. In comparison, Brazilian *Eucalyptus* plantations have an average annual increment of 40 m^3/ha/y (FAO, 2001). This low productivity has a number of causes.

[2] Forest is defined by the RWFA as a system with >10% canopy coverage, >7m (potential) tree height and an area of >0.25 ha (RWFA, 2017).

The deforestation in Rwanda has led to a lowered soil fertility. In the process of cutting down and extracting timber, the soils have lost a large amount of nutrients due to erosion and outwash. After clearing, these soils often have been converted to intensive, single-crop agricultural plots, which has contributed to further depletion of the nutrients in the soil (RWFA, 2017).

The second factor is poor silviculture. A lot of *Eucalyptus* stands have had no follow-up maintenance after establishment. During and after the civil war, a lot of stands, both public and privately owned, were neglected. Afterwards, the government had no capacity to maintain all the public stands either, so a lot of them were either abandoned or illegally harvested. However, *Eucalyptus* resprouts very easily from the stump after you cut down the tree, so a lot of production stands have transformed into degraded coppice stands. This is the same trait that made *Eucalyptus* a great species for farmers. They mainly needed charcoal and firewood, and without extensive silvicultural knowledge they could manage coppice plantations to supply their needs (Hakizimana *et al.*, 2020; SEAL, 2020).

The third factor is the quality of available genetic material. Officially, the seeds are distributed by the Tree Seed Centre. This institution gathers the seeds from selected seed trees that meet the set requirements and are then tested for quality. This test investigates factors like purity, germination rate, moisture content, etc. The quality, however, is currently quite poor due to bad selection and genetic bottlenecks. This has led to inbreeding and low genetic diversity in the stands, with low production levels as a consequence. This is especially the case for indigenous species, as the focus mainly has been on exotic species in the past. Therefore, there is also limited knowledge on indigenous species in terms of pre-sowing treatments, seed physiology, et cetera (Ministry of Lands and Forestry, 2018).

Figure 3 "Sawing pit". Photo by Berty van Hensbergen.

A major utilization of Rwandan forests is the production of sawn timber for construction projects. The most used species for this production are *Eucalyptus* and pine. This process is not so efficient as the sawmills in Rwanda are mostly outdated, and sometimes even sawing pits (*figure 3*) are still in use. Additionally, the drying process is inefficient. Especially *Eucalyptus* is hard to dry and there are few drying kilns in Rwanda. These factors lead to poor quality timber and wasteful processing (SEAL, 2020).

1.4.1. Current policy

In 2018, the Ministry of Lands and Forestry published the revised version of the 2010 National Forest Policy. This new policy has implemented a range of international development programmes. One of the programmes that are mentioned in the NFP is that of the Agenda 2030 Sustainable Development Goals. Specifically Goal 5 (Gender Equality), 13 (Climate Action) and 15 (Life on Land) are to be implemented in the NFP 2018 (Ministry of Lands and Forestry, 2018).

Another mentioned development programme is the Bonn Challenge. This initiative by the IUCN is a global effort to restore degraded lands, mainly by reforestation. In 2011, Rwanda pledged to reach a national forest cover of 30% by the year 2020, which was reached in 2019 (Ministry of Environment, 2019). However, in the pursuit to reach this goal of afforestation, other aspects of forestry, like ecology and silvicultural practises, were overlooked (Ministry of Lands and Forestry, 2018). The other commitment to the Bonn Challenge was the restoration of 2 million ha of degraded land by 2030. The development of agroforestry has been identified as the biggest opportunity to meet this pledge (Ministry of Lands and Forestry, 2018).

To reach both the international development goals and the national goals, there is a range of topics that the NFP 2018 focusses on. One of the focal points is to encourage the development of the private sector. 29% of the forest plantations in the country is public (owned by the state or districts). In 2018, the Ministry of Lands and Forestry concluded that they did not have the capacity and resources to manage this forest themselves and decided to outsource these forests to private companies. By 2022, 80% of these public plantations should be outsourced through long-term concession contracts (Ministry of Lands and Forestry, 2018).

Some of the other areas of focus are mitigation of climate change, preserving biodiversity, reducing the utilization of biomass energy (charcoal/ firewood), increased revenue from the forestry sector and job-creation, and finding a balance between sustainable yield and ecological conservation (Ministry of Lands and Forestry, 2018).

The most relevant part of the NFP for the scope of this research are two specific challenges in the Rwandan forestry sector that are mentioned:

1. *"The predominance of one species"*: The NFP recognizes that 80% of the trees used in reforestation and afforestation efforts are from the *Eucalyptus* genus and that this poses a threat in the outbreak of pests. Therefore, the government is now actively promoting the use of native species. This is a very recent strategy, so there are no results yet. However, later this year (2021), a government project in collaboration with the IUCN is planned to start, which is focussed on reforestation with regional native species. (Ministry of Lands and Forestry, 2018; Oral communication RFA, 2021).

2. *"Low productivity of existing manmade forests":* Another challenge they recognize is the low productivity of Rwandese plantations due to lack of site-matching, inadequate silvicultural regimes and the poor quality of genetic material. To address these challenges they will invest in the capacity of the tree seed centre and rely more on forest research (Ministry of Lands and Forestry, 2018).

This study begins to address these two challenges by presenting a management plan for a more balanced, sustainable and productive forestry regime with native Rwandan tree species that is adjusted for specific site conditions.

1.5. Research questions

The main question of this research is:

Can indigenous Rwandan species compete against the current mono-cultures of Eucalyptus and Pinus?

In order to answer that question the following sub-questions have to be researched:

1. *What are the requirements and desired traits for plantation-grown tree species in Rwanda?*
   To answer this question the distinguishment will be made between timber characteristics and general species traits, as timber production will be the main focus of this study. Therefore the requested timber products of SEAL and the Rwandan government will have to be identified.

2. *Which native species meet these requirements and desired traits?*

3. *Do these species have a clear advantage compared to the established plantation species?*

4. *Which species are compatible in a mixed-species stand?*

Finally a recommendation for a management plan for a mixed stand with a few promising species will be presented.

2. Methods

To get a clear idea of the issues of the Rwandan forestry sector, the current state and policies concerning the sector were analyzed. I spoke with actors from the private sector, the government and the academia. These actors were Klaas Jan Jonkman, CEO of SEAL ltd., Dismas Bakundukize, Director of the Forest Management Unit, and Dr. Beth Kaplin from the Biodiversity & Natural Resource Management department of the University of Rwanda. I used their input to get an indication of the situation, which I then confirmed and completed using the reports and strategies of the Rwandan Ministry of Environment.

To get started with the search for alternative native species to compete with the established exotic ones, I made a list of promising species. For this list, I relied on recommendations from SEAL ltd., the Rwandan Forest Authority (RFA) and literary articles. The criteria for this first list were only that they were native species, produced enough stem wood to be utilized as timber and that there had been experience with its products before.

SEAL recommended me to look into the species *Afrocarpus gracilior* and *Maesopsis eminii.* Dismas Bakundukize from the RFA recommended *Prunus africana* and *Pterygota mildbraedii.* Dr. Beth Kaplin mentioned *Carapa grandiflora* in her research proposal. Other species I have found in articles by Nduwamungu (2011) are *Croton megalocarpus, Entandrophragma excelsum, Markhamia lutea, Symphonia globulifera, Polyscias fulva* and *Milicia excelsa*.

After creating the list of potential species, the next step was to identify the desired products and traits. I relied mainly on interviews with the RFA, SEAL Ltd., Dr. Kaplin from the UR and employees from the TSC to get an understanding of which products were in demand and which traits were needed for those products. These interviews, which were semi-structured, were conducted via Zoom and recorded for correct quotation. The most important questions can be found in appendix 2 . The identification of the products was straight forward, but the desired traits were split up into two groups; Timber qualities and Non-Timber Forest Services (NTFS). Per timber product the required wood qualities were identified and ranked on a 1-3 scale, with “1” being irrelevant and “3” being crucial. The non-timber forest services were identified through the interviews and included possible benefits to the environment, economy and local population, that were not directly related to wood production.

After having established the issues, potential species and desired products and traits, I made a final species selection. These species were also ranked for their timber qualities[3] on a 1-3 scale, where “1” was considered poor and “3” excellent. These rankings were compared to the required qualities for different timber products. The species were ranked for their non-timber qualities[4] on a 1-3 scale as well. This scale was chosen because the information was often not complete or poorly defined/ standardized. With a simple scale could be compared as fairly as possible. The choice was made to exclude firewood and charcoal from this research. Although it is very important to the current Rwandan economy, the Rwandan government wants to make a fuel transition in the future. Therefore the production of firewood and charcoal will be a by-product for SEAL and not an aim.

All trees were checked for compatibility with the biophysical requirements (altitude, rain fall) of the Munkoto site and whether they were native to the original ecosystems of the region. For this check a species selection tool based on the VECEA map was used (Breugel *et al.*, 2015). The native species were not only compared to each other, but also to the exotic species *E. maidenii* and *P. patula.* The *E. maidenii* was chosen as it is the *Eucalyptus* species that is currently present at the future stand site (Munkoto), and the *Pinus* was chosen as it is SEAL’s best performing pine species and the most important species for their production of construction wood.

After reducing the possible species to only those that meet the biophysical constraints, a combination of species was recommended based on the diversity of services they can provide and compatibility on a stand level. This compatibility depends on factors like growth rate, shade tolerance, soil demands, etc. A rough management plan was created for these final species selection with a focus on spacing distance, rotations and positioning. This management plan is based on available information literature from the PROTA database and additional scientific reports.

2.1. Site description

2.1.1. SEAL Ltd.

In the NFP 2018 the Rwandan government decided to promote privatization of the forestry sector. At this moment SEAL Ltd. is the largest private actor, and has ambitions to implement a more sustainable approach to the forestry practices in Rwanda. One of the concrete plans to achieve this is the implementation of native

[3] Strength, saw ability, finish, durability, bole quality, drying ability, growth rate, preservative treatment
[4] Rareness, biodiversity, edibility, medicinal qualities, soil improvements

species in their plantations, which is the reason why they are supporting this research.

SEAL Ltd., short for Sawmill East Africa Limited, is a commercial forestry company that operates in Rwanda. It was founded in 2018 and currently employs *ca*. 350 people. In line with their goals in the NFP 2018, the Rwandan state hands out lease contracts of their public forests to SEAL. These concessions are valid for 49 years. Currently 5000 ha of public forest has been leased for the coming 5 years, but according to SEAL this will expand with 1000- 1500 ha per year after that. The precise amount depends on their production capacity and needs.

SEAL has forest concessions in four districts that are located in the Western and Southern Province (see Appendix 3). The majority of concessions that are given to SEAL consist of degraded and neglected *Eucalyptus* stands. These are mostly converted to monoculture stands of one of the six species they use most: *Eucalyptus grandis, E. microcoris, E. saligna, E. maidenii, Pinus patula* and *P. caribaea.* Not all public forests are converted to production stands. Some areas are too unproductive or degraded to be converted. These are to be converted to (near) natural forests (SEAL, 2020).

