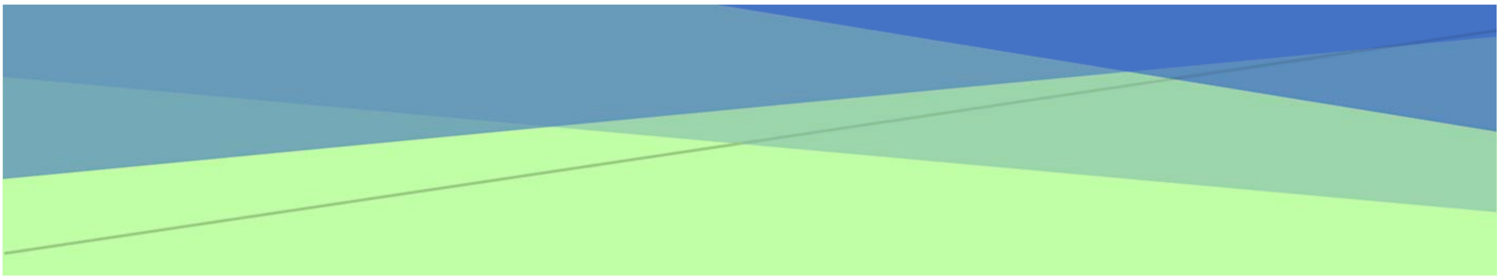

WOOD YIELDS FROM AGROFORESTRY PRACTICES IN AFRICA

A SPATIAL EXPLICIT ASSESSMENT OF SHORT ROTATION WOODY CROP YIELDS

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Date: 30-04-2018

Acknowledgements

This research has been written as part of my master's programme Energy Science at the Utrecht University, in collaboration with the International Renewable Energy Agency (IRENA). During a period of seven months I have been working as an intern at the office of IRENA in Bonn, Germany. I have gained a lot of knowledge on bioenergy and I have got to know myself a bit better. I'm very grateful that I had this opportunity.

I would like to thank Jeffrey Skeer and dr. Ric Hoefnagels in particular. Jeffrey Skeer was my daily supervisor at IRENA and gave useful feedback with a good dose of humour, which helped me writing this thesis. Dr. Ric Hoefnagels was my supervisor at the Utrecht University. He gave his feedback with a nice personal touch and helped me to put things in perspective in stressful moments.

Chaque humain tient une responsabilité envers lui-même et le monde de développer et d'utiliser ses talents.

« Grand-Mère » Denise Steegh-Gillot 10/10/1925 –01/03/2018 †

Contents

List of abbreviations

EJ	Exajoules
Km^2	Squared kilometers
SRWC	short rotation woody crops
GAEZ	The Global Agro- Ecological Zones
IRENA	International Renewable Energy Agency
PAR	photosynthetically active radiation
CO_2	carbon dioxide
CEC	Cation Exchange Capacity
FAO	Food and Agriculture Organization of the United Nations
CRU TS	Climate Research Unit Time Series database
LGP	Length of growing period
HSWD	The Harmonized World Soil database
GLADIS	Global Land Degradations Information System
Tv	Vertic Arenosol (Tv)
bnm	net maximum rate of biomass production (bnm)
bna	average rate of biomass production (bna)
bgm	maximum rate of gross biomass production (bgm)
FM	Fournier index
Mha	Milion hectares
TIN	Tamarindus Indica
CCA	Calliandra Calothyrus
Mt	Million ton
CEQ	Casuarina Equisetifolia
SSE	Sesbania Sesban
ANI	Acacia Nilotica
GRO	Grevillea Robusta
GSE	Gliricidia Sepium

Summary

The world's population continues to grow, requiring increased amounts of food, feed, fibre and fuels. In order to meet these demands, the current available lands should be used more efficiently and more arable lands should become available. In agroforestry systems short rotation woody crops (SRWCs) are planted alongside food crops and are proven to be more efficient compared with traditional agriculture. Combining these perennial woody crops with food crops on the same land has several benefits for the local environment. As a result that, the food production can increase substantially while fuelwood in grown in the same area. The benefits of agroforestry can also play a role in the conversion of degraded lands into arable lands.

Because agroforestry can be a good solution for the expected land scarcity problems, it is essential to quantify the actual yield potential of biomass in such systems. The Bioenergy Simulator of the International Renewable Energy Agency (IRENA) calculates the yield potential of short rotation woody crops, however this model doesn't take the local climate and soil conditions into account. Therefore, the aim of this research is to estimate the yield potential of short rotation woody crops for bioenergy production in Africa, while taking local soil climate and soil conditions and agroforestry practices into account.

A total of 15 nitrogen-fixing SRWCs have been analysed in this research. In order to calculate the yield potential of these species, a method has been developed that peels back from the theoretical to technical yield potential. For each species, first the constraint free biomass production potential has been calculated. This potential is based upon simple biophysical processes such as photosynthesis and respiration and can be calculated with temperature, precipitation and solar irradiation data. For all 15 species a climate and soil suitability analysis has been done. This constraint free yield is then reduced by the limitations imposed due the climate and soil conditions. The remain yield are considered as the theoretical yield potential. The technical yield potential is calculated by excluding all non-suitable land use system for the production of SRWCs. With the technical yield potential of all species known, an analysis has been done in order to select the right species in an area.

The results show that all 15 species are suitable to grow in Africa. The species achieve yields ranging from 2 t/ha up to 16 t/ha and the average total suitable land available for a species is 355 million hectare (Mh). Leuceana Leucocephala is the species that has the largest technical production potential on itself with 410 million tons (Mt) per year, while the average production is 171 Mt per year.

However, this research shows that it is of importance to choose the right species in an area and thereby the total production potential of SRWCs in agroforestry systems in Africa can increase significantly. Five of the 15 species are considered to be less suitable to grow in Africa, compared the yield potentials of the other species. The results of the best performing species analysis are analysed per suitable land use system. The analysis shows that agricultural lands achieve the highest yields and that 95% of the total arable lands in Africa are suitable for SRWC production. The largest total production potential can be achieved on Grasses and Shrub lands of which 30% of the total pasture land in Africa is suitable for SRWC production. There is a small area of sparsely vegetated lands where high yields yield of SRWCs can be achieved and there is a very low potential on Bare lands. The total suitable land when picking the right species is 555 Mha on which a total of 684 Mt SRWCs can be produced per year in Africa.

Since 95% of the total arable land in Africa is suitable for the implementation of agroforestry systems, the potential effects on food production can be enormous. Especially agricultural lands in arid regions can benefit from these systems. On top of that, this research shows that more than 40 Mha of marginal lands have the potential to be restored with agroforestry systems.

1 Introduction

Over the last three decades the use of bioenergy has increased worldwide (International Grains Council, 2015). The security of energy supply, high import costs of fossil fuels and the increase in demand for lower carbon emissions are the biggest drivers for this increase (World Energy Council, 2016). In 2016 the total consumed bioenergy was approximately 62.5 exajoules (EJ), of which about 65% was produced by traditional use of biomass (*e.g.* burning of fuelwood, charcoal and waste residues) (REN21, 2017). It is expected that the total use of primary bioenergy will increase up to 93 EJ in 2030 (IRENA, 2016).

Over the last 40 years, the global population has grown by a staggering 90% and the expectation is that by 2050 there will be a total of 9.1 billion people on this planet (FAO, 2009). This population increase is considered the main driver for the demand increase in food, feed and fibre and, according to Kslat (2012), the demand will continue to advance with the projected population boom. The developing countries will see the largest rise in inhabitants with some regions, such as Sub-Saharan Africa, growing by 114% (FAO, 2009). Research by Searchinger and Heimlich (2015) shows that the world's demand for food crops will grow by approximately 70% and the demand for meat, dairy, timber, and pulp will increase by over 80% in the next 30 years.

At present, the world's total available agricultural land is about 52 million squared kilometres (FAO, 2011). Of which approximately 69% is used for production of meat and dairy, while this type of food only serves 17% of the current caloric food demand (FAO, 2011). The remaining 83% of our food demand is produced on only 11 million km². The current total land use for the production of biofuels is relatively small; approximately 0,3 million km², which is less than 1 percent of the total agricultural land use (Junginger & Kramer, 2017).

The increasing demand for food, feed and, fibre has its effects on the land use in the world. Over the last 50 years the world´s agricultural production has grown by over 2.5 times while the amount of agricultural lands only grew by approximately 10% during that same period (Knickel, 2012). In particular, the production of food feed and fibre will play a big role in land scarcity, because most of the bioenergy is expected to be produced from agricultural waste, fuelwood and charcoal while plantations for bioenergy crops utilise less than 1% of the total available agricultural lands (IRENA, 2016). In order to meet these future demands a more efficient and intensive land use is required (Nachtergaele, Bruinsma, Valbo-Jorgensen, & Bartley, 2009).

The implementation of agroforestry systems could help tackle all these afore mentioned problems at once. Agroforestry is a dynamic, ecologically based, natural resource management system (Nair, 1985). Through the integration of trees on farms and in the agricultural landscape, it diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels. (FAO, 2017a).

One of the considerable benefits of agroforestry is the improvement of productivity of the soil due to the mixture of trees and vegetation. (Hansen & Ram, 2016). Research shows that food production in agroforestry systems can double or even triple compared with non-fertilized food production (Sileshi, Akinnifesi, Ajayi, & Place, 2008). Other services such as the improvement of moisture availability in the soil and a reduction of the top soil erosion, makes agroforestry systems a potential strategy to restore degraded lands (Hillbrand, 2017). Agroforestry systems are considered to have a high potential of carbon sequestration (FAO, 2011).

Typically, short rotation woody crops (SRWC) are used agroforestry systems. These tree species have a high growth ratio and can grow in areas with low fertility. The produced biomass from SRWCs are usable for many purposes such as heat and electricity production, and thereby contribute to the local energy independency and economy of a region (Pereira & Costa, 2017).

In other words, agroforestry systems improve food production, can be used for restoring degraded lands, has a high potential of carbon sequestration and provides biomass that can be used for bioenergy production.

The production of biomass for energy is a complex process wherein multiple factors influence the success of growth (Whiting, 2014). The local climate and soil conditions and the slope of the terrain are examples of these factors (Hatfield & Prueger, 2015);(Walter, 1973). Over the last few decades scientists have tried to capture these processes into a model with the goal of estimating the potential of crops (FAO, 2017b). The development of a model that calculates the growth potential of biomass can be useful for different purposes, it can support farmers and policymakers on investment decisions (Nelson et al., 2009) and can also help identify the best management strategies for specific regions (Jones et al., 2017).

The Global Agro- Ecological Zones (GAEZ) model of IIASA and FAO, which was produced in 2012, is a good example. This model calculates the growth potential of 23 different food crops, taking local climate and soil conditions into account (Fischer et al., 2012). However, the model is mainly focused on food production. While it also includes locally differentiated yields for grass species that are suited to bioenergy production, it does not include wood species such as would be employed in SRWC (FAO, 2017b).

This gap in GAEZ modelling presents a challenge for the Bioenergy Simulator that the International Renewable Energy Agency (IRENA) has produced help farmers calculate potential yields from different food and fuels crops and thus assist in their choice of crops to plant. In the absence of geographically differentiated data on wood crop yields, the Simulator is only able to apply global average values, which limits its utility to specific farmers in specific places to plant wood crops along with food crops. It follows that if a method could be devised to estimate wood crop yields based on publicly available data about sunshine, rainfall and soil conditions, the value of the Simulator could be greatly enhanced.

1.1 Research Aim

While there is an increasing demand for SRWC in agroforestry systems, there is no clear insight of the yield potential of SRWC in such systems. Therefore, this research aims to calculate the achievable yields for short rotation wood crop species on a locally differentiated basis and provide insight on how agroforestry systems might boost the yield of food crops in Africa. The core research theme is thus:

What are the achievable yields of short rotation woody crops, for bioenergy production Africa, in context of local soil and climate conditions and agroforestry practices?

In order to address this issue, a model that includes the local climate- and soil conditions to calculate the yield potential of SRWC has been developed. This model is built upon the methodology described in the first volume of the GAEZ report developed by FAO and IIASA (IASSA, 1991). The information given by that model is used to answer four main analytic questions:

1. What are the main factors that determine the yield of short rotation woody crop?
2. What short rotation woody crop types are suitable for agroforestry systems in Africa?
3. Which areas are suitable for the growth of short rotation woody crops in Africa?
4. What is the impact of agroforestry management strategies on the yield of food crops?

The biomass potential depends on the yields of cultivated biomass and the available area that is suitable to grow biomass on (Wicke, Smeets, Watson, & Faaij, 2011). The first two questions deal with the yields of cultivated biomass. In answering these questions, the model will provide insight on what SRWC can be cultivated in Sub-Saharan Africa. The third question gives insight on the available land area for the biomass potential. In answering the third question, on which soils are suitable for the growth of the SRWC, the model will provide insight on the available land area for agroforestry approaches combining wood and food crops. In answering the fourth question on how agroforestry strategies can boost food yields, in combination with the third, the model will provide insight on how much extra food and fuel could be produced.

2 Background on plant growth and agroforestry

In order to estimate the influence of local climate- and soil conditions on the yield potential, an understanding is needed of the biophysical processes that effect plant growth (Holding & Streich, 2013). This chapter explains what these processes are and how the environment effects these processes.

2.1 The three biophysical processes of plant growth

The growth and development of plants are determined by the three basic biophysical processes; photosynthesis, respiration and transpiration (Whiting, 2014).

Photosynthesis is the process in a plant where light, water and carbon dioxide are converted into oxygen, sugar and energy (Raven, 2013). This process can be divided into two steps. In the first step, incoming solar radiation initiates a chemical reaction within the plant cell where oxygen and energy for the second step is released, this process is called light reactions (Holding & Streich, 2013). In the second step, the dark reaction process, the released energy is stored by the so called Rubisco enzymes into three-carbon molecules (Holding & Streich, 2013). The Rubisco enzymes are essential of plant growth and consume nitrogen during this process.

Respiration is often called the opposite reaction of photosynthesis (Holding & Streich, 2013). During the process of respiration, plants convert oxygen from the atmosphere and sugars from photosynthesis into water, carbon dioxide and energy for growth and development (Whiting, 2014). Simplified, respiration can be divided into two components, maintenance respiration and respiration that is associated with biomass production (Bruhn, 2002). The energy needed for a plant to repair and maintain its cell tissue, is catered by the energy released due to maintenance respiration (Bruhn, 2002).

Transpiration is the evaporation of water molecules out of the plant into the atmosphere (ICT international, 2018). This process occurs when plant cells in the leaves open up in order to uptake the necessary carbon dioxide (Sterling, 2004). The evaporated water, is replaced by nutrient rich water absorbed in the roots of the plant and therefore enhances the nutrient uptake of plants (Sterling, 2004).

2.2 Environmental factors affecting plant growth

There are several environmental factors that play a role on plant growth, which are in this thesis divided by climate factors and soil factors.