SEAL works all along the chain, from nursery to the end-products. They buy their seeds from the TSC and germinate them in their own nurseries. They plan the planting, management and harvest of their stands, which are often executed by local contractors. They have a kiln in which they dry the timber and their own sawmill to fabricate the end-products. Currently, their main products are construction timber for schools, which are being built by decree of the government, furniture, chainsaw boards and wooden packaging. In the future, they are planning to supply electricity poles for another government project (RFA, 2021; SEAL, 2021).

In addition to these timber products SEAL has a couple side-projects. One of their side-projects is to convert wood waste into pellets for cookstoves. For this project they have partnered up with Biomassters Ltd. and the World Bank. Another project under development is a foundation that will finance and plant food forests for the local communities to benefit from. It will be financed by the profit of the SEAL company and gifts from other actors.

2.1.2. Munkoto forest

The forest site that SEAL has selected for the first trial with native species is called Munkoto Forest. This forest, which is 34.5 ha, is located about 25km west of the capital Kigali, in the Kamonyi District, Southern Province (2°01'48.9"S; 29°51'21.7"E). The climate zone in this district is described as Aw (Tropical Savannah) by the Köppen system and the forest is located at an altitude of 1700 masl. It is has an average rainfall of 1051-1140 mm/y (Rwanda Meteorology Agency, 2021) and an average daily temperature of 25 C^{o}.

The soil, which has a fine loamy texture, is mainly made up of acrisols, with a pH of 5.6 (For exact properties see Appendix 4)(de Sousa *et al.*, 2020; Morris, 2017). Acrisols can be recognized by the argic horizon, a subsurface horizon that has a much higher clay content than its overlying horizon. It develops over acidic parent rocks, which makes the soil acidic as well. It can be found in wet tropical climates on old land surfaces with hills (Driessen *et al*., 2000).

The stand was planted in 1943 and is currently a public forest under management of the local authorities, who manage it as a coppice rotation. It consists of a mixture of mature trees from the species *Eucalyptus maidenii* (70%) and *Eucalyptus microcorys* (30%). The current standing volume of the site is 185 m^3/ha. There is no available data on the productivity of the stand, as it is difficult to estimate the MAI in this coppice system. As no rangers are currently present in the area, firewood is often illegally extracted by locals. Under the management of SEAL, rangers would be contracted to regulate the extraction of products. (SEAL, 2021).

The VECEA project describes the natural forest systems in the Munkoto area as Lake Victoria Transitional Rain Forest (Ff) (Breugel *et al.*, 2015).

3. Results

3.1. Desired traits and requirements

Through literature reviews and interviews, I established which traits are desired for trees in a new forestry system. Those are divided into the requirements for timber products and all other services (NTFS).

Timber production is the priority of the planned mixed stand on the Munkoto site. Through interviews with SEAL Ltd. and the RFA I have identified the timber products that the government and the private sector prioritize nowadays and in the near future. Those products are described in Table 1, which also shows the required wood characteristics and their importance per product.

Currently the most important utilizations of plantation timber are the production of construction material and furniture. For construction wood, SEAL mainly uses the species *E. microcorys* and *P. patula.* Pine is the preferred species here as it dries more easily and is more stable afterwards. *Eucalyptus grandis* is difficult to dry and prone to splitting, and is dimensionally unstable as construction timber (Louppe *et al.*, 2008). The most important traits for construction wood are high volume growth, that the wood dries easily and dimensional stability. Durability and/ or the ability to treat it with preservatives is important as well, as is a straight, branch-free stem to saw long beams and planks from, and to make the sawing process efficient.

Wood for furniture has different desired qualities. The aesthetic aspect of the wood, the workability with hand and power tools and the ability to apply finish are important. Durability is of less importance when it concerns indoor furniture. SEAL is planning to expand their production of furniture in the near future.

The Rwandan government has a large project planned to connect Rwanda's rural areas with electricity poles, which SEAL will supply. For these poles, they need fast growing species with a very straight, branch-free bole. It has to be easily treatable with preservatives like tar or Chromated Copper Arsenate (CCA).

Other utilizations are wooden packaging and the sale of raw lumber on the auction. For wooden packaging, like crates and pallets, the main requirements are fast growth and cheap production. On the lumber auction, they sell logs and boards of valuable, high-quality wood species, mainly for export.

The table below shows the importance of wood properties per timber product.

Table 1 "Important wood properties per timber product"; Rated on a 1-3 scale. "1" = irrelevant, "2" = useful, "3" = crucial

Timber products	Strength	saw ability	Finish	Durability	Bole quality	Drying ability	Growth rate	Preservative treatment
Construction wood	3	2	1	2	2	3	2	2
Furniture	1	3	3	2	2	3	1	1
Electricity poles	1	1	1	1	3	2	3	3
Packaging material	1	1	1	1	1	1	2	1
Dimensional lumber (export)	1	1	2	2	2	2	1	2

In the process of producing timber, there is a lot of wood waste. Current practise is that the slash from the clear cuts is used as firewood or for the production of charcoal and wood pellets. However, this is of no further relevance for the desired species traits, as it is merely a by-product (SEAL, 2020; SEAL, 2021; RFA, 2021).

Besides timber production, trees supply Non-Timber Forest Services, like medicines and soil stabilization. In order to practice sustainable forestry it is important to take these into account as well.

The proposed stand should be able to support higher biodiversity than the current monocultures do. Therefore, a few native species are selected that are compatible in a mixed stand. It is also beneficial to the biodiversity of Rwanda's forest ecosystem if the species are a food source for animals like insects, monkeys and birds or provide a habitat for other species. The RFA specifically mentions that Rwanda is suffering from a declining bee population, so flowering tree species could have an extra benefit to support the insect populations.

Besides biodiversity, the RFA and SEAL want their species to be of value to the local economy and communities as well. Therefore it is valued if the species provide edible products, have medicinal traits or produce any other NTFS.

Rwanda is a densely populated country that relies heavily on agriculture. This intensive form of land-use has degraded the soils in many places. Therefore, it would also be beneficial to include trees with soil-improving qualities like nitrogen fixation and the supply of mulch.

3.2. Species

After reviewing the literature, eleven native species have been selected as potential candidates, which are described in this paragraph. In Appendix 5 pictures of the species can be found. Additionally two exotic, established plantation species will also be discussed

3.2.1. *Prunus africana*

Prunus africana (syn. Pygeum africanum), commonly known as the African cherry or red stinkwood, is an evergreen species from the Rosaceae family. Its range covers the majority of sub-Saharan Africa, from Cameroon and Ethiopia to South Africa. It is an Afromontane species that can grow up to 3400 masl (Orwa *et al.*, 2009). Despite its vast range, this species is listed by the IUCN as Vulnerable. (World Conservation Monitoring Centre, 1998), which is due to overharvesting of its bark. It is a sun-loving species and has a straight cylindrical stem (Bodeker *et al*., 2014) that can reach a diameter of 1.5m (Grace, 2019).

The timber is used mainly sold on local markets. Throughout its growing range, the wood is popular due to its strong characteristics and durability. In Cameroon, it is used for tool handles and door/ window frames, in South Africa for making wagons, and in West Africa for furniture, bridges, cabinets and truck beds. However popular and versatile the wood is, it is difficult to dry. The process of air drying needs to be slowed down to up to nine months to prevent cracking of the log ends and distortion of the wood. Kiln drying is recommended for this species, but kilns are often not available. Additional treatment with preservatives to further improve durability has little impact (Hall *et al.*, 2000). It is also regarded as excellent firewood, because it burns hot and produces little smoke, which is important when cooking indoors (Stewart, 2003).

The bark of the African cherry has medicinal qualities. It contains a range of medically active compounds and has been traditionally used for many different illnesses. Some of these include fever, gonorrhea, malaria (Bodeker *et al*., 2014), prostate enlargement, chest infections and as a purgative for cattle (Tsobeng *et al*., 2008). A lot of these medicinal properties have been scientifically documented and the bark's compounds are being used in medicinal products. The bark is harvested by stripping it from the stem. However, this is typically done in an unsustainable fashion. When done correctly, the tree will recover and a next harvest can be done after a couple years, but in reality the tree is often girdled and dies. The harvesting happens mainly in natural forests instead of managed plantations. This happens in Rwanda as well, so the *Prunus* trees that are left are restricted to national parks (Dismas, 2021).

The *P. africana* also has an important role in the montane ecosystems. Its fruit provides food for many birds and primates, and the tree provides habitat for a range of animals, plants and fungi (Bodeker *et al*., 2014).

3.2.2. *Maesopsis emini*

M. eminii, or the umbrella tree, is a large African rainforest tree that belongs to the Rhamnaceae family. It is native to West- and Central Africa, from Liberia to Western Kenya. The tree grows best on an elevation of 600-900m (can grow up to 1800m elevation) and with 1500-2500mm of rain per year. The species prefers deep, fertile sandy loam soils with neutral to acid pH levels. Although it does not naturally grow on steep slopes, it will perform well when planted there (Epila *et al*., 2017). According to IUCN it classifies as Least Concern (LC) (BGCI & IUCN, 2019). The umbrella reaches a height of 10-30m, but can grow up to 45m tall and have a trunk diameter of 1.2 m. It can have a straight, branch-free bole up to 21 m (Ani & Aminah, 2006).

The wood of the umbrella tree has a relatively low density of 380-480 kg/m^3. The wood dries quickly, but is prone to splitting during the felling or storage. This makes it a difficult species to kiln dry (ITTO, 2021). It is easy to saw and has a high absorbency, which makes it easily treatable with preservatives. These are necessary, because it has a low natural durability. It is a good species for cheap wood products like boxes and crates, pallets, plywood and some lumber, and its fast growth makes it a popular species for firewood (Orwa *et al*., 2009).

The *Maesopsis* leaves are excellent for fodder as they are easily digestible by livestock. Its seeds contain 40-50% oil, which can be pressed into an edible product. The tree has some medicinal traits. Its bark can be soaked as a purgative and its rootbark is used for the treatment of gonorrhoea (Orwa *et al*., 2009).

It is disputed whether *Maesopsis eminii* is a native species. Originally from West and Central tropical Africa, it has been introduced in East Africa for reforestation purposes and has become especially invasive in the mountains of East Tanzania. According to Epila *et al*. (2017) it has been invasive in Rwanda since the 1970s, but it has been naturalized by now. However, according other sources Rwanda is part of its native range (Orwa *et al*., 2009; IUCN, 2019). The umbrella tree is typically associated with the lowlands on the border between savannah and high forest, but it can grow in sub-montane areas as well (Epila *et al*., 2017). It is a real pioneer species that is adapted to colonize grasslands and disturbed area in the forest due to its rapid growth. It is light demanding and it can reach ages of 150 years old (Orwa *et al*., 2009). It is an important species for wildlife, as its fruits and seeds are an important food source for blue monkeys, chimpanzees, fruit bats, and hornbills and other birds. The species relies on these animals for its seed dispersal (Epila *et al*., 2017).

3.2.3. *Markhamia lutea*

The Nile tulip, which belongs to the *Bignoniaceae* family, is native to East Africa with its range stretching from Ethiopia to Tanzania. The evergreen tree grows up to 15-30 m tall (Sources contradict; Louppe *et al.*, 2008; Orwa *et al.,* 2009). It prefers red loam soils, but also tolerates well-drained heavy clay with a low pH. (Orwa *et al.,* 2009). The *M. lutea* is a gap specialist (Bussmann & Lange, 2000), and is often grown for shade and to prevent soil erosion. The species lists as Least Concern (BGCI & IUCN, 2019).

The tree is not fit for high volume wood production, but the timber is used for furniture, poles, tool handles and boat building. It has a good bending strength and can be used for medium structural construction, like roofs (Sseremba *et al.,* 2010). It is durable, easy to saw and fairly resistant to termites. The species also provides good charcoal (Orwa *et al.*, 2009). The wood is only traded locally (Maroyi, 2012).

Although it does not fix nitrogen, the Nile tulip provides good mulch and is known to improve the soil quality (RFA, 2017; Orwa *et al.*, 2009). A stand of *Markhamia* can raise the soil pH and is therefore recommended to plant on more acidic soils (Habumugisha *et al.,* 2019). It is also a good species to prevent erosion (Maroyi, 2012). The leaves, roots and bark have medicinal qualities. It is empirically used to treat stomach, tooth aches, headaches, and epilepsy. A scientific study has shown that the active compound in the leaves of *M. lutea* could indeed contribute to the treatment of epilepsy. Other research has shown that it is promising for the drug development for African sleeping disease (Ngoupaye *et al.*, 2021; Louppe *et al.*, 2008).

The Nile tulip flowers for most of the year and it relies on insect pollination and wind dispersal of its seeds, which have transparent wings. The leaves are a food source f\]or chimpanzees (*Pan troglodytes*) and colobus monkeys (*Colobus angolensis*). Its flowers are a source for honeybees (*Apis mellifera*) (Maroyi, 2012).

3.2.4. *Milicia excelsa*

The *Milicia excelsa* is also known as the African teak or the Iroko. Its natural range extends over the majority of sub-Saharan Africa, with the exception of South Africa, and naturally occurs in a wide range of forests, although it seems to have a preference for drier forest types. It often grows as lone trees on the savannah, in forest galleries and in forest islands. *M. excelsa* also grows on a variety of soils, as long as there is a sufficient level of potassium and phosphor present. According to IUCN is the species Near Threatened (WCMW, 1998). This tree can grow up to 50 m tall and has a straight cylindrical bole which can be branchless for up to 25 m, if grown in a stand. Lone trees on the savannah often develop crooked stems.

The species *M. excelsa* and the related *M. regia* are both sold on the market under the name Iroko. It is a valuable, high-grade timber with qualities similar to teak and is sometimes sold as teak (*Tectona grandis*). The heartwood is very durable and resistant to fungal attacks. The sapwood however, can be liable to attacks by insects, but can be easily treated with preservatives. Due to the durability of the wood iroko is commonly used for heavy duty purposes, like truck beds, ship building, flooring and construction. However, the wood is versatile enough to be used for finer woodwork as well, like carpentry, joinery and decorations.

African teak is notorious for its highly biomineralized tissue, also known as iroko stones. These stones are made up of calcium carbonate crystals and can be found in the trunk of the tree (Braissant *et al*., 2004). Although the wood's working properties are considered to be good, these stones can dull saw blades.

Milicia excelsa has a range of non timber uses. Its fruits are edible and the juice can be used as flavouring. The leaves provide good mulch and has a positive effect on the soil. Several parts of the tree are used in African traditional medicine. The bark, latex, roots, and leaves are used to treat a range of issues ranging from stomach aches to snake bites and gallstones. In a lot of cultures, the iroko also has an important cultural value.

Iroko is often harvested in an unsustainable fashion in natural forests and is seldom grown in pure stands, as it is very susceptible to attacks of the iroko gall bug (*Phytolyma lata*). This psyllid attacks the buds and leaves of seedlings and lays its eggs in gall formations on the leaves, shoots and stems, effectively killing the seedlings (Ugwu & Omoloye, 2014). However, study has shown that the survival rate of *Milicia* seedlings improves drastically when planted in a mixed stand (Ugwu & Omoloye, 2017).

3.2.5. *Polyscias fulva*

The parasol tree occurs mainly in the mountain regions of sub-Saharan Africa, from the West- to the East-coast., where it thrives in forests with high rainfall. The IUCN Red List does not distinguish between the *P. fulva* and the almost identical *P. kikuyuensis*, but has classified them together as Near Threatened (Luke *et al.*, 2018)

Its wood is soft and lacks strength, which excludes it from being used for construction. Traditionally it is mainly used for fine crafts like masks and instruments. Its inability to finish to a nice surface also does not make it a great choice for furniture production. It can however be a potential species for plywood and veneer production, with good aesthetics and a clear and straight bole. The wood dries easily, but is prone to splitting. Although the wood is not durable, is it easily treated with preservatives.

The bark and the leaves of the tree are used for medicinal purposes in DRC and Cameroon. They are used to treat diseases ranging from tuberculosis and malaria fever to normal cough or as purgative. As the leaves make for good mulch as well, the tree can be used as intercrop in agroforestry systems.

The tree's nectar is an important food source for bees (Orwa *et al.*, 2009).

3.2.6. *Entandrophragma excelsum*

The *E. excelsum* occurs in tropical East-Africa, from DRC to Mozambique. It grows in montane areas and some riverine forests where, being among Africa's largest trees, it dominates the canopy. It is listed as LC by the IUCN (WCMC, 1998).

The wood is not harvested on commercial scale, but can be used for construction, furniture, crafts, veneer, and plywood. The wood dries slowly and is very prone to warping, cupping, and cracking. The wood is fairly light-weight and has a wide variation in bending strength, reaching from poor to moderately good. It saws easily, but is difficult to finish properly due to its grain. Due to its low durability and resistance to preservatives, it is not a recommended species for heavy construction, but its straight logs make it suitable for the production of veneer and plywood.

In Burundi and Tanzania, the roots of *E. excelsum* are used medicinally to treat respectively blood cough and gonorrhoea (Louppe *et al.*, 2008).

3.2.7. *Croton megalocarpus*

This species, known as musine, occurs in tropical East-Africa. It is a fast-growing, successful pioneer species that regenerates in forest gaps and edges. It is classified as Least Concern on the IUCN Red List (Hills & Barberá, 2020). The trees grow up to 35m tall, with cylindrical boles from up to 20m. After 32 years it can produce 15m tall trees with a diameter of 24cm.

The timber that *C. megalocarpus* produces is quite versatile and is being used for veneer, plywood, construction and furniture. The wood is easy to handle with hand-tools, but can be a problem for machinery. It is moderately resistant to attacks by insects, and vulnerable to blue stain fungi. However, under pressure it is easily treatable with preservatives. During the drying process the wood is prone to split and distort, and once it is dry it often has a poor dimensional stability, especially with large sizes. Despite this flaw it is used for construction projects (Chudnoff, 1984).

C. megalocarpus is a frequently planted species on farms. It is used as shade tree for coffee and sugarcane plantations. It also has seeds rich in oil (30%), which can be used as biofuel

3.2.8. *Symphonia globulifera*

The boarwood occurs in the tropical rainforests of South- and Central America and Africa. It is theorized that the species dispersed via whole trunks that floated across the ocean (Louppe *et al,* 2008). The Symphonia's conservation status is Least Concern (BGCI & IUCN, 2019). The tree can grow up to 40m tall and has a straight bole that can be branchless up to 21m and reach a diameter of 80-100cm. It can grow on an altitude of up to 2600m.

Its wood is generally used as construction timber, for flooring, carpentry, package material and tool handles. It can also be used for plywood and veneer. The wood is of medium-weight, but dries rapidly. However, cracking of the end-grain and distortion pose a serious risk. The wood is easy to work with and quite durable, although it is susceptible to attacks by termites. Treatment with preservatives is difficult.

The Symphonia has some great medicinal traits. Certain compounds have been isolated from the roots that have shown HIV-inhibitory effect on infected cells. Other compounds in the root bark have a cytotoxic effect on cancer cells (Fromentin *et al.*, 2015).

The tree's fruits are a food source to monkeys and small mammal and its flowers sustain bird, bee and butterfly populations (Louppe *et al.*, 2008).

3.2.9. *Carapa grandiflora*

The East African crabwood, almost interchangeable with the *C. procera*, occurs in tropical Africa, ranging from eastern Central Africa to western Tanzania (Hutchinson & Dalziel, 1958). Its conservation status is Least Concern (Oldfield, 2021).

The crabwood can grow up to 24m tall, but it has a short bole with a wide crown. Its wood is easily workable and finishes well. It dries easily with little warping, but splitting can occur. There is very little knowledge on kiln treatments as the wood is not in commercial use, although on local scale its timber is used for joinery, flooring and furniture. It also seems to have good bending strength (ITTO, 2021). The wood is susceptible for attacks by fungi and insects. It is also difficult to impregnate with preservatives (Chudnoff, 1984).

The fatty fruits of the crabwood are locally utilized. In Uganda they are used to make a type of butter and in West Africa the oil is used to make insecticide and soap. The bark is used as a medicine (Orwa *et al.*, 2009).

Although its economical value is marginal, the *C. grandiflora* has an important role in the rainforest ecosystems. Its fruit is highly sought after by a range of birds and large mammals, like gorillas (*Gorilla beringei*) and elephants (*Loxodonta cyclotis*)(Mangambu, 2018; Nyiramana, 2012).

3.2.10. *Pterygota mildbraedii*

This species, which is quite widespread through equatorial Africa, occurs in tropical rainforests at an altitude of 750-1500 m. The tree can get up to 40m tall and has a long, branchless bole (Bytebier, 2008)

The tree however, is not used on any commercial scale and very little is known about the wood properties. What is known is that it is not durable but is easily treated with preservatives. On local markets, it is used for fuel and Ugandan 'beer vessels' (Louppe *et al.,* 2008).

The seeds, branches, and leaves are an important staple food for chimpanzees (Watts *et al.,* 2012).

3.2.11. *Afrocarpus gracilior*

The East African yellowwood is one of three species in the *Afrocarpus* genus. This genus was in 1988 recognized as separate from the *Podocarpus* genus based on a different chromosome number and seed characteristics, but in literature is often still referred to as *Podocarpus gracilior*. *A. gracilior* is almost identical to *A. falcatus,* which is native to South Africa, save for its more slender leaves. For this reason the *A. gracilior* is often also referred to as *A. falcatus* in literature (Louppe *et al.*, 2008).

The East African yellowwood occurs in montane evergreen rainforest at an altitude of 1500-2600 m. It is classified as Least Concern by the IUCN (Farjon, 2013). The species is often associated with *Juniperus procera* on highland plateaus, but can locally grow in nearly pure stands as well. It is a large tree that can grow up to 60 m tall with a straight clear bole up to 25 m, which makes it a popular timber tree. It grows fast, but is sensitive to competition.

The *Afrocarpus'* wood, often sold as podo, is fairly light weight and soft. It is very versatile and used for poles, furniture, ship-building, construction, veneer and plywood. It air-dries easily, although it should be done carefully to prevent cracking and warping. Once it has dried it has good dimensional stability. It saws and finishes well, and it can easily be treated with preservatives. However, untreated is the wood not durable, as it is susceptible to a range of insects and fungi.