2.2.1 Climate factors

Solar radiation is considered essential for the growth of any crop. In particular, the photosynthetically active radiation (PAR), which ranges between 400 to 700 nanometre wavelength. In general, with an increase of incoming PAR, biomass production increases proportionally (ALS Association, 2014). More light means more energy produced that can be used for the dark reactions in photosynthesis (RSC, 2014). The relation between the intensity of light on rate of photosynthesis is schematically shown in figure 2.1.

As stated before, **carbon dioxide** is an important factor in the processes of photosynthesis. An increase of the available carbon dioxide concentration will increase the rate of the dark reactions and thereby the rate of photosynthesis in general (RSC, 2014). Under normal conditions, the atmosphere has a low concentration of CO2, increasing this concentration will therefore cause a rapidly increasing rate of photosynthesis (RSC, 2014). See figure 2.2 for a schematic explanation of the relation between CO2 concentration and the rate of photosynthesis.

Temperature is another factor that plays an important role in plant growth. As described above, plants use enzymes in the dark reactions process in photosynthesis. The efficiency of those enzymes improves with the increase of temperature (Amedie, 2013). It is estimated that the rate of photosynthesis doubles every 10° celcius upto the optimum temperature (RSC, 2014). When the temperature increases above the optimal temperature, the rate of photosynthesis decreases rapidly (RSC, 2014). See figure 2.3 for a schematic overview of the relation between temperature and the rate of photosynthesis.

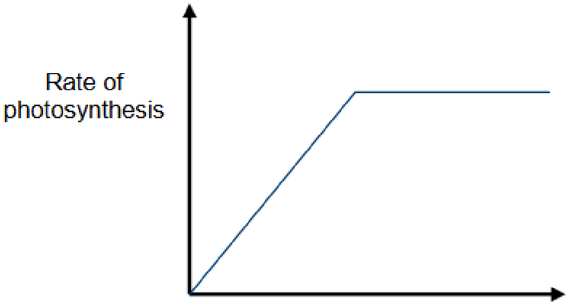


Figure 2.1; Rate of photosynthesis versus light. Source: RSC, 2014

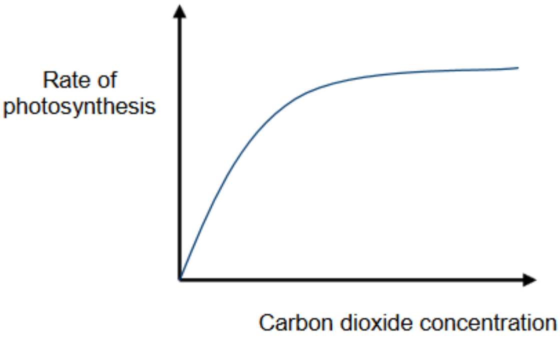


Figure 1.2 Relation between PM and CO2. Source: RSC, 2014

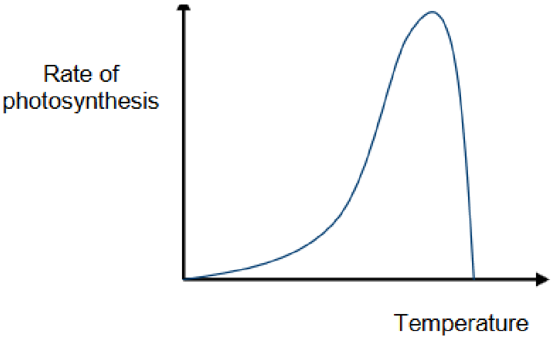


Figure 2.2; Relation between temperature and rate of photosynthesis. Source: RSC, 2014

Water availability is essential for a plant to survive. Plant cells consist for almost 90% out of water (Singh, 2007). Water fulfils several roles within plant growth. It serves as a reactant and as a solvent for chemical reactions that occur in the photosynthesis and respiration processes (Kramer & Boyer, 1995). Minerals are transported and distributed from the roots by water due to the hydraulic lift effect of transpiration (Whiting, 2014). Water also functions as a temperature regulator within the plant (Kramer and Boyer, 1995). Water deficit will decrease the productivity of a plant because photosynthesis, respiration and transpiration processes are all depending on the availability of water (Chavarria & dos Santos, 2012).

However, excessive water in the soil can be problematic for plants (Douglas, Street, Box, & Haven, 2003) as it limits the amount of oxygen and nutrient uptake of and thus the growth of plants (Taylor, 2006) (García, Mendoza, & Pomar, 2008).

2.2.2 Soil factors

The soil is one of the most important factors in plant development. Soils contain water and nutrients that are necessary for plant growth (Hewitt, 2004). It is also of importance that the soil provides has a favourable texture and hardness for a plant to develop its roots (Walter, 1973). This sub-chapter explains the effects of soil conditions on plant growth.

Nutrient availability is essential for plant growth. There are three main nutrients that are most important for plant development; nitrogen, potassium and phosphorus (Kramer & Boyer, 1995). Nitrogen is considered as the most important nutrient in plant growth, because it is responsible for the development of the foliage of plants. However, it is sensitive for leaching from the soil. Potassium is of importance because it is makes a plant more drought and disease resistance. Phosphorus promotes the development of the root system of plants (Crouse, 2018).

The soil texture is considered as an important factor in the development of a plant (Walter, 1973). The texture of a soil is basically the proportion of sand, silt and clay present in a soil (Cornell University, n.d.). In particular the share of clay is of importance, because it is negatively charged and has therefore the ability to hold on to nutrients which are positively charged. This mechanism is called the Cation Exchange Capacity (CEC) (Ketterings, Reid, & Rao, 2007). Another reason why the share of clay is of importance is that is has a relatively small grain size (Vander Voort, 1998). A small grain size means less space between the grains and therefore less leaching of nutrients (Hewitt, 2004). Since most soils are an aggregate of sand, silt and clay, the rule of thumb is therefore the smaller the grain size, the more suitable the soil (Fischer et al., 2012). However, when the pore size of a soil is too small, water can’t move through the soil profile what results in soil runoff (Cornell University, n.d.).

The slope of the soil is another factor that influences the development of a plant. The slope has influence on the nutrients and water available in the soil (LADA, 2013) . In general, steeper slopes have less nutrients and water available due to the runoff induced by rainfall (Fischer et al., 2012).

2.3 Background on agroforestry

The aim of this chapter is to explain what agroforestry is and how it effects the above mentioned climate and soil factors that influence crop growth. The definition of agroforestry has been a point of discussion over the last few decades, therefore the first subchapter will discuss the definition of agroforestry. The different types of agroforestry systems are mentioned in the second subchapter. The third subchapter explains the effect of agroforestry systems on the local soil and climate.

2.3.1 Agroforestry definition

The cultivation of perennial wood species combined with agricultural crops is an ancient practice that is still used throughout the world (Nair, 1993). In Europe, this type of agriculture has been practiced since the Middle Ages until the beginning of the 20th century. (Nair, 1993). Hence, one could say that agroforestry is a set of old practices (Nair, 1993). The research on the diversity and scope of agroforestry intensified in the 1970s and 1980s and as a result of that, there was no clear definition formulated. (Amonum, 2009).

Nair (1985) describes agroforestry as fallows: “an approach of integrated land-use that involves deliberate retention or an admixture of trees and other woody perennials in crop/animal production fields to benefit from the resulting ecological and economic interactions” (Nair, 1985). This definition was later rephrased as the purposeful growing or deliberate retention of trees with crops and/or animals in interacting combinations for multiple products or benefits from the same management unit (Nair, 1993).

The FAO provides two definitions of agroforestry. Firstly, agroforestry is a collective name for land-use systems and technologies where woody perennials are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. (FAO, 2017a). Secondly, a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels. (FAO, 2017a)

2.3.2 Types of agroforestry management systems

Nair (1993) has defined three major types of agroforestry systems.

1. Agrisilvicultural systems, where crops and trees are mixed
2. Silvopastoral systems, where pasture/animals and trees are mixed
3. Agrosilvopastoral systems, where crops, pasture/animals and trees are mixed.
4. Other, including multipurpose tree lots, apiculture with trees, aquaculture with tree etc.

Table 2.1 provides a list of agroforestry systems accompanied with a brief description.

Agroforestry practice	Brief description
Agrisilvicultural systems	**Crops and trees**
Improved fallow	Woody species planted and left to grow during the 'fallow phase'
Taungya	Combined stand of woody and agricultural species during early stages of estabilsment of plantations
Alley cropping	Woody species in hedges; agricultural speciies in alleys between hedges
Multilayer tree gardens	Multispecies, Multi dense plant associations with no organized planteing arrangements
Multipurpose trees on crop lands	Trees scattered haphazardly or according to some systematic patterns.
Plantation crop combination	Integrated multistory mixtures of plantation crops
Homegardens	Intimate multistorey combination of various trees and crops around homesteads
Trees in soil conservation and reclamation	Trees for soil reclamation
Shelterbelts and windbreaks	Trees around farmlands/plots
Fuel wood production	Interplanting firewood species on or around agricultural lands
Silvopastoral systems	**Trees + Pasture and/or animals**
Trees on rangeland or pasture	trees scattered irregulalry or arranged to some systematic pattern
Protein banks	Production of protein rich fodder on farm/rangelands for cut-and-carry fodder production
Plantation crops with pasture and animals	Example: cattle under coconut trees
Agrosilvopastoral systems	**Trees + crops + pasture/animals**
Homegardens involving animals	Intimate multistorey combination of various trees and crops and animals around homesteads
Multipurpose woody hedgerows	Woody hedges for browse, green manure, soil conservation, etc.
Apiculture with trees	Trees for honey production
Aquaforestry	Trees lining fish ponds
Multipurpose woodlots	For various purposes

Table 2.1 Major agroforestry systems and descriptions. Source: (Nair, 1993)

2.3.3 Benefits of agroforestry systems on the ecosystem

There are three major benefits of agroforestry systems on the ecosystem; the systems can improve the soil quality, reduce the impact of erosion and increase the water availability (Hillbrand, 2017). Each of these benefits is explained below.

Soil quality

Agroforestry systems have a positive impact on the quality of a soil. Compared with conventional agricultural systems is the nitrogen cycling more intensive in agroforestry systems. The amount of nitrogen leaving the system is lower and the rate of transfer of nitrogen within the system is higher compared with conventional agricultural systems (Tsonkova, Böhm, Quinkenstein, & Freese, 2012). A reason for a low output of nitrogen within the system, is due to the high efficiency of the nitrogen cycle. The deeper rooting system of some SRWC are able to intercept and uptake nitrogen from deeper soil layers and return it to the surface soil with litter fall (Allen, Jose, Nair, Brecke, & Ramsey, 2004). The cultivation of SRWC is therefore a viable option to recuperate nitrogen poor soils and to maintain fertility of agricultural land without additional fertilization. (Tsonkova et al., 2012).

Erosion control

The implementation of SRWC in agroforestry systems can contribute to the reduction of soil erosion (Béliveau et al., 2017). Due to the root system of the woody crops, the stability of the soil increases while the detachability decreases (Young, 1990). Trees could also act be used for the reduction of surface runoff, by physically blocking the incoming precipitation velocity and water flowing over the surface (Tsonkova et al., 2012).

Water regulation

Water availability is a significant factor for the growth of a plant and could be a limitation in the case of insufficiency (Walter, 1973). SRWC have the availability to supply neighbouring crops with water due to hydraulic lift of the deeper root system. In this process is water absorbed from deeper located soil layers up and released in upper layer soils. (Burgess, Adams, Turner, White, & Ong, 2001).

3 Input Data

3.1 Species overview

A total of 15 nitrogen-fixing short rotation woody crops have been analysed in this thesis. The FAO and IIASA have grouped these species into 6 classes, see table 3.1 for an overview of the species. The first distinction that can be made is based on the optimum temperature for the maximum photosynthesis rate (IASSA, 1991). Some species perform better under cooler conditions with the optimum temperature ranging between 15° and 20° Celsius (IASSA, 1991). Other species are functioning better in warmer conditions with mean optimum temperatures ranging between 20° and 30° degrees Celsius (IASSA, 1991). Within those two groups a distinction can be made based on the maximum rate of photosynthesis (Pm) of the species (IASSA, 1991). Three classes of photosynthetic rate (PM) have been identified by the FAO and IIASA (1991);

- Low rate: PM = 5 – 10 kg CH_2O ha-1 hr-1
- Medium rate: Pm = 10 – 20 kg CH_2O ha-1 hr-1
- High rate: Pm= 20-30 kg CH2O ha-1 hr-1

Characteristics	**Group I (<20 °C) Species Suited to Cooler Climates**	**Group II (> 20°C) Species Suited to Warmer Climates**
Temperature for maximal photosynthesis:	**15°C - 20°C**	**20°C - 30°C**
LOW RATE OF PHOTOSYNTHESIS (Pm = 5-10 kg CH2O ha-1 hr-1)	**Acacia Gerrardii**	**Acacia Albida**
	Croton Megalocarpus	**Acacia Nilotica**
	Grevillea Robusta	**Acacia Senegal**
		Acacia Tortilis
		Calliandra Calothyrus
		Conocarpus Lancifolius
		Gliricidia Sepium
		Tamarindus Indica
MODERATE RATE OF PHOTOSYNTHESIS (Pm = 10-20 kg CH2O ha-1 hr-1)	**Casuarina Cunninghamiana**	**Casuarina Equisetifolia**
HIGH RATE OF PHOTOSYNTHESIS (Pm= 20-30 kg CH2O ha-1 hr-1)	**Sesbania Sesban**	**Leucaena Leucocophala**
		Sesbania Sesban

Table 3.1: Classification of species by Pm and temperature. Source: FAO & IASSA, 1991

3.2 Climate data

The calculation of the yield potential of short rotation woody crops is based on on four climatic variables: temperature, precipitation, the length of growing period and solar radiation.

The temperature and precipitation data is derived from the Time Series database of the Climate Research Unit (CRU TS) and contains monthly temperature and precipitation data for the period of 1950 – 2016 with a 30 arc-minutes resolution. The latest version CRU TS 4.01 is used for this research, this database revises and extends the earlier version CRU TS 2.1. See appendix A1.1 and A1.2 for the gridded temperature and precipitation maps respectively.

The **solar radiation** comes from the WorldClim V2 database. This database is produced by (Hijmans & Fick, 2017) and provides a detailed 30 arc – seconds gridded monthly average solar radiation map for the period 1970-2000. See appendix A1.3 for the average yearly solar radiation of Africa.

The availability of moisture content in the soil can be expressed as **the length of growing period** (LGP). This is the total amount of days per year when precipitation exceeds half of the potential evapotranspiration (FAO, 1978). The data for the Length of Growing Period (LGP) is derived from the Global Agro-Ecological Zonas report conducted by FAO and IIASA (2007). This map is a 5 arc – minute sized raster layer and each cell contains information on the length of growing period. See appendix A1.4 for the LGP map of Africa (FAO, 2017b)

The temperature, precipitation and LGP data are interpolated into a 30 arc-second raster. In order to loss minimal information by interpolation, a Cubic interpolation method was applied within Arcmap 10.5. This method calculates the value of each pixel by fitting a smooth curve based on the surround 16 pixels.