The yellowwood's seeds contain an edible oil, which is also traditionally used to treat gonorrhea. The bark is used to treat rash and stomach ache, and it can be used for tanning, although the tannin levels are low. The ripe fruits and seeds are a food source for bats, rodents, colobus monkeys and birds (Orwa *et al.,* 2009).

3.2.12. *Eucalyptus maidenii* (exotic)

The Maiden's gum, often also referred to as the *Eucalyptus globulus subsp. maidenii,* is a large tree native to Australia. It can reach a height of 30-45m and a bole width of 2,5 m (Nogueira et al., 2018).

The timber of *E. maidenii* is hard, has decent strength and is durable, although it is susceptible to attacks by the *Lyctus* borer. Unlike *E. grandis*, the maiden's gum has decent dimensional stability once it has dried and can be used for (heavy) construction (Nogueira et al., 2018). Its bending strength is also better than the *E. saligna*, another widely present species in Rwanda (Elaieb et al., 2019). The maiden's gum's timber dries quite well, without excessive cracking of the boards

(Kimberley, 2002). The wood is hard and can blunt machinery, but it finishes to a smooth surface and holds most finishes well (Louppe *et al.*, 2008).

Besides timber can essential oils be extracted from its leaves and fruits, and its leaves and bark have some medicinal qualities that are used to treat cough and head ache (Prabhu et al., 2014). Its bark can also supply tannins. As an exotic species it contributes little to the species diversity in Rwandan forests. *Eucalyptus* is however known to have a negative effect on groundwater levels due to its high evaporation. A study in Ethiopia has shown that a small patch of *Eucalyptus spp*. reached twice the reference evapotranspiration levels during the dry season (Enku et al., 2020).

3.2.13. *Pinus patula* (exotic)

The patula pine is a *Pinus* species that is native to the highlands of Mexico. It is a fast-growing species that can grow up to 35 m high and reaches an MAI of 15-30 m^3/ha/y (RFWA, 2018). It is a true pioneer species that is becoming an invasive species in Southern Africa (Louppe *et al.*, 2008).

The *Pinus patula* produces good wood, which can be used for construction, furniture, flooring, cabinetry, veneer, etc. In South-Africa it is also used as pulpwood for the paper production. Its wood is light but strong, dries well and is decently stable after drying. It saws quite easily when done carefully, but boring and turning can be harder. The wood is not durable as it is vulnerable to attacks by a range of fungi and insects. However, it is easily treated with preservatives. It gives great firewood and is also used in the charcoal production.

The species is sometimes planted to prevent soil erosion, as its dropped needles have good water-holding capacities (Louppe *et al.*, 2008).

3.3. Selection

3.3.1. Biophysical limitations

With these eleven tree species we have to make a selection for in the mixed stand. For all species the biophysical limitations were determined. The two factors that have been investigated are the altitude and the rainfall limitations. The findings, which are shown in the figures below (figure 4, figure 5), have been compared to the elevation and rainfall of Munkoto Forest, where SEAL is planning to create the mixed stand. These numbers are respectively ca. 1700 masl and 1100mm/ year.

Figure 4 "Altitude range per species, compared to the altitude of the Munkoto site."

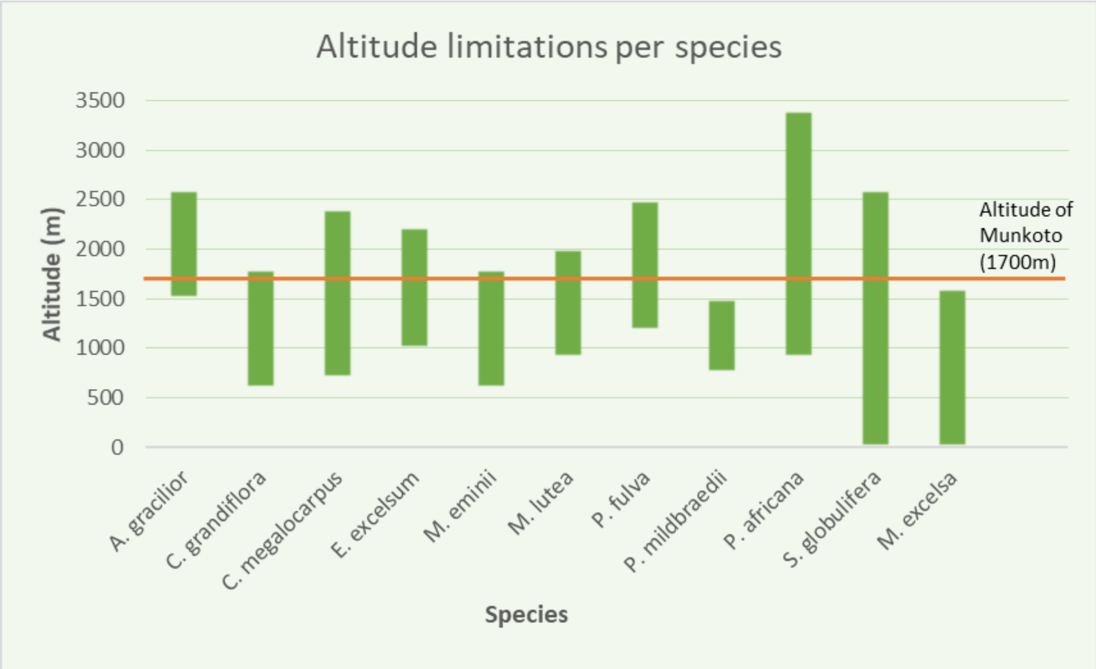
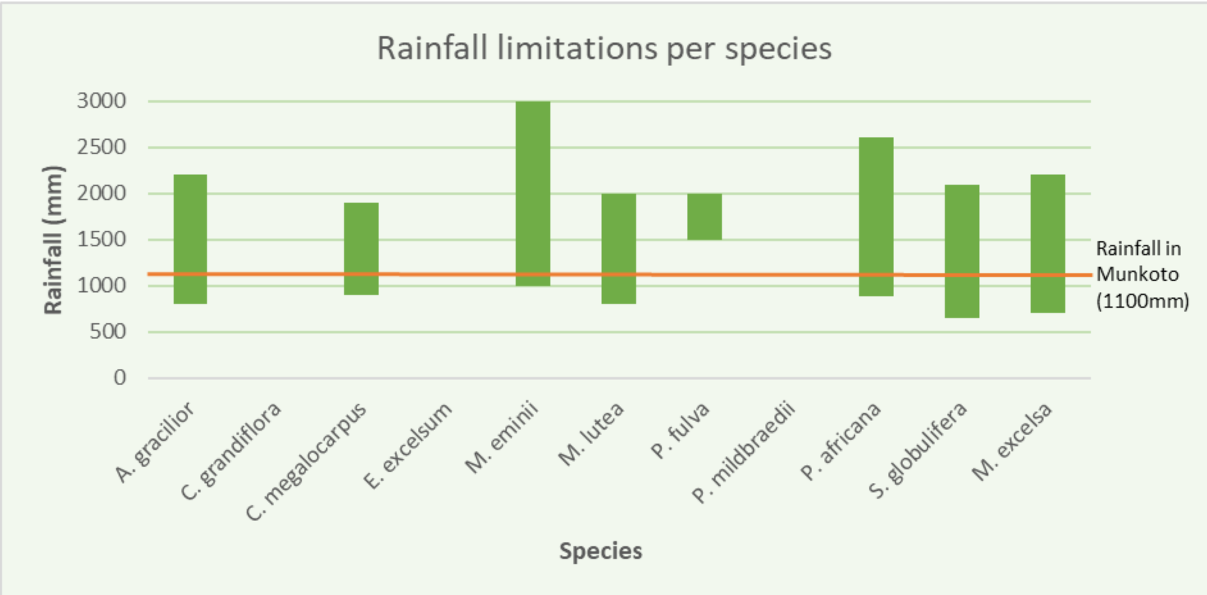


Figure 5 "Upper and lower rainfall limitations per species, compared to the rainfall of the Munkoto site."



The species that had limitations above or far below the site specifics of the Munkoto Forest were excluded from the selection. We have to take into account that due to global warming there will be a shift in the climate in Tropical Africa. If the global temperature rises with 1.5 C^{o}, the temperature in Rwanda will increase with 1.5-2.0 C^{o} (Hoegh-Guldberg *et al.*, 2018). Consequently, the upper-elevation limitations of most species in montane tropical Africa will shift to higher elevations

(Jacob *et al.*, 2015). Therefore some species that have limits just below the altitude of Munkoto have been included as well.

After the first selection, I have used the maps and datasets by the VECEA team (Breugel *et al.*, 2015) to check which trees were present in the natural ecosystems around the Munkoto site.

3.3.2. Traits

All eleven native species, as well as *Eucalyptus maidenii* and *Pinus patula*, were compared for timber qualities and for non-timber forest services (Table 2 & 3). The timber qualities in Table 2 correspond with the descriptions of the tree species as described in paragraph 3.2. The accumulative score of all qualities shows an indication of the all-round performance of the wood.

Table 2 "Timber properties per investigated species". Rated on a 0-3 scale; 0 = unknown; 1 = poor; 2 = intermediate; 3 = good.

Species	strength	saw ability	Finish	Durability	Bole quality	Drying ability	Growth rate	Preservative treatment	Total
M. lutea	3	3	3	2	2	2	3	2	**20**
M. eminii	2	3	1	1	3	3	3	3	**19**
M. excelsa	3	1	2	3	3	3	2	2	**19**
A. gracilior	2	3	3	1	3	2	2	3	**19**
C. megalocarpus	3	2	3	2	3	1	2	2	**18**
P. fulva	1	3	1	1	3	2	3	3	**17**
C. grandiflora	3	3	3	2	1	3	1	1	**17**
P. africana	3	3	2	3	2	1	1	1	**16**
S. globulifera	2	3	1	2	3	1	1	1	**14**
E. excelsum	2	2	1	1	3	1	2	2	**14**
P. mildbraedii	1	0	0	1	3	0	3	3	**11**
E. maidenii	2	2	2	2	3	2	3	3	**19**
P. patula	2	2	2	1	3	3	3	3	**19**

The Non-Timber Forest Services in Table 3 are also rated 1-3, but with more complicated requirements. The Rareness is based on the IUCN Red List. A '1' is given when the status is Least Concern, a '2' is given for Near Threatened and '3' for Vulnerable. The Biodiversity scale is based on the amount of animal species that rely on the trees for habitat of food sources and how threatened those species are. On the Edibility scale a '1' is non-edible, '2' is known edibility or oil production and a '3' is given to species with a commercial fruit production. For Medicinal qualities a '1' is no known qualities. '2' is known traditional uses and '3' is scientifically proven and interesting for pharmaceutics. In the Soil improvement column '1' is negative or no effect on the soil, '2' is good mulch and/ or pH improving and '3' is also N-fixating.

This table shows the added value of the trees besides timber production. The total score gives an indication of the 'usefulness' of each species when it comes to NTFS.

Table 3 "Non-Timber forest services per investigated species". Rated on a 1-3 scale. 1 = no use; 2 = useable; 3 = extremely useful. See text for further explanation.

Species	Rareness (IUCN)	Biodiversity	Edibility	Medicinal qualities	Soil improvements	Total
P. africana	3	3	1	3	1	**11**
M. eminii	1	3	2	2	2	**10**
C. grandiflora	1	3	2	2	1	**9**
A gracilior	1	3	2	2	1	**9**
M. lutea	1	2	1	3	2	**9**
P. fulva	2	2	1	2	2	**9**
M. excelsa	2	1	2	2	2	**9**
C. megalocarpus	1	2	1	2	2	**8**
S. globulifera	1	1	1	3	2	**8**
E. excelsum	1	1	1	2	1	**6**
P. mildbraedii	1	1	1	1	1	**5**
E. maidenii	1	1	1	2	1	**6**
P. patula	1	1	1	1	1	**5**

During the interviews with SEAL Ltd. we have established that the main priority of their stand is the production of timber for various end-products. Therefore the overall timber score is assigned the same weight as all the NTFS combined. Table 4 shows the total score of each species all-round performance.

Table 4 "Overall score. Combined of equally weighted timber score and NTFS score"

Species	NTFS	Timber	Total score
M. eminii	10	19	**29**
M. lutea	9	20	**29**
A. gracilior	9	19	**28**
M. excelsa	9	19	**28**
P. africana	11	16	**27**
C. grandiflora	9	17	**26**
C. megalocarpus	8	18	**26**
P. fulva	9	17	**26**
S. globulifera	8	14	**22**
E. excelsum	6	14	**20**
P. mildbraedii	5	11	**16**
E. maidenii	6	19	**25**
P. patula	5	19	**24**

4. Synthesis

4.1. What are the requirements and desired traits for plantation-grown tree species in Rwanda?

Based on the interviews with several actors and the analyses of the policy documents from the Rwandan Ministry of Lands and Forestry, a couple conclusions can be drawn. For both SEAL and the government timber production still is the main priority. Timber products that will be most important for SEAL in the near future are construction timber and furniture. For construction timber, it is important that the wood has at least decent strength, with good drying ability and is either durable or easy to treat with preservatives. For the production of furniture drying ability is also important, as well as the sawing ability and the ability to get a good finish. The government also has a large demand for electricity poles, which requires tall, straight boles which can be treated with preservatives. All other utilizations and their required timber properties can be found in Table 1.

Both SEAL and the government realise that the NTFP are also important. SEAL mentions the support of species biodiversity as an important factor, as does the RFA, who specifically mentions the support of declining bee populations. Ideally can the species be of use to local communities, in edible or medicinal products.

4.2. Which native species meet these requirements and desired traits?

To get to this answer eleven species were analysed rated for a range of traits and services. The biophysical limitations have excluded two species from our selection: *Pterygota mildbraedii* (max. 1500m) can be excluded based on its altitude limitations and *Polyscias fulva* (min. 1500mm) is excluded based on its rainfall requirement. Two species have been excluded based on their natural absence in the Munkoto area: *Afrocarpus gracilior* and *Carapa grandiflora.*

Entandrophragma excelsum scores low on the wood qualities (14). Its only great feature is its excellent bole quality, but the drying ability and durability are poor. It also provides hardly any NTFS (6). *Symphonia globulifera* has an equally low timber score (14) and performs especially bad on drying ability. Although it might prove to be a valuable species in the battle against HIV, its overall NTFS are low (8). These scores put these two species on the bottom of the list, which excludes them from the selection.

Croton megalocarpus is a decent all-round species, with good timber qualities. However, it is difficult to dry and despite its strength it has poor dimensional stability after the drying process. It also does not have a great growth rate. These factors make it unsuitable for construction and furniture and therefore can not contribute to SEAL's production goals.

This leaves us with four species: *Maesopsis eminii, Prunus africana, Milicia excelsa* and *Markhamia lutea.*

M. eminii is a definite candidate. It scores high on the timber qualities (19), with growth rate, drying ability and strength as excellent features. These qualities make a good fit with SEAL's goals of producing construction and furniture wood. It is also the only plantation species which Rwanda has any experience with. Its durability is low, but this is compensated by its ability to absorb preservatives. The good timber score in combination with a decent NTFP score (10) gives this species the best all-round score as well (29).

P. africana has the best score on NTFP (11). The species is listed as vulnerable and therefore it would be beneficial to grow it commercially. There is a high demand for its bark in the pharmaceutical industry. This bark can be harvested without felling or killing the tree, so this species can be lucrative before the felling. When the tree has matured enough, its timber can be sold as well. It is difficult to dry, but it is popular for its strength and durability. The biggest advantage of using this species is to prevent it from disappearing, as it is listed as Vulnerable by the IUCN and has almost disappeared from Rwanda.

M. lutea has the best overall timber score (20). The species is due to its limited size not good for bulk production, despite its fast growth rate. However, its wood qualities are great and make for both good furniture and construction. Its leaves have medicinal properties that could be promising for the pharmaceutical sector, and the species would have a positive impact on the insect biodiversity in the stand.

The last species is *M. excelsa*. This tree does not have a great growth rate, but the wood is very valuable, especially on the export market.

4.3. Do these species have a clear advantage compared to the established plantation species?

When we purely look at the production rate, the native tree cannot compete with the theoretical production levels of *Eucalyptus* and *Pinus*. For *Eucalyptus grandis* and *E. microcorys*, two of SEAL's species, a MAI of resp. 30-40 m3/ha/y and 25-35 m3/ha/y can be expected in Rwanda and for *Pinus patula* 15-30 m3/ha/y. *Maesopsis eminii*, the best performing bulk species in Rwanda, reaches 20 m3/ha/y (RFWA, 2018). However, this is largely dependent on the stand management, as the current average production level of Rwandan plantations, which are mainly *Eucalyptus* and *Pinus*, is 8 m3/ha/y.

The proposed mixed stand, given that *Maesopsis* has the highest production of the native species, will always have lower production rate than a well managed *Eucalyptus* stand, but the revenue in the mixed stand is not limited to wood production as the bark harvest can also be a source on income. Additionally, the stand has a lot more ecosystem services and benefits to the local population than the exotic stands, and of course the resilience of the stand is a lot better. In these categories the established exotic species score really poor.

Whether the native species are competitive in wood quality is more up for debate. The four selected species should each perform better than most *Eucalyptus* species in Rwanda, especially on drying and dimensional stability. *E. maidenii* is the exception here, as it performs a lot better than the rest of the *Eucalyptus spp.* on these traits and scores equally good as the four selected species (19). *P. patula* also performs equally good as the best native species on wood properties.

4.4. Which species are compatible in a mixed-species stand?

As has been established in the previous sections the four species that have been selected are *Maesopsis eminii*, *Prunus africana*, *Milicia excelsa* and *Markhamia lutea*. All these species are sun-loving. Two of these four species, *M. eminii* and *M. lutea*, are fast growing, whereas *M. excelsa* and *P. africana* have a slow growth. These different growth rates mean, given that all species require a lot of sunlight, that one needs to beware of inter-specific competition for sunlight. This problem will especially become apparent for *P. africana* and *M. lutea*. *Markhamia lutea* has a way faster growth and a large and dense crown, which might be a problem for the light demanding stinkwood.

We have previously established that these four species have the proper biophysical requirement for the Munkoto site and are suitable for its soil type. They all require drained soils, which our site has due to its location on a hill, and they can all grow on a site with a pH of 5,8. Whereas *M. lutea* and *P. Africana* are quite tolerant to a broad range of soil types, *M. eminii* and *M. excelsa* require fertile soils. They should however all be able to thrive on the soil in Munkoto.

5. Conclusion

The research-question of this study has partly been answered: Native tree species in Rwanda seem to be a competitive alternative to *Eucalyptus* and *Pinus* species in the Rwandan forestry sector. They will not outcompete the exotic species in terms of production, but they can match the standard of wood quality and even out-perform the exotic species, and the higher scoring NTFS and increased resilience of the plantations will make it worthwhile to invest in native species.

However, this is not the definite answer. This study has not covered all important aspects for successful stand management, like an economical analyses, germination and nursing processes, and post-harvest processes. Additionally choices have been made as to which products (both timber and non-timber) will be investigated, but the species are a lot more versatile still than described in this paper. Those options (i.e. firewood/ charcoal, biofuel) would be worth investigating in the future. Also much more research is needed to understand the full potential of these species. The commercial silviculture of most of these species is still at an early stage, so a lot is still unknown about these species, like their biophysical limitations, growth models and responses to different silvicultural treatments. This makes it also difficult to make a fair comparison and give a definitive answer to this study's questions. However, it also means that there is still a lot of opportunity to improve. With more research on genetics, treatment and site matching, the productivity of native species might improve a lot and become competitive with the exotic species after all. Another interesting research would be the combination of highly productive exotic species and N-fixating native species (i.e. *Milicia excelsa*) (Liu *et al.*, 2018).

The first step in this research could be to closely monitor this proposed mixed-species stand and to learn as much as possible to implement in future experiments.

5.1. Recommended management plan

One of the aims of this thesis was to recommend a management plan for a mixed-species stand with a few species. The selected species that will make up this stand are *Maesopsis eminii, Markhamia lutea, Prunus africana* and *Milicia excelsa.*

The lay-out of the stand can be seen in Figure 6. The spacing distance will be 2,5x2,5 m, which is a density of 1600 stems/ha. This is the same spacing distance as SEAL Ltd. currently uses for their *Eucalyptus* and *Pinus* plantations, and is a good fit for this stand. As all species require sunlight, it is unwise to have too high planting densities. The seedlings will do too much self-thinning, which will both be a waste of seeding costs and will possibly give one species a competitive advantage. However, too wide a spacing and the trees will not do self-pruning and their will be too much branching. The bulk of the stand will be made up of *M. eminii,* which is the best species for high volume production. This fast growing species comes the closest to the exotic hardwood species in terms of production rate, so this is where most of the revenue must come from. This species will be planted in double rows. In between the *Maesopsis* will be a row of *Markhamia lutea*. This species has a slightly slower growth rate and height, but tolerates some shade. The *M. lutea* develops a large and dense crown, but this should not be an issue for the faster growing *M. eminii,* and will even improve its stem form. As it would impose a problem for the slow growing, light demanding *Prunus africana,* it has been decided that this species is planted along the edge of the stand. This will allow it to get plenty of light. For the *Prunus* the bole shape is also less important, as its bark production will be the focus. The last species is *M. excelsa,* the iroko. This species is very difficult to grow in plantations, as it is very susceptible to *Phytoloma* gall. Because of this issue *Milicia* is planted in very low densities in between the *Prunus* along the outer edge.