3.3 Soil data

In this research, the soil suitability of an area for a species is based on data of the physical and chemical composition of the soil, the soil texture and the soil slope. The Harmonized World Soil database (HSWD) has provided the data for these three variables. The information of this database is stored as 30 arc-seconds in a GIS raster, which is linked to an attribute database in Microsoft Access format containing harmonized soil profile data (FAO & IIASA, 2009).

Physical and chemical composition (soil units)

One of the first attempts to identify soils all over the world was the FAO-UNESCO Soil Map of the World (Soil Survey Staff, 2014). In order to identify what soils are present in a certain region, the FAO has classified all soils based on their physical and chemical composition into so called soil units (FAO, 1974). This classification is called the FAO74 Classification. The FAO revised and further improved the FAO74 Classification in 1988, that classification is called the FAO90 Classification (FAO, 1988).

The soil unit data provided by the HWSD consists out of FAO74 and FAO90 classified data. See figure 3.1 for the distribution of the different classifications.

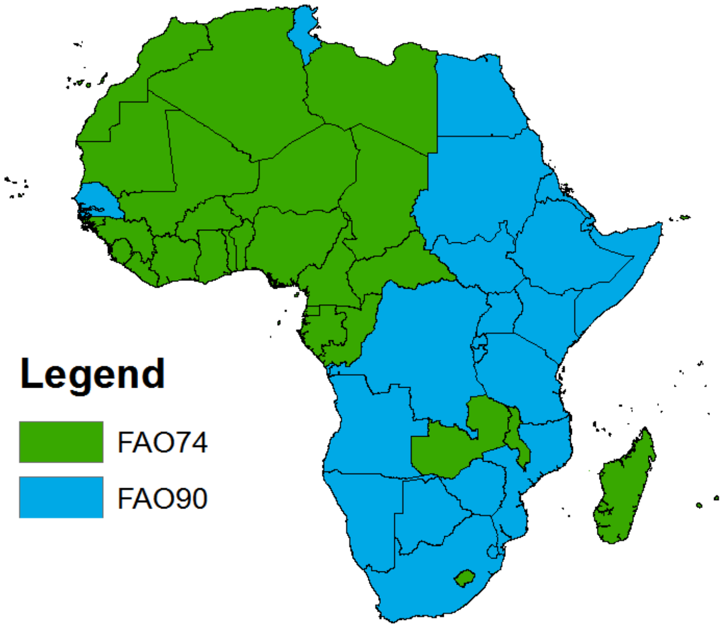


Figure 3.1 Soil unit classification in Africa from the HWSD. Source: FAO & IASSA, 2009

Land use system data

The data of the currently used land use systems in Africa is derived from the Global Land Degradations Information System analysis (GLADIS) (LADA, 2013). Based on satellite imagery 8 main land cover types have been recognized (LADA, 2013). These landcovers are divided into 41 different land use systems, based on statistics and other data layers (LADA, 2013). See figure 3.2 for the 8 main land use systems (LADA, 2013). The data has a resolution of 5 arc minutes and has been resampled into 30 arc seconds with the use of the cubic interpolation resample tool of Arcmap 10.5.

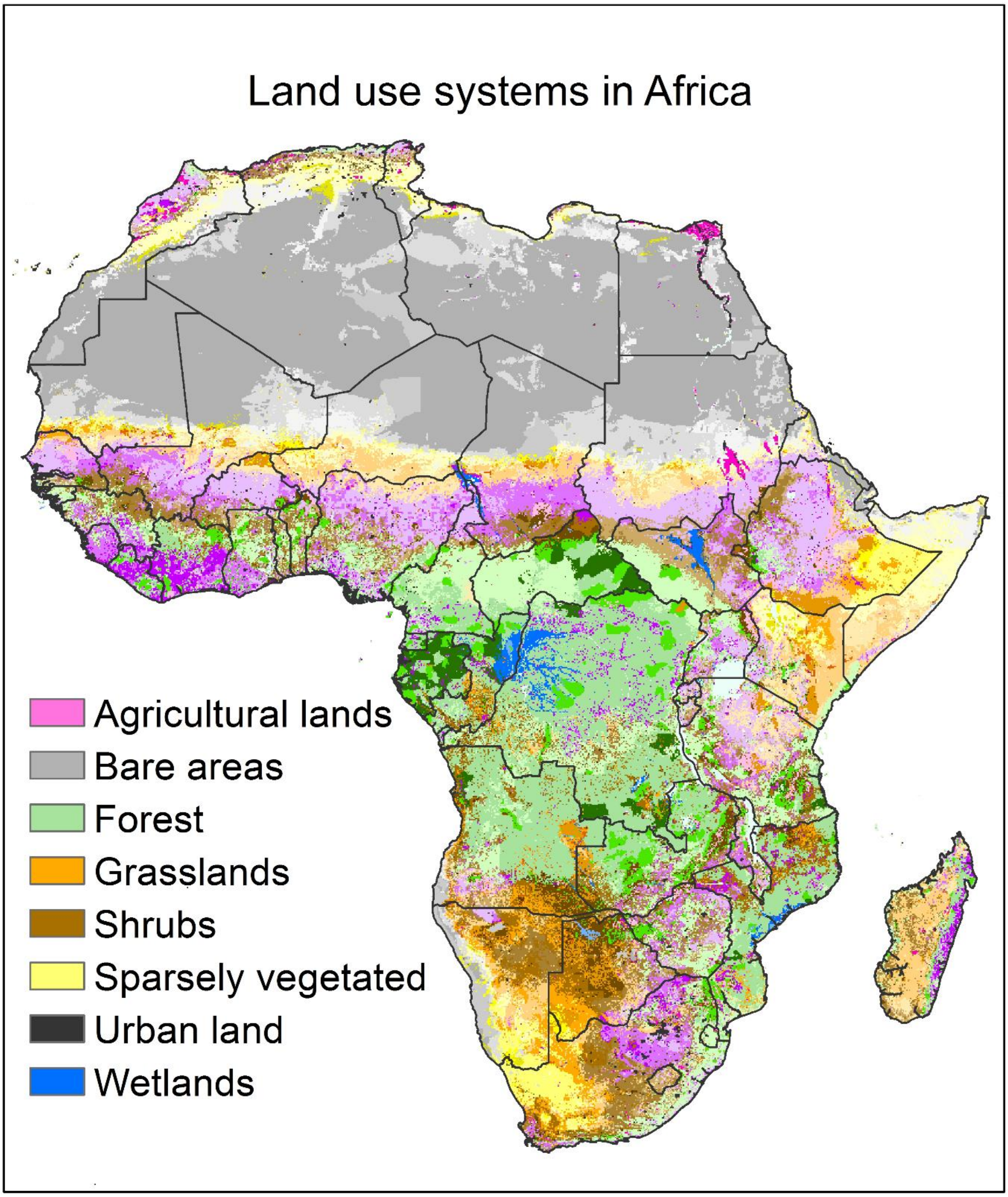


Figure 3.2; 8 main categories of Land use Systems in Africa, Source: LADA, 2013

4 Method

In the present study, the yield potential of SRWC in agroforestry systems in Africa was calculated, while taking local soil- and climate conditions into account. This yield potential can be divided into the theoretical and technical yield potential. The theoretical potential is defined as the theoretical upper limit of biomass production limited by physical and biological barriers, the soil and climate conditions. The technical potential is defined as the fraction of theoretical potential that is limited by non-suitable land use systems in Africa (Smeets, Faaij, Lewandowski, & Turkenburg, 2007).

To do so, the following seven steps were conducted, see figure 4.1 for a schematic overview of the method.

Step 1: **Maximum constraint free yield potential calculation:** In order to calculate the theoretical yield potential, first the upper limit of SRWC production was analysed. The methodology for this calculation was derived from the Agro-Ecological Zones report of the FAO, 1978. With the use of temperature- and solar radiation data, the constraint free yield was calculated.

Step 2: **Climate suitability analysis:** In this step the suitability of the local climate for SRWC production has been analysed. For each specie the temperature- and length of growing period suitability has been mapped. The suitability analyses are based on expert knowledge derived from the Agro-Ecological Zones report, 1991.

Step 3: **Soil suitability analysis:** the soil suitability of an area is defined based on three components; soil unit-, soil texture- and soil slope suitability. The first two components are based on expert knowledge, derived from FAO (1991). The slope suitability is based on expert knowledge, derived from Fischer et al. (2012).

Step 4: **Theoretical yield potential calculation:** Step 1,2 and 3 provide the information necessary for the theoretical yield potential calculation. In this step the maximum constraint free yield potential (step 1) is reduced by climate- and edaphic constraints (step 2 and 3, respectively).

Step 5: **Land use system limitations:** The areas that are considered suitable from a physiological and biological point of view (step 4), are not necessarily available for SRWC production, i.e. urban areas. This step analyses all available land uses for SRWC production in Africa.

Step 6: **Technical yield potential calculation:** the land use systems that are identified in step 5 are excluded from the theoretical yield potential calculation. The remaining yield potential is considered as the technical yield potential.

Step 7: **Selecting most useful species for biomass production:** At this point in the analysis, the technical yield of all nitrogen fixing SRWC is known. In most areas the climate and soil conditions meet the requirements of multiple different species. As a result of that, some areas have multiple species that will achieve the same technical yield potential per hectare. In order to calculate the maximum yield potential a preference of species has been made based on the quantity of utilization options of the SRWC.

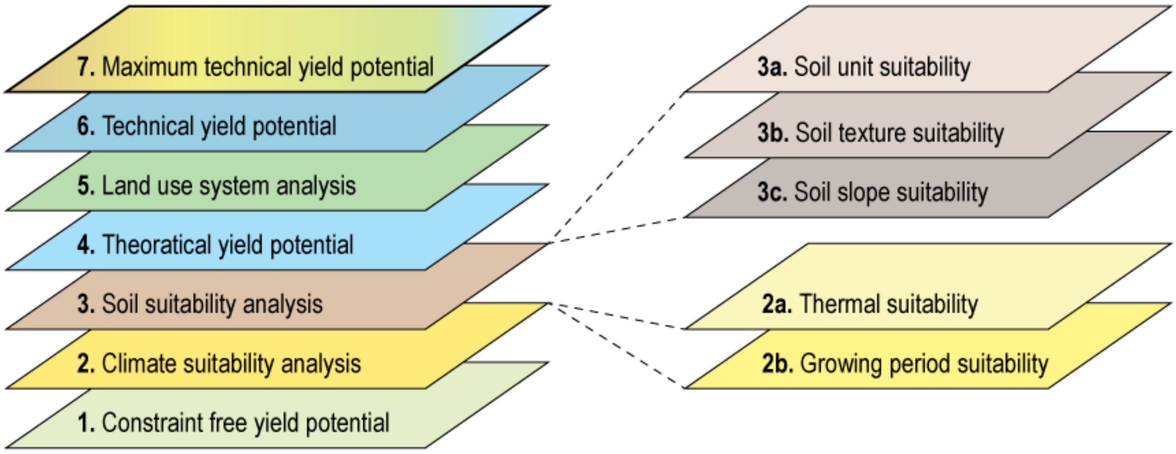


Figure 4.1; Schematic overview of the seven steps in the method. Own production

4.1 Constraint free yield potential

The first step of defining the theoretical yield potential is the calculation of the constraint free biomass production potential (Smeets et al., 2007). In this research, the methodology of the constraint free yield potential is completely derived from the agro-ecological zones project developed by the FAO in 1978. This methodology calculates the yield potential on basic eco-physiological principles and is briefly explained in this chapter.

Gross and net biomass production

As explained in chapter 2.1, the biomass production of a plant is dependent of the photosynthesis- and respiration processes. The FAO report simplifies these processes in an equation where the total gross biomass production (i.e. photosynthesis) is reduced by losses that occur during the respiration process (FAO, 1978). This equation is formulated as follows:

$$Bn = Bg - R \tag{1}$$

- Bn = Net biomass production
- Bg = Gross biomass production
- R = Respiration losses

The rate of which a plant produces biomass can therefore be expressed as (FAO,1978):

$$bn = bg - r \tag{2}$$

- bn = rate of net biomass production
- bg = rate of gross biomass production
- r = respiration rate

So in other words, the net maximum rate of biomass production (bnm) mainly depends on the rate of gross biomass production (the rate of photosynthesis). Since photosynthesis occurs in the leaves of the plants, the bnm is achieved when the soil surface is completely covered by the crop (FAO,1978). When plotted, the growth rate of a plant has therefore the shape of a cumulative growth rate. A more developed plant has more leaves and will therefore grow faster. The first derivative of a cumulative growth curve has the shape of a normal distribution curve, see figure 4.2 for a schematic overview of the growth rate a of a plant. The GAEZ model assumes that the average rate of biomass production (bna) over het whole growing period, is half of the maximum growth rate (FAO,1978). Therefore the following equation has been formulated by the FAO:

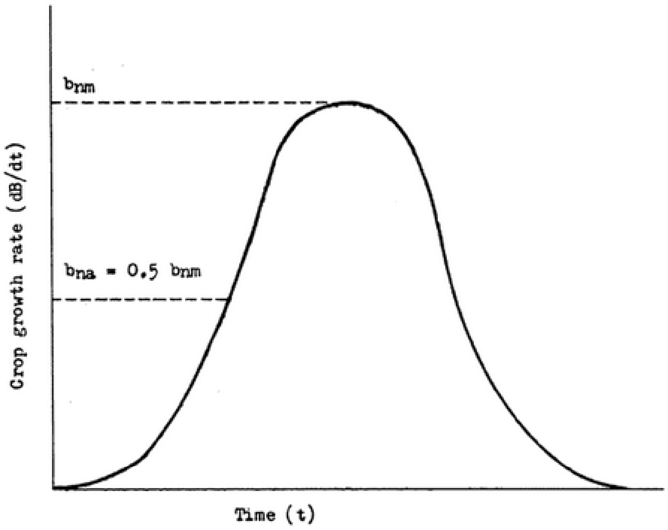


Figure 4.2: Growth rate over time. Source: FAO, 1978

$$Bn = 0.5\ bnm \times LGP \tag{3}$$

- Bn = Net biomass production
- bnm = maximum rate of net biomass production
- LGP = length growth period in days

As explained in chapter 3.1.2, the LGP is a given factor depending on the moisture availability of a region. Therefore, if the maximum rate of biomass production is known, the net biomass production can be calculated (FAO, 1978). Equation 2 shows that the rate of net biomass production depends on the rate of gross biomass production and the respiration loss. So in order to calculate the net biomass production, the maximum gross biomass production (bgm) and the associated respiration loss need to be known.