Maesopsis eminii will be easiest to plant. The seeds are readily available with the TSC. What will be a challenge is that the seeds need a 3 month pre-sowing treatment, after which they must be nursed (TSC, 2021). For *Markhamia lutea* there are seeds available as well. The seedlings need to be nursed 4-6 months before planting them in the stand (Louppe *et al.,* 2008). Seeds for *P. africana* need to be gathered from Nyungwe National Park, as they are not readily available with the TSC. This might make it more expensive to plant this species. If this poses a problem, the number of planted *Prunus* in the stand could be reduced and replaced by *Maesopsis.* The seedlings need to be nursed 8-12 months before planting (Hall *et al.,* 2000). The seeds for *M. excelsa* are not available with the TSC and might need to be imported from neighbouring countries. They have to be nursed for four months before planting. (TSC, 2021).

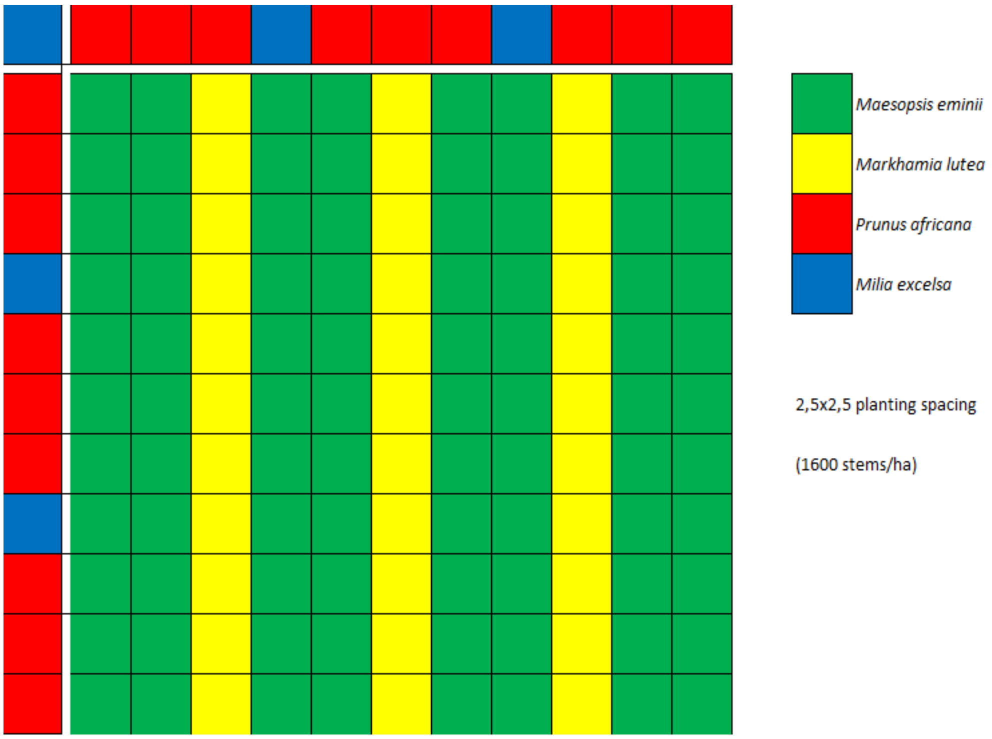
Two years after planting the *Markhamia* can be pruned to reduce shading and improve stem form. *Milicia* and *Prunus* also need to be pruned. The *Maesopsis* is self-pruning, so as long as the density is sufficient pruning is not necessary. After five years *Maesopsis* can be thinned to 850 stems/ha, so almost half of the stems can be removed (Schabel & Latiff, 1997). It is recommended to retain the stems with the best bole shape. *Markhamia* should also be thinned, *Prunus* only if suppressed. *Milicia* is so sparsely planted that it should just be pruned again to retain good bole shape. After ten years the *Maesopsis* can be thinned again. In Malaysia the best production rates were achieved at 125 stems/ha (Schabel & Latiff, 1997).

The bark of the *Prunus* can be harvested for the first time when the tree reaches a dbh of 30cm, which is after ca. 12 years. After that it can be harvested with roughly an 8 year interval. The amount of bark per harvest is variable, but 55 kg per tree is the most quoted number (Hall *et al.*, 2000).

The harvesting age of the plantation will be 40 years, except for the *Milicia*. All trees of *Maesopsis, Markhamia* and *Prunus* can be clear-cut and sold for timber. The cycle of the *Milicia* is 20-40 years longer and should be retained while establishing the next stand. As the density per hectare is so low for *Milicia,* the shade should not be any problem for a next stand of sun-loving species.

During the rotation cycle the *Milicia* and the *Maesopsis* produce edible fruits, which can be gathered/ plucked by the local communities. Additionally they could benefit from the slash after pruning and thinning, which they could use as firewood or for charcoal production.

Figure 6 "Recommended planting lay-out for mixed, even-aged stand consisting of four species."



References

Ani, S., & Aminah, H. (2006). Plantation timber of Maesopsis eminii. *Journal of Tropical Forest Science*, 87-90.

Amsallem, I., Koné, P. D., & Wilkie, M. L. (2002). Status and trends in forest management in central Africa. *FAO, Roma*.

Binggeli, P., & Hamilton, A. C. (1993). Biological invasion by Maesopsis eminii in the East Usambara forests, Tanzania. *Opera Botanica*, 121, 229-235.

Bodeker, G., van ‘t Klooster, C., & Weisbord, E. (2014). Prunus africana (Hook. f.) Kalkman: the overexploitation of a medicinal plant species and its legal context. *The Journal of Alternative and Complementary Medicine*, 20(11), 810-822.

Botanic Gardens Conservation International (BGCI) & IUCN SSC Global Tree Specialist Group. 2019. Maesopsis eminii. The IUCN Red List of Threatened Species 2019: e.T49841506A146205771. Downloaded on 11 May 2021.

Braissant, O., Cailleau, G., Aragno, M., & Verrecchia, E. P. (2004). Biologically induced mineralization in the tree Milicia excelsa (Moraceae): its causes and consequences to the environment. Geobiology, 2(1), 59-66.

Breugel P van, Kindt R, Lillesø JPB, Bingham M, Demissew S, Dudley C, Friis I, Gachathi F, Kalema J, Mbago F, Moshi HN, Mulumba, J, Namaganda M, Ndangalasi HJ, Ruffo CK, Védaste M, Jamnadass R and Graudal L (2015) Potential Natural Vegetation Map of Eastern Africa (Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia). Version 2.0. Forest and Landscape (Denmark) and World Agroforestry Centre (ICRAF). URL: //vegetationmap4africa.org

Bussmann, R. W., & Lange, S. (2000). Germination of important East African mountain forest trees. Journal of East African Natural History, 89(1), 101-111.

Bytebier, B. (2008). Flora of Tropical East Africa. *Journal of East African Natural History*, *97*(2), 259-260.

Chudnoff, Martin. 1984. Tropical Timbers of the World. USDA Forest Service. Ag. Handbook No. 607

Dalena, Maria & Ntazinda, Erasme & Habonimana, Herve Villard. (2015). National Risk Atlas of Rwanda.

Driessen, P., Deckers, J., Spaargaren, O., & Nachtergaele, F. (2000). Lecture notes on the major soils of the world (No. 94). Food and Agriculture Organization (FAO).

Elaieb, M. T., Ayed, S. B., Ouellani, S., Khouja, M. L., Touhami, I., & Candelier, K. (2019). Collapse and physical properties of native and pre-steamed Eucalyptus camaldulensis and Eucalyptus saligna wood from Tunisia. *Journal of Tropical Forest Science*, *31*(2), 162-174.

Enku, T., Melesse, A.M., Ayana, E.K. et al. Groundwater use of a small Eucalyptus patch during the dry monsoon phase. Biologia 75, 853–864 (2020).

Epila, J., Verbeeck, H., Otim-Epila, T., Okullo, P., Kearsley, E., & Steppe, K. (2017). The ecology of Maesopsis eminii Engl. in tropical Africa. *African journal of ecology*, 55(4), 679-692.

FAO (2001). Mean annual volume increment of selected industrial forest plantation species by L Ugalde & O Pérez. Forest Plantation Thematic Papers, WorkingPaper 1. Forest Resources Development Service, Forest Resources Division. FAO, Rome (unpublished).

Farjon, A. 2013. Afrocarpus gracilior. The IUCN Red List of Threatened Species 2013: e.T42439A2980350. Downloaded on 11 May 2021

Forrester, D. I., Bauhus, J., & Cowie, A. L. (2005). On the success and failure of mixed-species tree plantations: lessons learned from a model system of Eucalyptus globulus and Acacia mearnsii. *Forest Ecology and Management*, *209*(1-2), 147-155.

Fromentin, Y., Cottet, K., Kritsanida, M., Michel, S., Gaboriaud-Kolar, N., & Lallemand, M. C. (2015). Symphonia globulifera, a widespread source of complex metabolites with potent biological activities. *Planta medica*, *81*(02), 95-107.

Grace, A. (2019). Assessment of abundance, distribution and threats on Prunus africana in Rwanda, Case study: Nyungwe and Gishwati-Mukura National Parks. *Final Report*.

Habumugisha, V., Mourad, K. A., & Hashakimana, L. (2019). The Effects of Trees on Soil Chemistry. Current Environmental Engineering, 6(1), 35-44.

Haggag, M., Kalisa, J. C., & Abdeldayem, A. W. (2016). Projections of precipitation, air temperature and potential evapotranspiration in Rwanda under changing climate conditions. *African Journal of Environmental Science and Technology*, *10*(1), 18-33.

Hakizimana, E., Wali, U. G., Sandoval, D., & Venant, K. (2020). Environmental Impacts of Biomass Energy Sources in Rwanda.

Hall, J.B., O'Brien, E.M., Sinclair, F.L. 2000. Prunus africana: a monograph. School of Agricultural and Forest Sciences Publication Number 18, University of Wales, Bangor. 104 pp.

Hills, R. & Barberá, P. 2020. Croton megalocarpus. The IUCN Red List of Threatened Species 2020: e.T62003321A62003323. Downloaded on 11 May 2021.

Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou, 2018: Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X.

Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press. https://www.ipcc.ch/sr15/chapter/chapter-3/
Hutchinson, J., & Dalziel, J. M. (1958). Flora of Tropical West Africa vol. 1 (2) Crown agents. London. Invest. New Drugs, 29(4), 583-592.
ITTO. (2021). *Carapa procera.* http://www.tropicaltimber.info/specie/andiroba-carapa-procera/#lower-content
ITTO. (2021). *Maesopsis eminii.* http://www.tropicaltimber.info/specie/musizi-maesopsis-eminii/
Jacob, M., Annys, S., Frankl, A., De Ridder, M., Beeckman, H., Guyassa, E., & Nyssen, J. (2015). Tree line dynamics in the tropical A frican highlands–identifying drivers and dynamics. *Journal of Vegetation Science*, *26*(1), 9-20.
Kamatali, J. M. (2014). State-building in Rwanda. *Reconstructing the Authoritarian State in Africa*, 154.Ndayambaje, J. D. (2013). *Trees and woodlots in Rwanda and their role in fuelwood supply*.
Kimberley, M. (2002). Wood properties of young Eucalyptus nitens, E. globulus, and E. maidenii in Northland, New Zealand. New Zealand Journal of Forestry Science, 32(3), 334-356.
Liu, C. L. C., Kuchma, O., & Krutovsky, K. V. (2018). Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Global Ecology and Conservation*, *15*, e00419.
Louppe, D., Oteng-Amoako, A.A. & Brink, M. (Editors), 2008. Plant Resources of Tropical Africa 7(1). Timbers 1. PROTA foundation, Wageningen, Netherlands/ Backhuys Publishers, Leiden, Netherlands/ CTA, Wageningen, Netherlands. 704 pp.
Luke, W.R.Q., Musili, P., Barasa, J. & Mathenge, J. 2018. Polyscias kikuyuensis. The IUCN Red List of Threatened Species 2018. Downloaded on 11 May 2021.
Mangambu, J., Rwabika, A., Basinyize, P., Anataka, J., Nyamuto, G., Shafula, N., Lokumu, L., Ntahobavuka, H. (2018). Spatial structure and abundance in the Kahuzi-Biega Mountain vegetation formation in DR Congo (Albertine Rift): Case of Carapa grandiflora SPRAGUE and Symphonia globulifera L. F. in the resort of Tshivanga. International Journal of Biosciences. Vol. 12, No. 2, p. 216-231
Maroyi, A., 2012. Markhamia lutea (Benth.) K.Schum. [Internet] Record from PROTA4U. Lemmens, R.H.M.J., Louppe, D. & Oteng-Amoako, A.A. (Editors). PROTA (Plant Resources of Tropical Africa / Ressources végétales de l'Afrique tropicale), Wageningen, Netherlands. <http://www.prota4u.org/search.asp>. Accessed 29 March 2021.
Morris, L.A. 2017. Textural Classes Used in the Soils Family. University of Georgia Warnell School of Forestry and Natural Resources – Center for Invasive Species and Ecosystem Health. BW-2017-14. 3 p.
Ministry of Environment. (2019). Forest Mapping Report, November 2019.
Ministry of Environment. (2019). Forestry Research Strategy and
Guidelines for Rwanda (2018-2024).
Ministry of Lands and Forestry. (2018). Rwanda National Forest Policy 2018.
Ministry of Lands and Forestry. (2018). National Tree Reproductive Materials Strategy 2018 – 2024.

Nduwamungu, J. (2011). Forest plantations and woodlots in Rwanda. In *African Forest Forum (AFF) Working Paper Series* (Vol. 1, No. 14).

Nduwamungu, J., Nyandwi, E., Mazimpaka, J. D., Mugiraneza, T., Mukashema, A., Rwanyiziri, G., & Nzabanita, V. (2013). RWANDA FOREST COVER MAPPING USING HIGH RESOLUTION AERIAL PHOTOGRAPHS 1. Global Geospatial Conference, Addis Ababa, Ethiopia.

Ngoupaye, G. T., Adassi, M. B., Foutsop, A. F., Noungoua, C. M., Yaya, J., Kom, T. D., & Bum, E. N. (2021). Anticonvulsant effect and acute toxicity study of the aqueous lyophilized extract of four medicinal plants of Cameroon: Malvaviscus arboreus, Alchemilla kiwuensis and mixture of Drymaria cordata and Markhamia lutea. Advances in Traditional Medicine, 1-15.

Nogueira, M. C. D. J. A., De Araujo, V. A., Vasconcelos, J. S., Da Cruz, J. N., Prataviera, F., Christoforo, A. L., & Lahr, F. A. R. (2018). Characterization of Eucalyptus maidenii timber for structural application: Physical and mechanical properties at two moisture conditions. South-east European forestry: SEEFOR, 9(2), 141-146.

Nyiramana, A. (2012). Production de fruits, dissémination et devenir des graines de Carapa grandiflora sprague (Meliacée) dans le Parc National de Nyungwe, Rwanda (Doctoral dissertation, Paris, Muséum national d'histoire naturelle).

Oldfield, S. 2021. Carapa grandiflora. The IUCN Red List of Threatened Species 2021: e.T61793991A61793995. Downloaded on 11 May 2021.

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Simons, A. (2009). Agroforestree Database: a tree reference and selection guide. Version 4.

Plumptre, A. J., Davenport, T. R., Behangana, M., Kityo, R., Eilu, G., Ssegawa, P., ... & Peterhans, J. K. (2007). The biodiversity of the Albertine Rift. Biological conservation, 134(2), 178-194.

Prabhu, S., Vijayakumar, S., Yabesh, J. M., Ravichandran, K., & Sakthivel, B. (2014). Documentation and quantitative analysis of the local knowledge on medicinal plants in Kalrayan hills of Villupuram district, Tamil Nadu, India. Journal of ethnopharmacology, 157, 7-20.

Rennie, J. K. (1972). The precolonial kingdom of Rwanda: a reinterpretation. *Transafrican Journal of History*, *2*(2), 11-54.

Rwanda Forest Authority. (2021). Oral communication with Dismas Bakundukize on 2021-03-14.

Rwanda Meteorology Agency. (2021). *Climatology of Rwanda.* https://www.meteorwanda.gov.rw/index.php?id=30

Rwanda Water and Forest Authority. (2017). Forest Investment Program for Rwanda. *Ministry of Lands and Forestry.*

Schabel, H.G. & Latiff, A., 1997. Maesopsis eminii Engler[Internet] Record from Proseabase. Faridah Hanum, I & van der Maesen, L.J.G. (Editors). PROSEA (Plant Resources of South-East Asia) Foundation, Bogor, Indonesia. http://www.proseanet.org.

SEAL Ltd., written & oral communication with Klaas Jan Jonkman & Nepo Hakizimana. December 2020

SEAL Ltd., oral communication with Klaas Jan Jonkman & Nepo Hakizimana. March 2021

Seimon, A. (2012). Climatology and Potential Climate Change Impacts in the Nyungwe Forest National Park, Rwanda. New York: Wildlife Conservation Society.

de Sousa, L. M., Poggio, L., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Riberio, E., and Rossiter, D.: SoilGrids 2.0: producing quality-assessed soil information for the globe, SOIL Discuss. https://doi.org/10.5194/soil-2020-65, in review, 2020. www.soilgrid.org (lat. -2.0300, long. 29.8515)

Sseremba, O. E., Kaboggoza, J. S., Ziraba, N. Y., Mugabi, P., Banana, A. Y., Zziwa, A., ... & Ndawula, J. (2010). Selected strength and machining properties of the wood of Albizia coriaria Welw. Ex Oliv. 442, Markhamia lutea (Benth.) K. Schum. and Chrysophyllum albidum G. Don 40 used in Uganda's furniture industry. *International Wood Products Journal*, *1*(2), 96-101.

Stewart, K. M. (2003). The African Cherry (Prunus africana): From hoe-handles to the international herb market. *Economic Botany*, 57(4), 559-569.

Tree Seed Centre, written & oral communication with Eric Kazubwenge & Emmanuel Niyigena. March 2021

Tsobeng, A., Degrande, A., Tientcheu, M. L. A., Tchoundjeu, Z., & Tabuna, H. (2008). Cultivation and sustainable bark collection of Prunus africana. Technical Note. ICRAF. Yaounde, ICRAF.

Ugwu, J. A., & Omoloye, A. A. (2014). Biology of Iroko Gall Bug, Phytolyma lata Scott.(Homoptera; Psylidae) on Milicia excelsa (Welw) CC Berg. Journal of Entomology, 11(1), 34-41.

Ugwu, J. A., & Omoloye, A. A. (2017). Evaluation of mixed planting and weeding regime for the control of Iroko gall bug on Milicia excelsa. Journal of Entomology, 14(2), 81-86.

Watts, D. P., Potts, K. B., Lwanga, J. S., & Mitani, J. C. (2012). Diet of chimpanzees (Pan troglodytes schweinfurthii) at Ngogo, Kibale National Park, Uganda, 1. Diet composition and diversity. American Journal of Primatology, 74(2), 114-129.

World Conservation Monitoring Centre. 1998. Prunus africana. The IUCN Red List of Threatened Species 1998

White, F. (1983). *The vegetation of Africa* (Vol. 20).

Acknowledgements

This research would not have been possible without the advice and knowledge of many people.

First I would like to thank my supervisors dr. Rosa Goodman from the Swedish University of Agricultural Sciences and dr. Beth Kaplin from the University of Rwanda, for their wisdom and criticism.

I would also like to thank Klaas Jan Jonkman and Nepo Hakizimana from SEAL Ltd. for their support of this research and their knowledge on local silviculture.

I want to thank Dismas Bakundukize from the RFA for sharing his insight in Rwandan forest policy, as well as Eric Kazubwenge and Emmanuel Niyigena from the Tree Seed Centre for the insight in their organization.

And finally I want to thank my friend Joakim Isaksson, who's knowledge on silviculture and critical perspective proved to be useful.

Appendix 1

Figure 7 "Mature Fa forest in Rwanda" C. K. Ruffo 2008; Figure 3.2 in VECEA Volume 2

Figure 8 "Mature Ff forest in Rwanda" F. Gachathi; Figure 8.2 in VECEA Volume 2

Figure 9 "Be landscape in Eastern Rwanda" M. Namaganda 2008; Figure 4.1 in VECEA Volume 4

Appendix 2

Interview questions

Beth Kaplin (Rwanda University) - 2021/03/10

- What is the RU’s current relationship with SEAL?
- Which native trees are already being utilized by smallholders?
- Which traits are needed in Rwanda (charcoal, medicines, food, shade, construction, fine woodwork, etc.)
- Which species would specifically benefit local communities and are the most popular food trees?
- Does the UR have available data on the tree species? (production models of exotic and/ or native species, soil maps)

Dismas Bakundukize (RFA) – 2021/03/14

- Does the government have a formal vision for the future of forestry?
- What has been the effect since the reforesting project from 2011?
- What is the effect of the forest strategy from 2018?
- Which tree traits are needed for that vision?
- And what are the government’s production goals?
- What will the government use wood for?
- Does the government have available data on the tree species? (production models of exotic and/ or native species, soil maps)
- What is holding back the implementation of native species (FIP)?

Klaas Jan Jonkman (SEAL) – 2021/03/08

- How large is the area on which SEAL is willing to plant mixed species?
- What kind of sites is SEAL willing to use for this?

Nepo Hakizimana (SEAL) – 2021/02/25

- What are SEAL’s current production species used for?
- What do you value in Pinus/ Eucalyptus and what are you dissatisfied with
- Which traits in new species have priority?
- Does SEAL have soil data on potential sites?

Eric Kazubwenge (TSC) – 2021/06//04

- What qualities are new species tested for?
- Are the standards for native and exotic species identical?
- Which native species can the seed tree centre deliver?