Maximum rate of gross biomass production

As explained in chapter 2.1, photosynthesis is the main process of biomass production. Therefore the maximum rate of gross biomass production (bgm), is depending on the maximum rate of photosynthesis (Pm). Pm is on its turn is depending on two factors; incoming photosynthetically active radiation (PAR) and temperature

The AEZ report, 1978 states that the maximum rate of gross biomass production of a day is the sum of biomass produced during the time that the sky is overcast and the biomass produced during the time that the sky is clear. De Wit (1965) presents the daily gross photosynthesis rate for completely overcast days (bo) and for very clear days (bc), see table 4.1. With the use of those values and the fraction of the daytime the sky is overcast, bgm can be calculated (FAO, 1978). The report therefore formulates bgm as follows:

$$bgm = F \times bo + (1-F)\ bc \tag{4}$$

- F = fraction of the day-time when the sky is overcast.
- *bo* = gross dry matter production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha-1 day-1) (de Wit, 1965)
- *bc* = gross dry matter production rate of a standard crop for a given location and time of the year on a perfectly clear day, (kg ha-1 day-1) (de Wit, 1965)

The fraction of day-time when the sky is covered with clouds can be calculated by dividing the actual incoming PAR by the incoming PAR on a very clear day (FAO, 1978). De Wit, (1965) has estimated the total amount of photosynthetically active radiation on a very clear day (Ac) for the 0°, 10°, 20°, 30° and 40° northern latitudes, see table 4.1. For this research it is assumed that these values are equal for the southern latitudes, respectively. It is assumed that on a totally overcast day, only 20 percent of the total amount of PAR reaches the surface compared to a perfectly clear day (FAO 1978). As explained in chapter 2.1, 50 percent of the incoming shortwave radiation is considered as the PAR. Therefore the GAEZ report states that the fraction of the day-time when the sky is overcast (F) is then (FAO, 1978):

$$F = (Ac - 0.5Rg) / 0.8\,Ac \qquad (5)$$

- F = Fraction of day-time when the sky is overcast
- Ac = Maximum active incoming photosynthetically radiation on a clear day (de Wit, 1965).
- Rg = incoming shortwave radiation

See appendix A1.5 for the F value mapped for Africa.

De Wit (1965) has calculated the values of bo and bc for plants with a photosynthesis rate of 20 kg CH2O/ha/h. However as stated before, the rate of photosynthesis is dependent on the temperature. The Technical Annex (FAO,1991) gives the relationship between temperature and the rate of photosynthesis are given for the six adaptability classes is given in table 4.2. Bases on actual case studies, the FAO has therefore the bgm equation (4) adjusted for different photosynthesis rates (FAO, 2017b).

When *Pm* is greater than 20 kg ha-1 hr-1, *bgm* is given by the equation:

$$bgm = F\,(0.8 + 0.01Pm)\,bo + (1 - F)\,(0.5 + 0.025\,Pm)\,bc \qquad (6)$$

When *Pm* is less than 20 kg ha-1 hr-1, bgm is calculated according to:

$$bgm = F\,(0.5 + 0.025\,Pm)\,bo + (1 - F)\,(0.05\,Pm)\,bc \qquad (7)$$

	Values of AC, BC and BO											
North lat.		**Jan**	**Feb**	**March**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
0°	**AC**	343	360	369	364	349	337	342	357	368	365	349	337
	BC	413	424	429	426	417	410	413	422	429	427	418	410
	BO	219	226	228	228	221	216	218	225	230	228	222	216
10°	**AC**	299	332	359	375	377	374	375	377	369	345	311	291
	BC	376	401	422	437	440	440	440	439	431	411	385	370
	BO	197	212	225	234	236	235	236	235	230	218	203	193
20°	**AC**	249	293	337	375	394	400	399	386	357	313	264	238
	BC	334	371	407	439	460	468	465	451	425	387	348	325
	BO	170	193	215	235	246	250	249	242	226	203	178	164
30°	**AC**	191	245	303	363	400	417	411	384	333	270	210	179
	BC	281	333	385	437	471	489	483	456	412	356	299	269
	BO	137	168	200	232	251	261	258	243	216	182	148	130
40°	**AC**	131	190	260	339	396	422	413	369	298	220	151	118
	BC	218	283	353	427	480	506	497	455	390	314	241	204
	BO	99	137	178	223	253	268	263	239	200	155	112	91

Table 4.1; Values for AC, BO and BC for northern latitudes. Source: De Wit, 1965

	Temperature (°C)							
Adaptability class	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
1 A	0.75	3	6	7.5	7.5	6	3	1.5
1 B	1.5	6	12	15	15	12	6	3
1 C	2.5	10	20	25	25	20	10	5
2 A	0	0.75	4	6	7.5	7.5	6	4
2 B	0	1.5	8	12	15	25	12	8
2 C	0	2.5	15	20	25	25	20	15

Table 4.2; Relationship between temperature and rate of photosynthesis (kg CH2O/ha/hr); Source: FAO, 1991)

Respiration loss

As equation 2 shows, respiration loss is the other factor that is needed for the calculation of the net rate of biomass production. As explained in chapter 2.1, respiration can be divided into growth respiration and maintenance respiration.

A Study of McCree (1974), shows that the growth respiration is a linear function of the rate of gross biomass production (bg) and maintenance respiration a linear function of net biomass that has already been accumulated (*B*) (FAO, 1978).

The equation of the respiration rate that is associated with the maximum rate of biomass production is therefore :

$$rm = k\ bgm + c\ Bm \qquad (8)$$

where:

- k = The proportionality constant for growth respiration
- c = The proportionality constant for maintenance respiration
- Bm = The net biomass that already has been accumulated at the time of maximum rate of net biomass production.

For both legume and non-legume crops *k* equals 0.28 (McCree, 1974). However, *c* is temperature dependent and differs for the two crop groups. At 30°C, factor *c* for a legume crop equals 0.0283 and for a non-legume crop 0.0108 (McCree, 1974). The temperature dependence of *c* for both crop groups is modelled with a quadratic function:

$$ct = c30\ (0.0044+0.0019\ T+0.0010\ T^2) \qquad (9)$$

Where:

- Ct = temperature dependent proportionality constant of maintenance respiration
- C30 = value of the proportionality constant for maintenance respiration at 30 °c
- T = temperature (°c)

The difference in maintenance respiration between legume and non-legume species arises because the exact value depends on the chemical composition of the biomass, particularly the rate of turnover of protein. In other words, it is costlier in terms of energy to synthesis and maintain biomass richer in protein.

So if the net biomass that already has been accumulated to the point where a plant reaches the rate of maximum biomass production (Bm) is known, rm can be calculated (see figure X, for a schematic explanation of bgm). The GEAZ model (2017b) assumes that when a crop reaches the bgm rate, half of the total biomass that a crop produces over its lifetime has been produced. Therefore Bm = 0.5 Bn; and from equation (3), Bm for a crop of N days is (FAO, 1978):

$$Bm = 0.25\ bnm \times LGP \qquad (10)$$

Where,

- Bm = The net biomass that already has been accumulated at the time of maximum rate of net biomass production.
- bnm = the maximum rate of net biomass production
- LGP = length growing period

Net biomass production

According to equation of the rate of net biomass production (2), the maximum rate of net biomass production can be calculated by combining the gross biomass production equation (6) and the respiration equation (8) (FAO, 1978).
The maximum rate of net biomass production can therefore be formulated as (FAO,1978) :

$$bnm = 0.72\ bgm / (1 + 0.25\ ct * LGP) \tag{11}$$

Where,

- bnm = maximum rate of net biomass production
- bgm = maximum rate of gross biomass production
- ct = temperature dependent proportionality constant of maintenance respiration
- LGP = length of growing period in days per year

Now bnm can be calculated, the net biomass production can be calculated by using equation (3) (FAO, 1978). The net biomass production (*Bn*) for a crop of *N* days can be derived as:

$$Bn = (0.36\ bgm \times L) / (1/N + 0.25\ ct) \tag{12}$$

where:

- *bgm* = maximum rate of gross biomass production at leaf area index (LAI) of 5
- *L* = growth ratio, equal to the ratio of *bgm* at actual LAI to *bgm* at LAI of 5
- *N* = length of growing period
- *ct* = maintenance respiration, dependent on both crop and temperature according to equation (9)

Potential yield (*Yp*) is estimated from net biomass (*Bn*) using the equation:

$$Yp = Hi \times Bn \tag{13}$$

where:

Hi = harvest index, i.e., proportion of the net biomass of a crop that is economically useful

4.2 Climate suitability

The climate suitability has been analysed based on the thermal- and LGP suitability of the SRWC. The method of the climate suitability is derived from the Agro-Ecological Zones report of the FAO, 1991. Both types of suitability's are based on expert opinions given by the FAO, 1991. The input data necessary for the analysis, however, have been updated with most recent data sets. See figure 4.3 for a schematic overview of the climate suitability analysis.

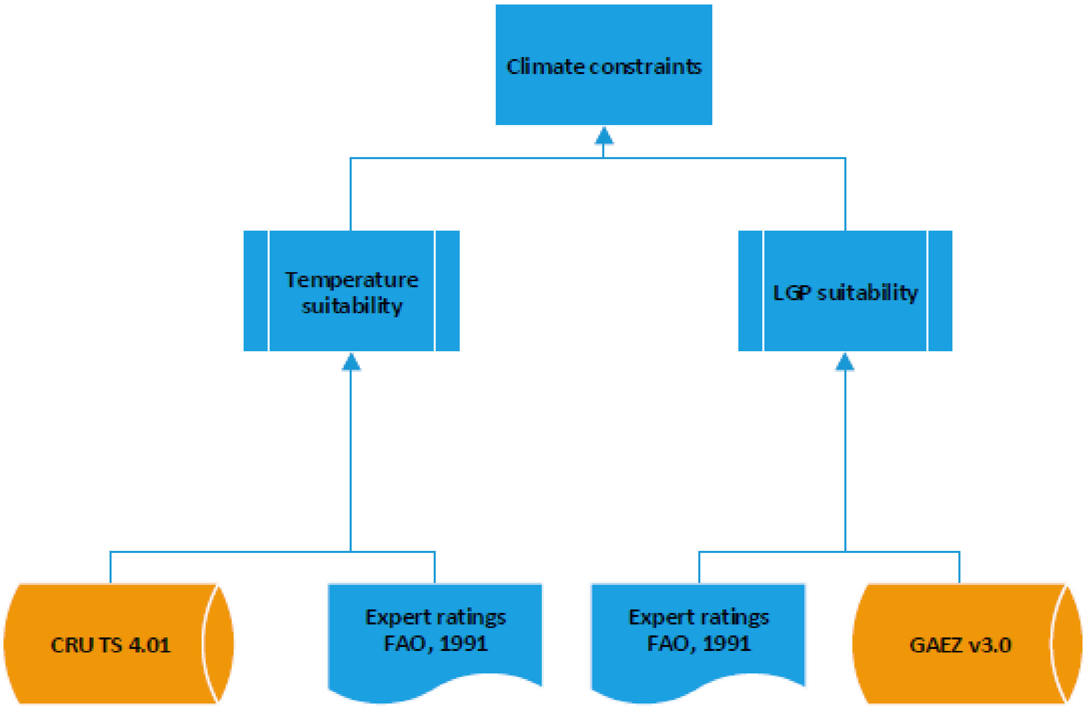


Figure 4.3 Schematic overview of the climatic suitability. Source: Own production

Thermal suitability

As explained in chapter 2.1, temperature can effect photosynthesis, respiration and transpiration and plays therefore an important role in biomass production. Based on expert knowledge, the FAO (1991) provides information on the thermal suitability of SRWCs. For all species, the suitability has been expressed in percentages for a range of temperatures. Where 100% means no limitations and 0% means no growth potential respectively.

		Thermal zones (mean daily temperatures °C)								
Species	Temperature group	< 5.0	5.0 - 10.0	10.0 - 12.5	12.5 - 15.0	15.0 - 17.5	17.5 - 20.0	20.0 - 22.5	22.5 - 25.0	>25.0
Acacia Albida	> 20°C	0%	0%	0%	0%	25%	50%	100%	100%	100%
Acacia Gerrardii	< 20 °C	0%	0%	50%	100%	100%	100%	100%	50%	25%
Acacia Nilotica	> 20°C	0%	0%	0%	0%	50%	100%	100%	100%	100%
Acacia Senegal	> 20°C	0%	0%	0%	0%	25%	50%	100%	100%	100%
Acacia Tortilis	> 20°C	0%	0%	0%	0%	25%	50%	100%	100%	100%
Calliandra Calothyrus	> 20°C	0%	0%	0%	0%	25%	50%	100%	100%	100%
Casuarina Cunninghamiana	< 20 °C	0%	0%	50%	100%	100%	100%	100%	50%	25%
Casuarina Equisetifolia	> 20°C	0%	0%	0%	0%	50%	100%	100%	100%	100%
Conocarpus Lancifolius	> 20°C	0%	0%	0%	0%	0%	0%	25%	50%	100%
Croton Megalocarpus	<20 °C	0%	0%	50%	100%	100%	100%	100%	50%	25%
Gliricidia Sepium	> 20°C	0%	0%	0%	0%	50%	100%	100%	100%	100%
Grevillea Robusta	< 20 °C	0%	0%	75%	100%	100%	100%	100%	50%	25%
Leucaena Leucocophala	> 20°C	0%	0%	0%	0%	25%	50%	100%	100%	100%
Sesbania Sesban	<20 °C AND > 20°C	0%	0%	50%	100%	100%	100%	100%	100%	100%
Tamarindus Indica	> 20°C	0%	0%	0%	0%	25%	50%	100%	100%	100%

Table 4.3, Thermal suitability per specie; Source: (FAO, 1991)

Length of growing period suitability

As explained in chapter 2.1, the availability of water plays an important role in biomass production. The availability of moisture content can be expressed as the length of growing period (LGP). This is the total amount of days per year when precipitation exceeds half the potential evapotranspiration (FAO, 1978). In other words, it is the amount of days per year where there is more water in the soil than can be evaporated during the day. The demand for water and dry periods differs per SRWC (IASSA, 1991), some plants are more drought resistant than others (Singh, 2007). The Agro-Ecological Zones rapport of the FAO and IIASA, 1991, provides information on the suitable length of growing period of the SRWCs, see table 4.5. The table shows the range of days that are suitable for the growth of a specific species. See appendix A1.5 for an example of the LGP suitability mapped for Gliricidia Sepium.

Species	Length of Growing Period (LGP) (Days/year)														
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365 +
Acacia albida			🟦	🟦	🟦	🟦	🟦	🟦	🟦						
Acacia gerradii					🟦	🟦	🟦	🟦	🟦	🟦	🟦				
Acacia nilotica			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
Acacia Senegal			🟦	🟦	🟦	🟦	🟦	🟦	🟦						
Acacia tortilis			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
Calliandra calothyrsus								🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Casuarina equisetifolia					🟦	🟦	🟦	🟦	🟦	🟦	🟦				
Casuarina cunninghamiana						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Conocarpus lancifolius			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
Croton megalocarpus						🟦	🟦	🟦	🟦	🟦	🟦				
Gliricidia sepium							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Grevillea robusta						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Leucaena leucocephala						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Sesbania sesban						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Tamarindus indica			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					

Table 4.4 LGP suitability for all species. Source: FAO, 1991

4.3 Soil suitability

The edaphic suitability analysis consists out of the soil unit-, soil texture- and soil slope suitability. , The first volume of the GAEZ report from FAO and IIASA, 1991, provides a soil unit and soil texture suitability rating for all mentioned SRWC species (IASSA, 1991). The soil slope suitability analysis is based on the ratings given by experts in the latest version of the GAEZ report (Fischer et al., 2012). See figure 4.4 for a schematic overview.

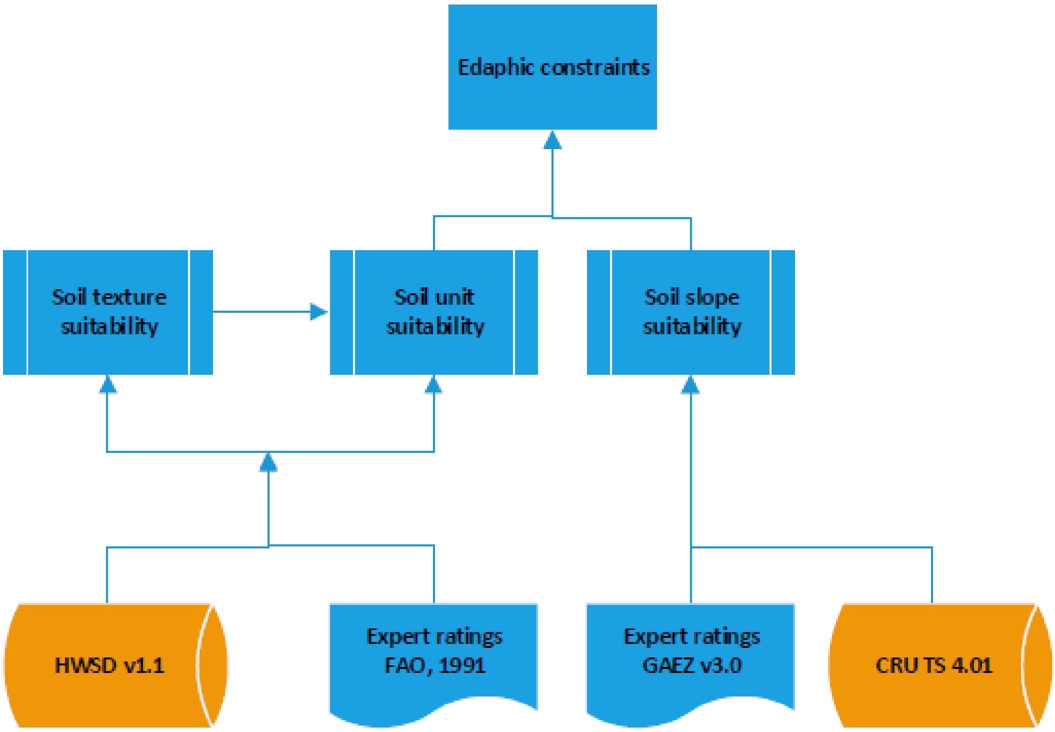


Figure 4.4: schematic overview of soil suitability

Soil unit suitability

One of the first attempts to identify soils all over the world was done by a collaboration between the FAO and UNESCO (Soil Survey Staff, 2014). In order to identify what type of soils are present in a certain region, the FAO has classified the soils based on their physical and chemical composition, this classification is called the FAO74 Classification (FAO, 1974). In the end of the ’90, FAO revised and updated the soil FAO74 classification and reclassified all soils units and that classification is called FAO90 (FAO, 1988).

Based on expert knowledge, the FAO (1991) provides information on the soil unit suitability for all earlier mentioned SRWC species. All soil units are given a rating varying from S1, S2, S3, S4 and NS and are weighted the same as the thermal suitability. However, the ratings determined by experts are based on the FAO74 Classification (IASSA, 1991). As mention in the chapter 3, the available soil unit data from the HWSD consists out data with FAO74- and FAO90 classification (FAO & IIASA, 2009). In order to use the suitability ratings given by the FAO (1991), the soil unit data with the classification of FAO90 is converted to the FAO74 classification. This is done based on the study of (Dewitte et al., 2013). See table A1.7 in the appendix for the suitability ratings derived from the FAO report (1991).

Soil texture suitability

As explained in chapter 2.3.2, the texture of the soil influences the biomass production of SRWC. In general, the fertility of a soil improves with a decreasing size of the grains of a soil. The FAO report (1991) states that all soil units that have a coarse texture, should decrease with one step in the suitability rating. For example, when a soil unit has been given a score of S1 but has a coarse texture, the new score for that same soil unit will become S2.

The Harmonized World Soil Database provides information on the texture of the soil, giving a soil a score of 3,2 or 1, where 3 means coarse, 2 means medium coarse and 1 means fine (FAO & IIASA, 2009). This is the case for all types of soil units, with an exception of Andosols (Q, Qa, Qc, Qf, Qkc, Ql)) and Vertic Arenosol (Tv) (IASSA, 1991). The in red marked area in figure 4.3 shows which soil textures are imposing a limitation on the biomass growth (FAO, 2017b).

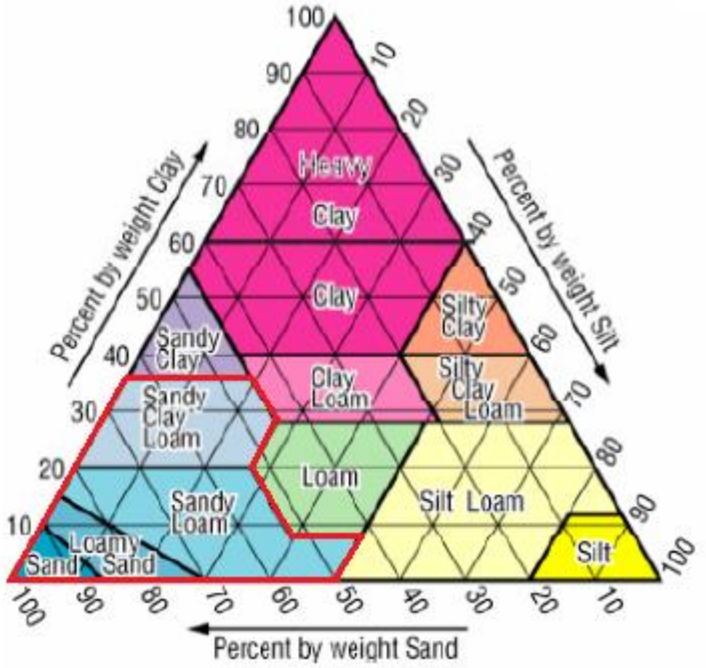


Figure 4.3, Coarse diagram, Source: (Fischer et al., 2012)

Soil Slope Limitation

As explained in chapter 2.3.1, the slope of a terrain has its effect on the growth potential of biomass, mainly in the form of a maximum angle a tree can grow and also on the losses of fertilizers and topsoil caused by runoff (Kramer and Boyer, 1995). The FAO report (1991) has set the maximum angle for a plant to grow 45%.

Rainfall is an important factor that causes runoff, in particular the intensity of rainfall (FAO, 2017b). Monthly rainfall data is available, but that rainfall does not say anything about the intensity. To account for clearly existing differences in both amount and within-year distribution of rainfall, use has been made of the modified Fournier index (FM), which reflects the combined effect of rainfall amount and distribution (FAO/UNEP, 1977) as follows:

$$F_m = \frac{12\sum_{i=1}^{12} P_i{}^2}{\sum_{i=1}^{12} P_i}$$

Where P_i = precipitation of month i

Based on the Fournier index, the FAO and IIASA (2012) have produced suitability ratings for a set of slope gradient classes. See table 4.6 for an overview of the scores given per slope gradient.

Slope gradient classes	**Suitability score**
0 - 0.5 %	100%
0.5 - 2 %	100%
2 - 5 %	100%
5 - 8 %	100%
8 - 16 %	100%
16 - 30 %	50%
30 - 45 %	25%
>45 %	0%

Table 4.6; Slope suitability per slope gradient class. Source Fisher et al, 2012

4.4 Calculation of the theoretical yield potential

As mentioned before, the theoretical yield potential is defined as the theoretical upper limit of biomass production reduced by climate and soil constraints. The findings in step 1, 2 and 3 are used to calculate the theoretical yield potential. This analysis has been done with the use of the ArcMap 10.5 software and stored in a 30 arc-seconds raster file.

For each raster, the constraint free biomass potential has been multiplied with the climate and soil suitability's.

$Y_{th} = Bcf * Ct * Clgp * Su *St *Sl$

With

- Yth = Theoretical yield potential (t/ha/yr)
- Bcf = Constraint free biomass production (t/ha/yr)
- Ct = Thermal suitability (percentage)
- Clgp = LGP suitability (percentage)
- Su = Soil unit suitability (percentage)
- St = Soil texture suitability (percentage)
- Sl = Soil slope suitability (percentage

4.5 Land use system limitations

At this point in the analysis, the theoretical yield potential shows the suitability of an area for biomass production while taking locale climate and soil conditions into account. However, not all suitable areas are currently used in a suitable manner to produce SRWC, e.g. urban areas. Therefore, a selection has been made of land uses that are suitable for the production of biomass. The land use systems data of Africa is derived from the Land Degradation Assessment in Drylands report (LADA, 2013).

The first step was the exclusion of land uses that are generally considered as unsuitable for the production of short rotation woody crops. The following land uses are considered part of this category.

- Urban land
- Open water

The second category that is excluded from the theoretical yield potential map, are land uses that are considered not suitable for sustainable bioenergy production. Based on the sustainability criteria described by Beringer et al. (2011) the following land uses were excluded.

- Protected areas
- Forests
- Wetlands

Therefore, for this thesis, the remaining land use systems that are considered suitable for biomass production are the following:

- Agricultural lands
    - Crops, large scale irrigation with moderate or higher livestock density
    - Crops and moderate intensive livestock density
    - Crops and high livestock density
    - Agriculture – large scale irrigation
    - Rainfed crops
- Grasslands
    - Grasslands – unmanaged
    - Grasslands – low livestock density
    - Grasslands – moderate livestock density
    - Grasslands – high livestock density
- Land covered with Shrubs
    - Shrubs – unmanaged
    - Shrubs – low livestock density
    - Shrubs – moderate livestock density
    - Shrubs – high livestock density
- Sparsely vegetated lands
    - Sparsely vegetated lands – unmanaged
    - Sparsely vegetated lands – With low livestock density
- Bare areas
    - Bare areas – unmanaged
    - Bare areas – with low livestock density
    - Bare areas – with moderate livestock density

In agroforestry systems, SRWCS are planted alongside food crops are therefore sharing the arable land. In this research it is assumed that 20% of the total suitable lands are used of SRWC production, meaning that the reaming 80% can be used for food production.

4.6 Technical yield potential calculation

The technical yield potential is considered as the fraction of the theoretical yield potential that is limited to the suitable land available (Smeets et al., 2007). Therefore the technical yield potential is calculated as follows:

Yte = Yth * LUS

With

- Yte = Technical yield potential (t/ha)
- Yth =Theoretical yield potential (t/ha)
- Ls = Land use systems suitability (percentage)

4.7 Selecting most useful species for production

Now the suitable and available land for SRWC production is known the last step of the analysis is the calculation of the maximum achievable technical yield potential. With the use of Arcmap 10.5 a technical potential map of all SRWC has been made. These maps are compared with each other and only the specie with the highest biomass production per hectare has been selected. However, in some areas there are multiple species are even as productive. In that case the specie that has the most utilization possibilities has been selected.

See table 4.7 for the overview and order of preference of the species.

Utilization :

- C = charcoal
- D = dye
- Fb = firebreak
- Fo = fodder
- Fr = fruit
- G = gum
- H = hedge
- Ho = honey
- M = manure
- O = Oil
- Or = ornamental
- P = pulp (wood)
- Pl = plywood, board, etc.
- S = shading
- Sb = shelterbelt
- T = timber
- Wb = windbreak

Species	Products	Rank
Gliricidia Sepium	C, Fb, Fo, Ho, M, Vr, S, T	1
Leucaena Leucocophala	C, Fb, Fo, M, Or, P, S, T	2
Casuarina Cunninghamiana	C, D, Fo, P, T, Wb	3
Acacia Nilotica	C, Fo, G, Ho, S	4
Calliandra Calothyrus	Fo, Ho, H, Or	5
Conocarpus Lancifolius	C, Fo, T	6
Grevillea Robusta	C, Ho, T	7
Acacia Senegal	C, Fo, G	8
Croton Megalocarpus	C, T	9
Tamarindus Indica	C, T	10
Casuarina Equisetifolia	C	11
Sesbania Sesban	Fo	12
Acacia Albida	Fo	13
Acacia Gerrardii	Fo	14
Acacia Tortilis	Fo	15

Table 4.7: list of most preferred species based on utilization options. Source: FAO, 1991

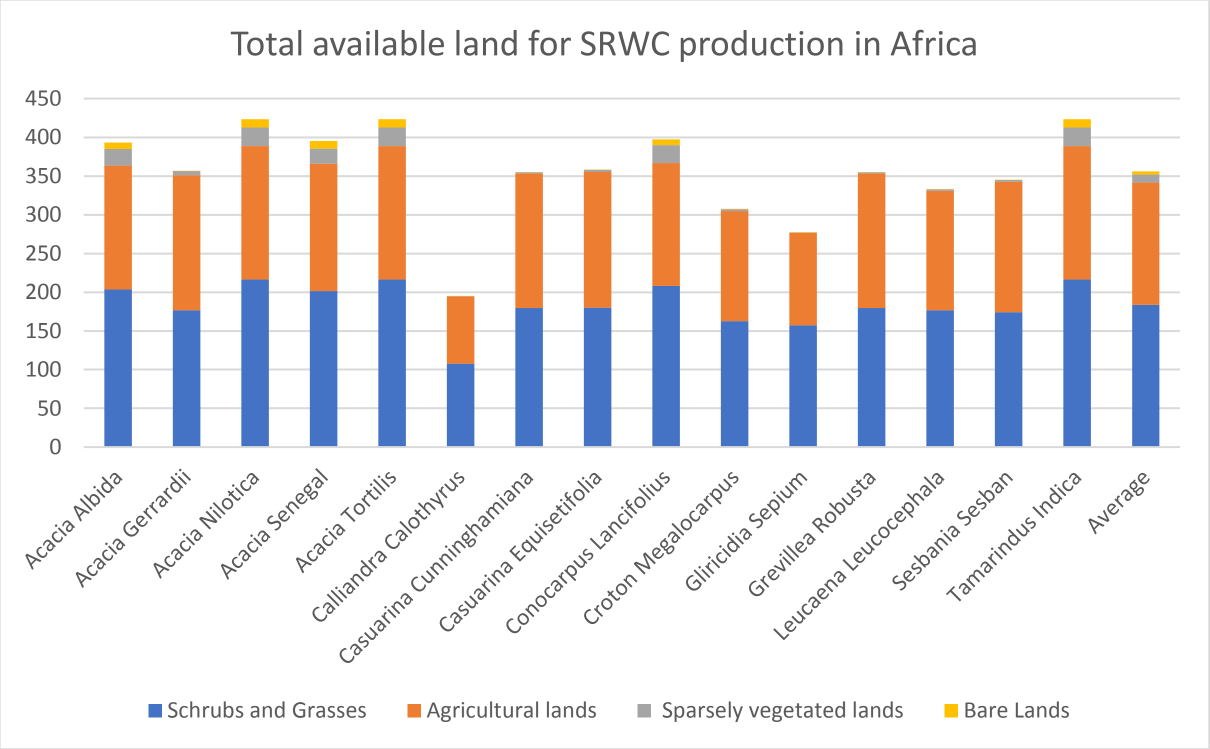
5 Results

The main goal of this thesis is to provide insight on the performance of short rotation woody crops in agroforestry systems, while taking local soil and climate conditions into account. The results are summarised below following this structure:

1. The total available land and the associated yields per hectare are analysed for each species individually.
2. The results of the maximum yield potential analysis are mapped for Africa as its whole. A more detailed analysis has been done for Agricultural lands, Grasses and Shrubs, Sparsely vegetated lands and Bare lands.
3. The potential effect of SRWCs in agroforestry systems on food production has been analysed.