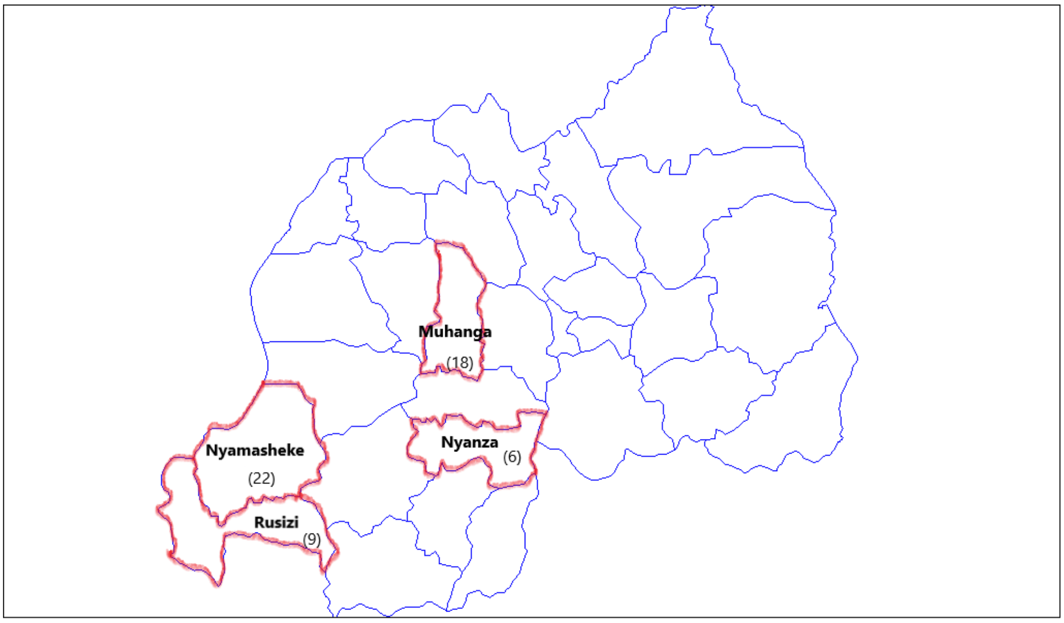
- What could complications for large scale implementation of new native species be?

Emmanuel Niyigena (TSC) – 2021/09/04

- For which species are the seeds available with TSC?
- How can the unavailable seeds be collected/ bought?

Appendix 3

Figure 10 "Rwandan districts where SEAL Ltd. owns stands". Own map.



Appendix 4

Figure 11 "soil properties in Munkoto forest (1)". De Soussa (2020).

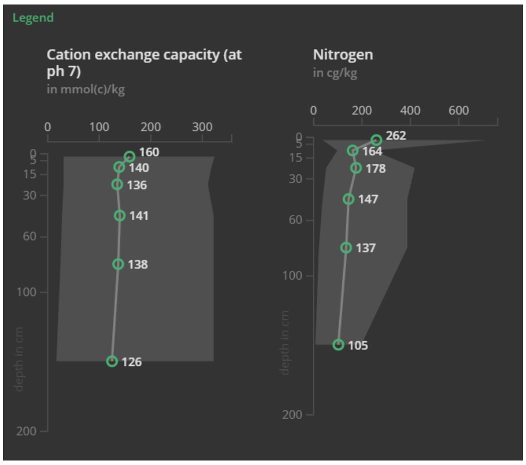


Figure 12 "soil properties in Munkoto forest (2)". De Soussa (2020).

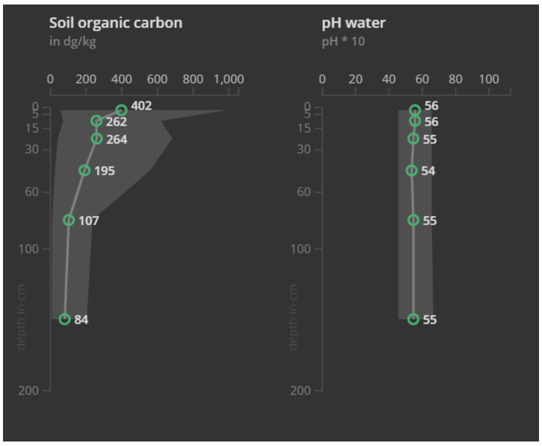


Figure 13 "soil properties Munkoto (3)". De Soussa (2020).

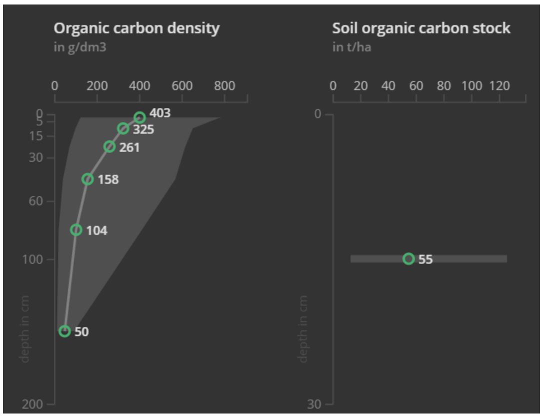


Figure 14 "soil properties Munkoto (4)". De Soussa (2020).

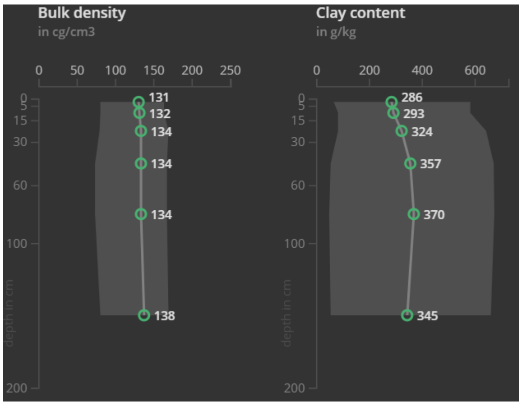


Figure 15 "soil properties Munkoto (5)". De Soussa (2020).

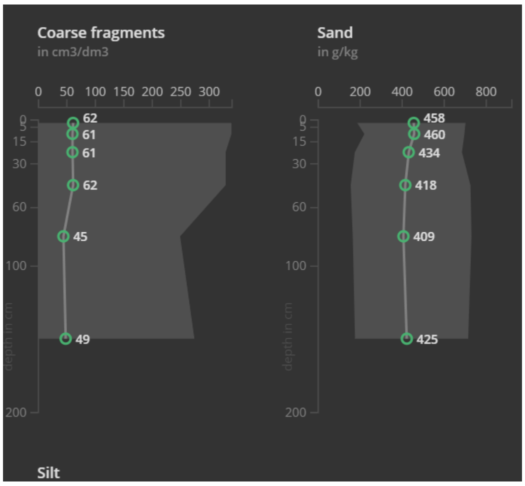


Figure 16 "soil properties Munkoto (6)". De Soussa (2020).

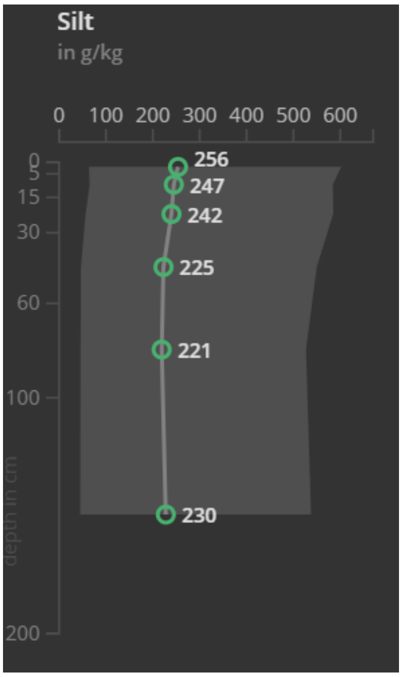


Figure 17 "soil properties Munkoto (7)". De Soussa (2020).

World Reference Base (2006) Soil Groups

Soil group	Probability
Acrisols	37%
Ferralsols	15%
Cambisols	11%
Phaeozems	9%
Vertisols	9%

Appendix 5

Prunus africana

(Marco Schmidt, 2007, wikimedia)

Maesopsis eminii

(Vinayaraj, 2013, wikimedia)

Markhamia lutea

(mauro guanandi, 2009, wikimedia)

Milicia excelsa

(Deni Brown/ IITA, 2010, flickr)

Polyscias fulva

(Impembati, 1998, Flickr)

Entandrophragma excelsum

(Andres Hemp, 2013, wikimedia)

Symphonia globulifera

(Alex popovkin, 2007, Wikimedia)

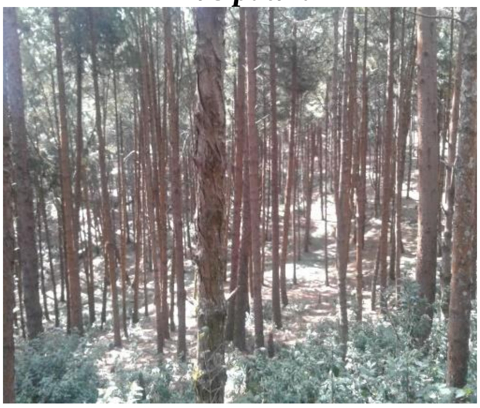
Afrocarpus gracilior

(Forest Starr, 2006, Wikimedia)

Eucalyptus maidenii

(Nepo Hakizimana, 2021)

Pinus patula



(Nepo Hakizimana, 2021)

Croton megalocarpus

(Scamperdale, 2009, Flickr)

SENASTE UTGIVNA NUMMER

2020:01	Författare: Mikaela Rosendahl Fysiska och psykiska hälsoeffekter av att vistas i naturen – En pilotstudie utförd på Stora Fjäderägg, Västerbottens län
2020:02	Författare: Jessica Åström Evaluating abundance of deciduous trees in production forests along small streams – can Sweden meet current policy goals without intensive management
2020:03	Författare: Brita Asplund 5§3 – en statlig storstädning av skogslandskapet
2020:04	Författare: Mikaela Casselgård Effects of 100 years of drainage on peat properties in a drained peatland forest in northern Sweden
2020:05	Författare: Therese Prestberg 1900- talets skogsbruk i kronoparksskogar – En skogshistorisk studie om Håckren och Bjurfors kronoparker
2020:06	Författare: Nils Södermark Inverkan av trädslagsval och plantstorlek på tall- och granbestånds anläggningskostnad, skadeutveckling och tillväxt i norra Sveriges kust- och inland
2021:01	Författare: Torben Svensson Tallsåddens potential för återbeskogning av marker med tjocka humustäcken eller torv i norra Sverige.
2021:02	Författare: Therese Strömvall Nyberg Vad betyder det att skydda natur? – En europeisk jämförelse av skyddade områden
2021:03	Författare: Oscar Nilzén The Guardian Forest – sacred trees and ceremonial forestry in Japan
2021:04	Författare: Gustaf Nilsson Riparian buffer zones widths, windthrows and recruitment of dead wood A study of headwaters in northern Sweden
2021:05	Författare: Louise Almén Naturhälsokartan - Hälsofrämjande naturområden i Väster- och Österbotten
2021:06	Författare: Lisa Lindberg Trait variation of Lodgepole Pine – do populations differ in traits depending on if they are invasive or in their home range?
2021:07	Författare: David Falk Drivers of topsoil saturated hydraulic conductivity in three contrasting landscapes in Kenya - Restoring soil hydraulic conductivity in degraded tropical landscapes
2021:08	Författare: Jon Nordström En märr som hette Mor – De sista härjedalska hästkörarnas berättelser från tiden innan skogsbrukets mekanisering.
2021:09	Författare: Roberto Stelstra Implementation of native tree species in Rwandan forest plantations – Recommendations for a sustainable sector