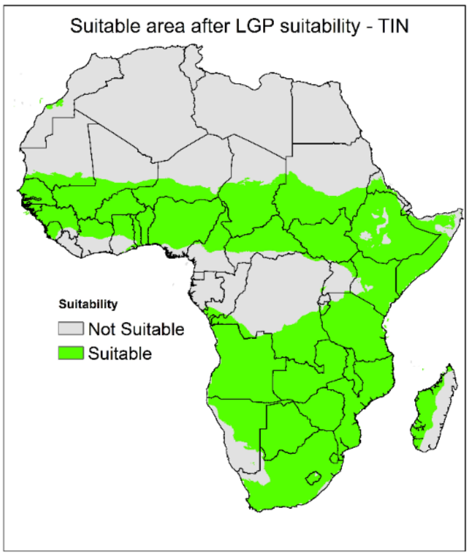
5.1 Technical yield potential for all nitrogen-fixing species

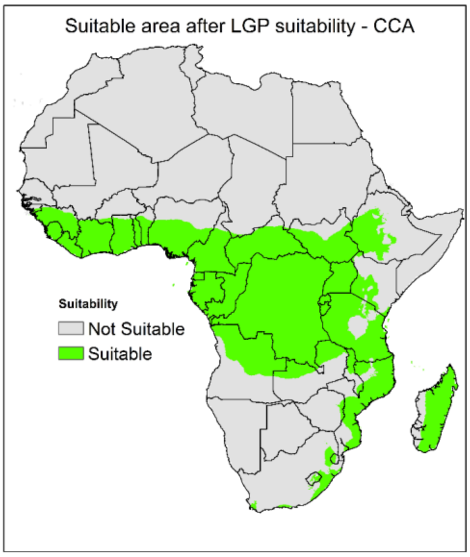
The total suitable land available for short rotation woody crops production in Africa is displayed in figure 5.1. The figure shows the total available area that is suitable for SRWC growth after the climate-, soil- and land use restrictions.



As a result of the differences of the soil and climate suitability's between the species, the total suitable area varies, ranging from 195 Mha (Calliandra Calothyrus) up to 423 Mha (Tamarindus Indica) and the average suitable area is 355 Mha. On average, the largest share of suitable land is classified as Shrubs and Grasses with a total of 184 Mha, which is 20% of the total pasture land in Africa (Slade, Saunders, Gross, & Bauen, 2011). Agricultural lands are on average the second best land use system with a total suitable area of 158 Mha, which is 62% of the total arable lands in Africa (Slade et al., 2011).

The total suitable area on sparsely vegetated lands and bare lands varies between the species. Some species are not suitable to grow on these lands, while others are able to. The main reason for these differences can be found in the length of growing period suitability of the species. Those that are suitable in these types of land use systems are able to grow with a lower minimum amount of LGP days. For example, the total suitable area for Tamarindus Indica (TIN) is larger than the total suitable area of Calliandra Calothyrus (CCA) after the LGP suitability analysis. See figure 5.2 and 5.3 for the differences between those species.





The weighted mean yield per hectare that are achieved on the suitable lands are shown in figure 5.4. The figure shows that most species have a relatively low mean biomass production per hectare, of around 2 t/ha. However, for all species the range between the minimum and maximum achieved yields is relatively large, indicating that the productivity of a species is location dependent. The maximum biomass production per hectare is for Acacia Gerrardii, Causarina Cunninghamiana, Croton Megalocarpus and Grevillea Robusta are almost four times bigger than the mean production per hectare. The productivity of these species are therefore more dependent on the location than the other species.

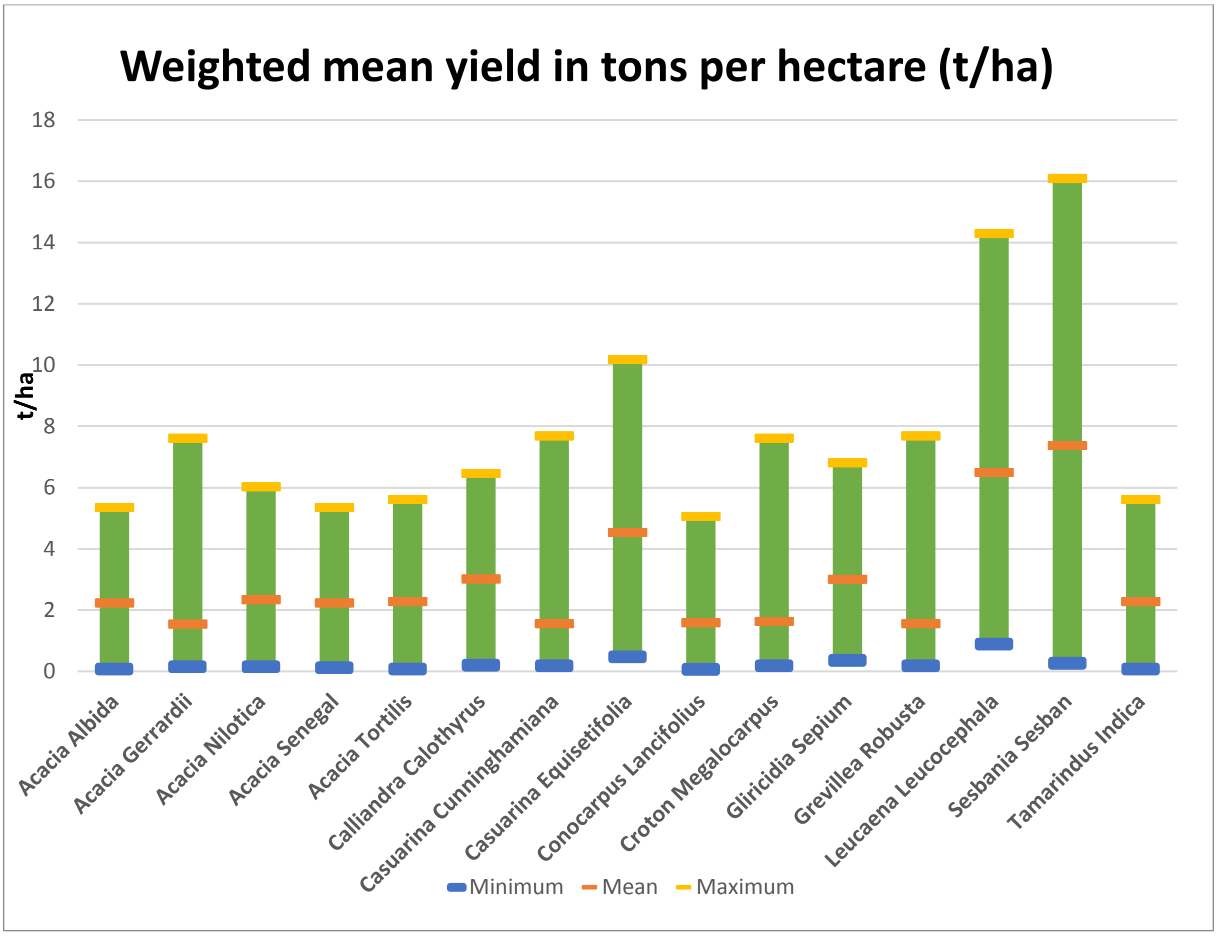


Figure 5.4: weighted mean yield per hectare in t/ha

The main reason for the differences between the species can be explained by the photosynthetic productivity. As explained in chapter 3.1.1, the species can be classified by the rate of photosynthesis. Leuceana Leucocephala (LLE) and Sesbania Sesban (SSE) are categorized in the class with the highest productivity and are therefore achieving the highest maximum- and mean yields per hectare. Casuarina Cunninghamiana (CCU) and Casuarina Equisetifolia (CEQ) are classified as medium productive and are therefore achieving the third and fourth highest maximum yields. However, the mean yield of CCU is notable low, this can be explained by the poor thermal suitability of that species.The rest of the species are grouped in the lowest productivity class and are therefore achieving the lowest mean yields.

With the use of the total suitable land, the mean yields per hectare and the land share limitation of 20%, the total SRWC production potential in agroforestry systems of all species has been calculated, see figure 5.5. Most of the production potential comes from Grasses and Shrubs and Agricultural lands. The best performing species is Leuceana Leucocephala with 410 Mt per year, because this species achieves high yields in agricultural lands. The average production potential is 171 Mt per year.

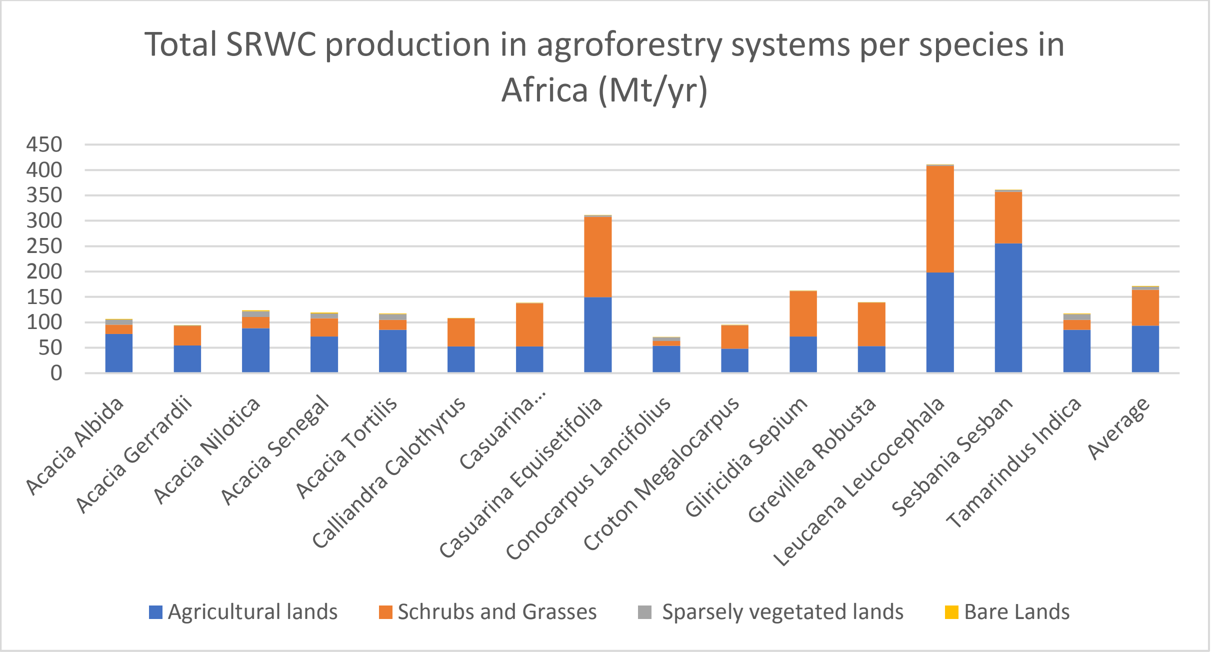


Figure 5.5; Total SRWC production in agroforestry systes in Africa per species

5.2 Selection of the most suitable species

The results of the analysis described in chapter 5.1 shows that the performance of the species depends on the location. For that reason, a location specific maximum yield potential analysis has been done. For each plot of land, the best performing species has been analysed, based on step 7 in the method. Figure 5.6 shows the maximum achievable yields per hectare, and figure 5.7 shows what species can achieve those yields.

The biomass production ranges from 0.1 to 16 t/ha. The highest yields are achieved near the equator, where the thermal-, LGP- and soil conditions for SRWC production are optimal for those species. However, large parts of that area are covered by forests land use systems and are therefore excluded from the analysis. The highest yields are achieved in Kenya, Ethiopia and Madagascar. Soudan, Mali and South Africa have large areas covered with a relatively low yield, these areas have a low amount of LGP-days and are therefore classified as sparsely vegetated- and bare lands.

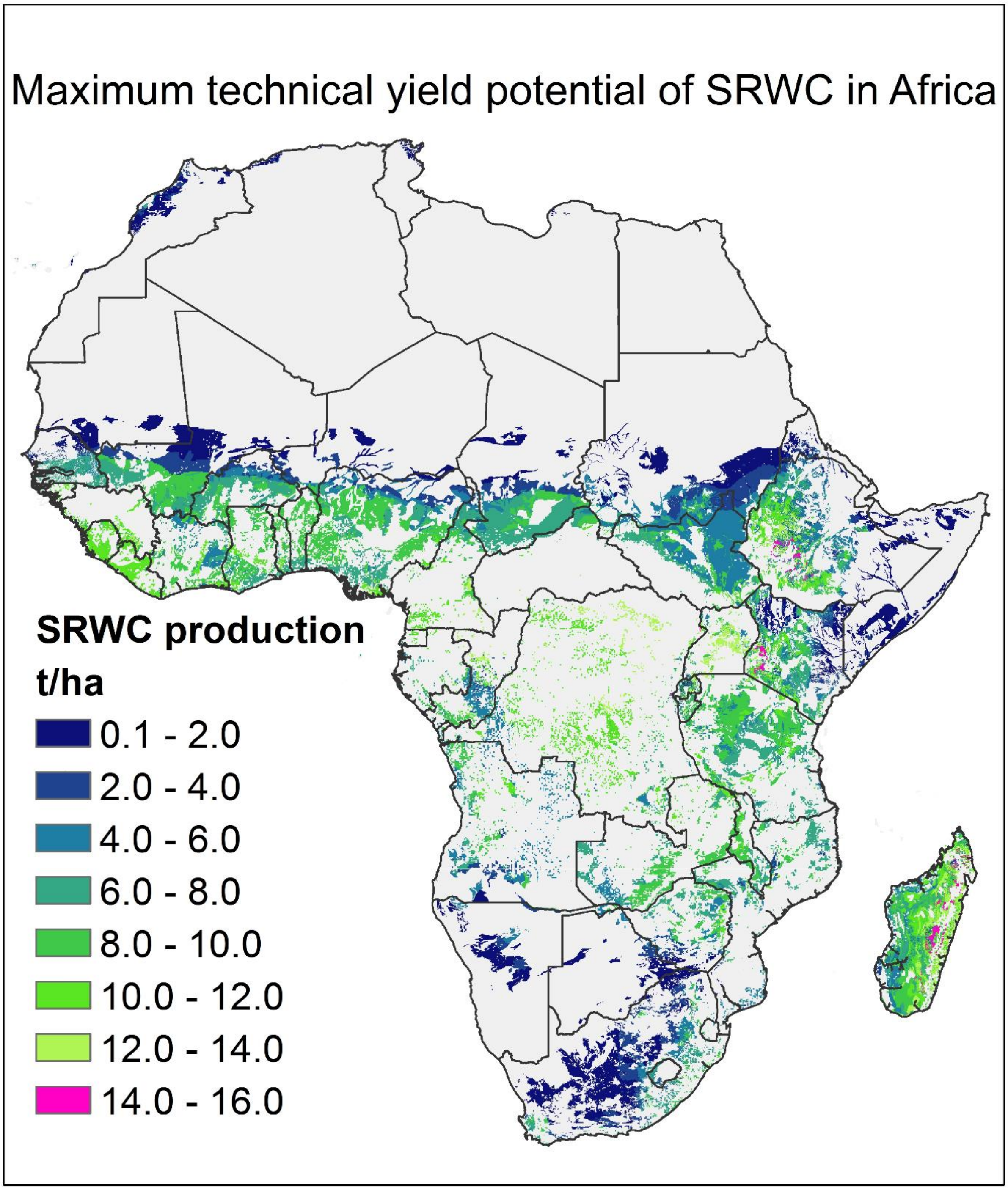


Figure 5.6: Maximum technical SRWC yield potential in Africa

The species that achieve these yields are shown in Figure 5.7. The species Acacia Albida, Acacia Tortilis, Calliandra Calothyrus, Conocarpus Lancifolious and Tamarindus Indica are not included in the analysis because other species achieve higher yields or produce more products than these species and are therefore not displayed in the figure.

Sesbania Sesban (SSE) and **Leuceana Leucocephala (LLE)** are the two most striking species on the map. As explained in 5.1, these species have the highest yield per hectare in general due to their high photosynthesis rate. The difference in soil suitability is the main reason for the distribution of those two species, better soils for LLE are more prevailing in east Africa while the soil in west Africa is more suitable for SSE.

Casuarina Equisetifolia (CEQ) belongs to the second best productivity class and is more drought resistant than SSE and LLE and achieves therefore the highest yields in the areas that do not meet the LGP-suitability of SSE and LLE.

Acacia Senegal (ASE) and **Acacia Nilotica (ANI)** belong in the lowest productivity group and are more prevailing in the areas that have a low amount of LGP days per year, note that these two species also have a relatively high preference rank compared with the other drought resistant species.

Grevillea Robusta (GRO) and **Croton Megalocarpus (CME)** are the most dominant species in North Africa, in particular Morocco, because this area is relatively cold and therefore most species are not able to produce biomass in this region.

Gliricidia Sepium (GSE) achieves the highest yield in west Congo, other species (i.e. ASE) achieve a similar yield per hectare but have less utility options than Gliricidia Sepium.

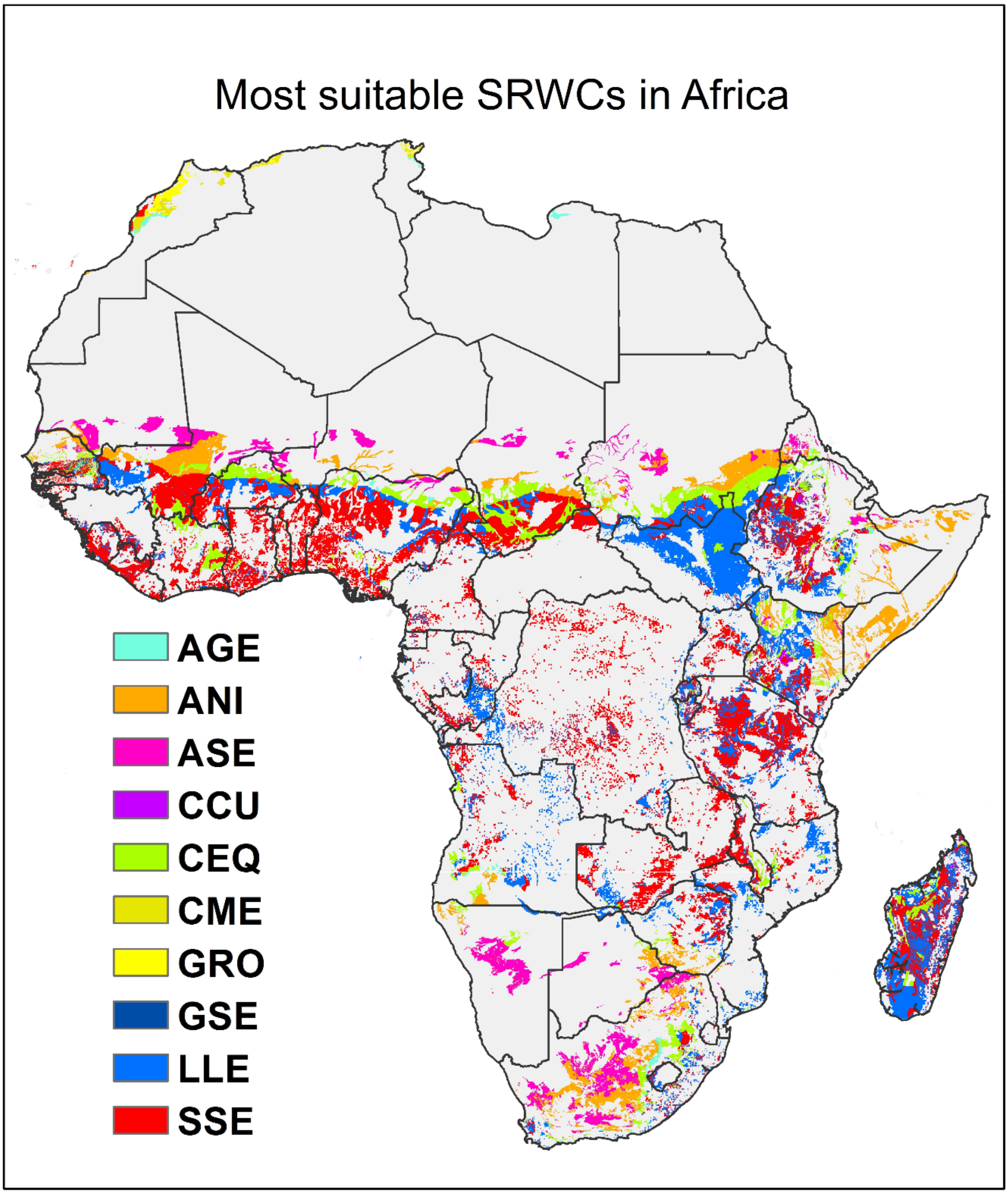


Figure 5.7: identification of best performing species. Own production

5.2.1 Land use system specific analysis

In order to provide more insight on the potential of SRWC production in agroforestry systems, the total suitable land available and the associated yields are presented in a table for all land use systems separately. The tables make a distinction of three levels of yields per hectare; yield smaller than 4 t/ha, yields between 4 and 8 t/ha and yields larger than 8 t/ha. On top of that, for each land use system is a figure has been made that shows the top 10 SRWC producing countries. Note, agroforestry land share limitation of 20% was applied for these values.

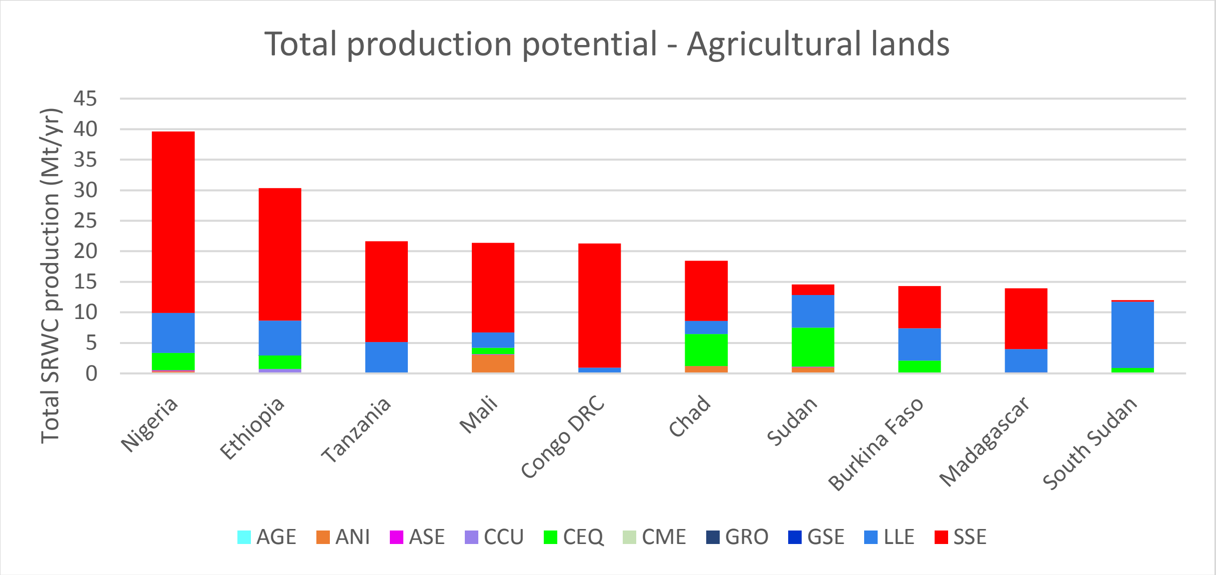
Agricultural lands

Table 5.1 shows the total amount of suitable land available for the production of SRWC on agricultural lands with agroforestry management systems. The total available land is 48 Mha and has a production potential of 325 Mt per year. The largest share of available land has a mean yield above 8 t/ha and covers 19.27 Mha. Sesbania Sesban (SSE) is with a total production potential of 219 Mt per year the best performing specie on agricultural lands. Half of the total suitable land is occupied with Sesbania Sesban, in particular the area with the highest mean yield per hectare. Leuceana Leucocephala is the second best performing specie with 65 Mt per year. Together they are responsible for 88% of the total production potential. Acacia Nilotica and Casuarina Equisetifolia have the most potential in areas where low yields are achieved (<4 t/ha), this is because these species are more draught resistant.

	Agricultural lands							
	Total suitable land available (Mha)				**Total SRWC production (Mt/yr)**			
	< 4 t/ha	**4 - 8 t/h**	**> 8 t/ha**	**Total**	**< 4 t/ha**	**4 - 8 t/h**	**> 8 t/ha**	**Total**
AGE	0,30	-	-	0,30	0,41	-	-	0,41
ANI	4,02	-	-	4,02	8,12	-	-	8,12
ASE	1,25	-	-	1,25	2,42	-	-	2,42
CCU	0,01	0,12	-	0,13	0,04	0,63	-	0,67
CEQ	3,41	3,37	0,16	6,94	9,36	18,24	1,38	28,98
CME	0,30	-	-	0,30	0,15	-	-	0,15
GRO	0,48	0,00	-	0,48	0,85	0,00	-	0,86
GSE	0,04	-	-	0,04	0,11	-	-	0,11
LLE	0,79	7,39	2,29	10,47	2,75	39,92	21,83	64,49
SSE	0,19	7,07	16,82	24,08	0,48	47,86	170,45	218,80
Total	10,79	17,95	19,27	48,00	24,70	106,65	193,66	325,01

Table 5.1: Overview of the performance of the species on agricultural lands. Source: own production

Figure 5.8 shows top ten countries with the highest production potential on agricultural lands. Nigeria has the largest production potential with almost 40 Mt/yr. Half of the total production potential of Casuarina Equisetifolia (CEQ) is produced in Chad and Sudan.



Figuur 5.8: production potential on agricultural lands, top 10 producing countries.

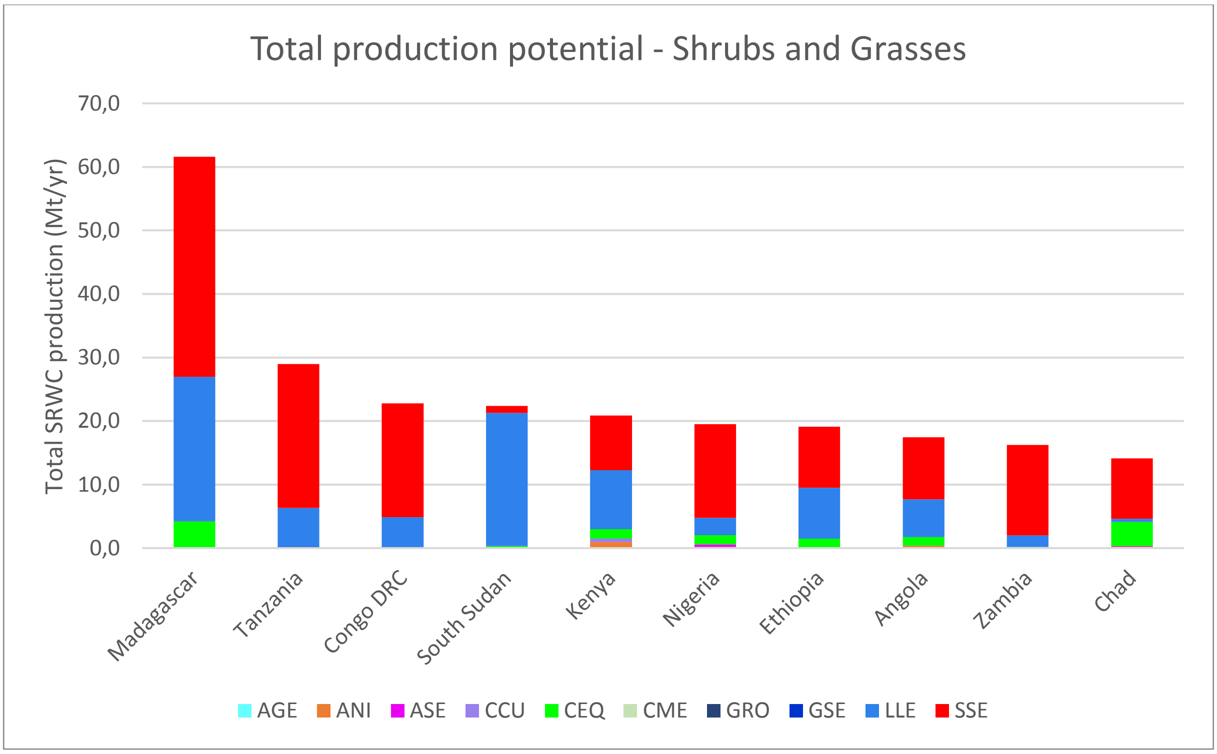
Shrubs and grasses

Table 5.2 shows the total amount of suitable land available of the production of SRWC on Shrubs and grasses with agroforestry management systems. The total available land is 55 Mha and has a production potential of 349 Mt per year. Again, Sesbania Sesban is the best perform specie, followed by Leuceana Leucocephala. However, compared with the agricultural lands, the difference between the total production potential of those two species is less due to the better performance of LLE on lands with a mean yield of 4 – 8 t/ha. The largest share of suitable land has a mean yield between 4 – 8 t/ha. In the areas with a mean yield of less than 4 t/ha, Acacia Senegal is the best performing specie.

	Shrubs and grasses							
	Total suitable land available (Mha)				**Total SRWC production (Mt)**			
	< 4 t/ha	**4 - 8 t/h**	**> 8 t/ha**	**Total**	**< 4 t/ha**	**4 - 8 t/h**	**> 8 t/ha**	**Total**
AGE	0,18	-	-	0,18	0,36	-	-	0,36
ANI	5,82	-	-	5,82	7,74	-	-	7,74
ASE	5,38	-	-	5,38	8,94	-	-	8,94
CCU	0,01	0,09	-	0,10	0,04	0,53	-	0,58
CEQ	1,03	3,17	0,28	4,48	3,30	18,53	2,44	24,27
CME	0,09	-	-	0,09	0,04	-	-	0,04
GRO	0,06	-	-	0,06	0,11	-	-	0,11
GSE	0,08	0,00	-	0,08	0,23	0,00	-	0,23
LLE	0,59	12,00	4,41	17,00	2,12	66,30	41,62	110,05
SSE	0,06	7,24	14,43	21,72	0,15	50,99	145,52	196,66
Total	13,31	22,49	19,11	54,91	23,04	136,36	189,59	348,98

Table 5.2: Overview of the performance of the species on Schrubs and Grasses. Source: own production

Figure 5.9 shows the total top 10 producing countries with the highest production potential on Shrubs and Grasses lands. Madagascar is by far the best performing country with a potential of more than 60 Mt per year, the climate and soil conditions are relatively good for the production of the LLE and SSE. As figure 5.6 shows, the minimal achieved mean yield per hectare is 8 t/ha or higher in Madagascar.



Figuur 5.9: production potential on Schrubs and Grasses, top 10 producing countries. Source: Own production

Sparsely vegetated lands

Table 5.3 shows the total production potential of SRWC on sparsely vegetated lands in agroforestry management systems. The total potential biomass production is 8.03 Mt per year. Acaica Nilotica is with 2.21 Mha the specie that has the largest amount of suitable land available and has a production potential of 1.60 Mt dry matter per year. Leucaena Leucocephala (LLE) has the largest production potential on sparsely vegetated lands with a total of 2.47 Mt dry matter per year. However LLE achieves this potential with only half of the total land available compared with ANI, indicating that the mean yield of LLE is higher than that of ANI. Gliricidia Sepium is the only specie that has no potential at all on sparsely vegetated lands.

	Sparsely vegetated lands							
	Total suitable land available (Mha)				Total SRWC production (Mt)			
	< 4 t/ha	4 - 8 t/h	> 8 t/ha	Total	< 4 t/ha	4 - 8 t/h	> 8 t/ha	Total
AGE	0,13	-	-	0,13	0,06	-	-	0,06
ANI	2,21	-	-	2,21	1,60	-	-	1,60
ASE	1,97	-	-	1,97	2,42	-	-	2,42
CCU	0,00	0,01	-	0,01	0,01	0,01	-	0,02
CEQ	0,29	0,07	-	0,62	0,56	0,35	-	0,92
CME	0,12	-	-	0,12	0,08	-	-	0,08
GRO	0,05	-	-	0,05	0,08	-	-	0,08
GSE	-	-	-	-	-	-	-	-
LLE	0,02	0,17	0,14	1,03	0,08	1,15	1,24	2,47
SSE	0,01	0,05	0,01	0,27	0,02	0,30	0,07	0,38
Total	4,79	0,29	0,15	5,24	4,91	1,81	1,31	8,03

Table 5.3: Overview of the performance of the species on Sparsely vegetated lands. Source: own production

Figure 5.10 shows that Kenya has the largest total SRWC production potential, mainly due to LLE and CEQ. The figure shows that more than 90% of the total production potentials of LLE and CEQ are achieved in Kenya. Both species can reach mean yields of above 4 t/ha, indicating that the climate and soil conditions are reasonably well in these areas, but still have a sparsely vegetated area classification. Acacia Senegal is for the other countries the best performing species.

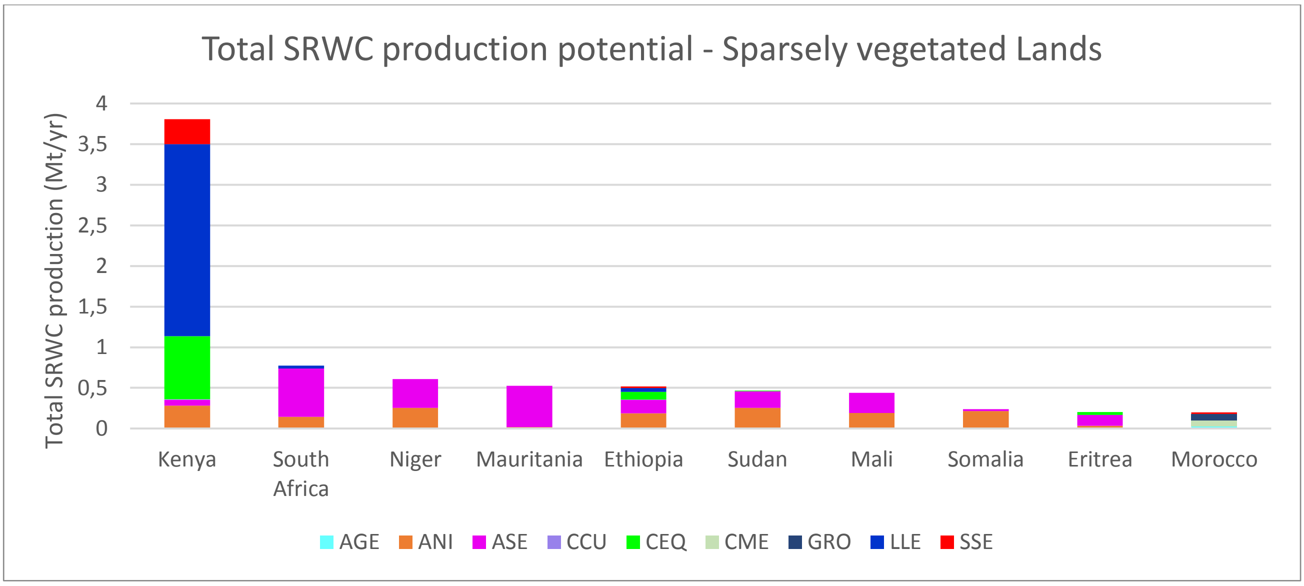


Figure 5.10: production potential on Sparsely vegetated lands, top 10 producing countries. Source: Own production

Bare lands

Table 5.4 shows the total suitable land available and its associated total dry matter production per specie. The total available land for the production SRWC on bare lands in Africa is 2.80Mha and has a production potential of 2.29 Mt dry matter per year. Two third of this production potential is produced by Acacia Senegal but has a yield of less than 1 t/ha.

	Bare lands							
	Total suitable land available (Mha)				**Total SRWC production (Mt)**			
	< 4 t/ha	**4 - 8 t/h**	**> 8 t/ha**	**Total**	**< 4 t/ha**	**4 - 8 t/h**	**> 8 t/ha**	**Total**
AGE	-	-	-	-	-	-	-	-
ANI	0,60	-	-	0,60	0,34	-	-	0,34
ASE	1,57	-	-	1,57	1,53	-	-	1,53
CCU	-	-	-	-	-	-	-	-
CEQ	0,00	0,01	-	0,01	0,01	0,05	-	0,06
CME	0,01	-	-	0,01	0,01	-	-	0,01
GRO	-	-	-	-	-	-	-	-
GSE	-	-	-	-	-	-	-	-
LLE	0,60	-	-	0,60	0,34	-	-	0,34
SSE	-	-	-	-	-	0,02	-	0,02
Total	2,80	0,01	-	2,81	2,22	0,07	-	2,29

Table 5.4: Overview of the performance of the species on Bare lands. Source: own production

Figure 5.11 shows the top ten performing countries of SRWC production on bare lands. The figure shows that the top 9 producing countries are responsible for 95% of the total potential of SRWC production on Bare lands. Sudan has the most potential with just over 0.5 Mt per year.

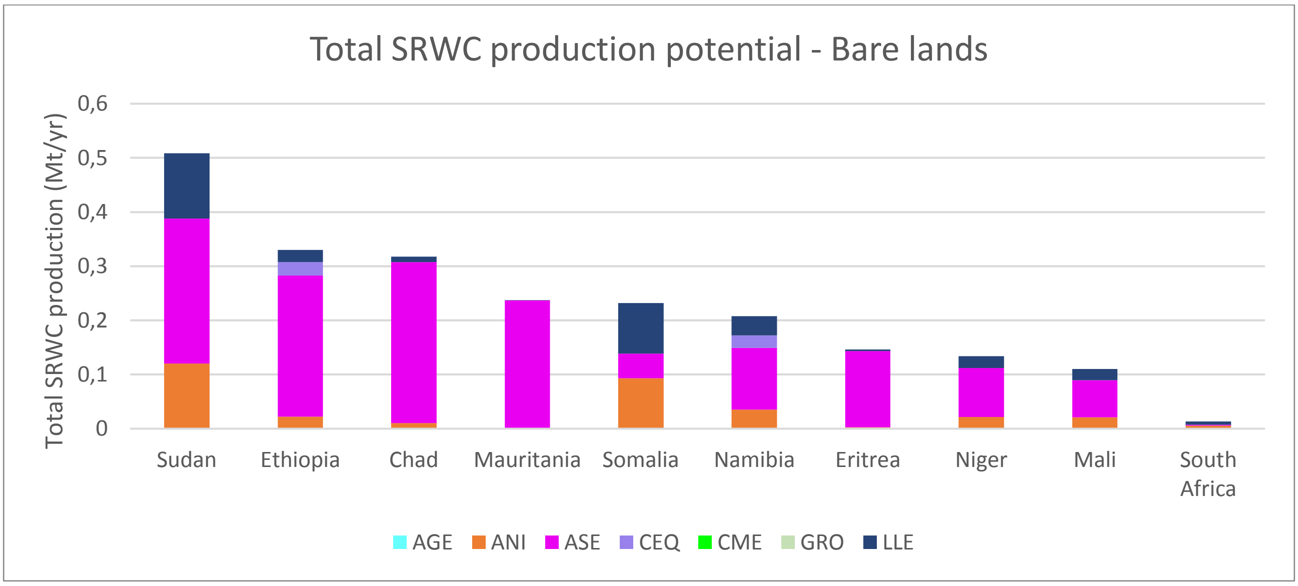


Figure 5.11: production potential on Bare lands, top 10 producing countries. Source: Own production

5.3 Potential effect of SRWC production in agroforestry systems on the food production in Africa

As explained in chapter 2, agroforestry systems can have several benefits for the local environment. Agroforestry can improve the soil quality, reduce the soil erosion and increase the total amount of available water in the soil (Young, 1990). Research shows that because of these benefits, food production in agroforestry systems can compete or even achieve higher yields than fertilized crops (Sarvade, Singh, Vikas, Kachawaya, & Khachi, 2014). The benefits of agroforestry systems are also used to convert degraded lands into arable lands (Hillbrand, 2017).

This research has focused on analysing the suitability of short rotation woody crop growth in Africa. Since these trees can be used in agroforestry systems, an analysis has been made on the potential impact of those trees on the food production in Africa. The potential benefits that can be induced by agroforestry will be explained per land use system.

5.3.1 Benefits of agroforestry systems on more efficient land use

In agroforestry systems, food crops and woody crops share land to produce biomass in an harmonious manner and achieve therefore a more efficient land use (source). However, implementing SRWC on agricultural lands, means that there is less lands can be used for the production of food. In this thesis, it is assumed that the land share of SRWC and food crops is 20% and 80%, respectively. In order to maintain the same volume of food production, the loss of land needs to be compensated by a more efficient growth of the food crop.

Research shows that food crops grown in agroforestry systems achieve similar of better yields per hectare compared with a synthetically fertilized food crop plantation (ICRAF, 1998). Compared with unfertilized maize, the yields of maize in agroforestry systems can even double or triple, depending on the local climate and soil conditions and woody crop species (Sileshi et al., 2008). The yields of corn when combined with Leucaena Leucocephala could boost grain production significantly (Côté, 1977). Another research shows that interplanting Acacia Albida with millet, yields can improve up to 600% (charreau, poulaine, 1963). In other words, there are many examples given where food crop yields improved significantly in agroforestry systems to compensate the land loss for SRWC production, depending on the species used and local climate and soil conditions.

This research shows that the total suitable land for SRWC production on agricultural lands is approximately 240 Mha. The total arable land in Africa is estimated at 253 Mha (Slade et al., 2011), indicating that almost 95% of the arable land is suitable for SRWC production in agroforestry systems. As mentioned before, improving the water availability in the soil is one of the benefits of using agroforestry systems. With an increase of the soil moisture, the length of growing period of an area can improve. Therefore agroforestry systems can have a big impact on food production in arid areas (Ministry of Environment and Natural Resources, 2016). The FAO and IIASA (2012) defined arid areas as regions with less than 60 LGP-days per year.

This research shows that the total amount of arid land which is suitable for the production of SRWC and is currently used for agriculture purposes is 4.93 Mha in Africa. In particular South Africa has a large potential, with 1.79 Mha. The top five countries with the most suitable lands available for agroforestry systems under arid conditions are shown in figure 5.12.

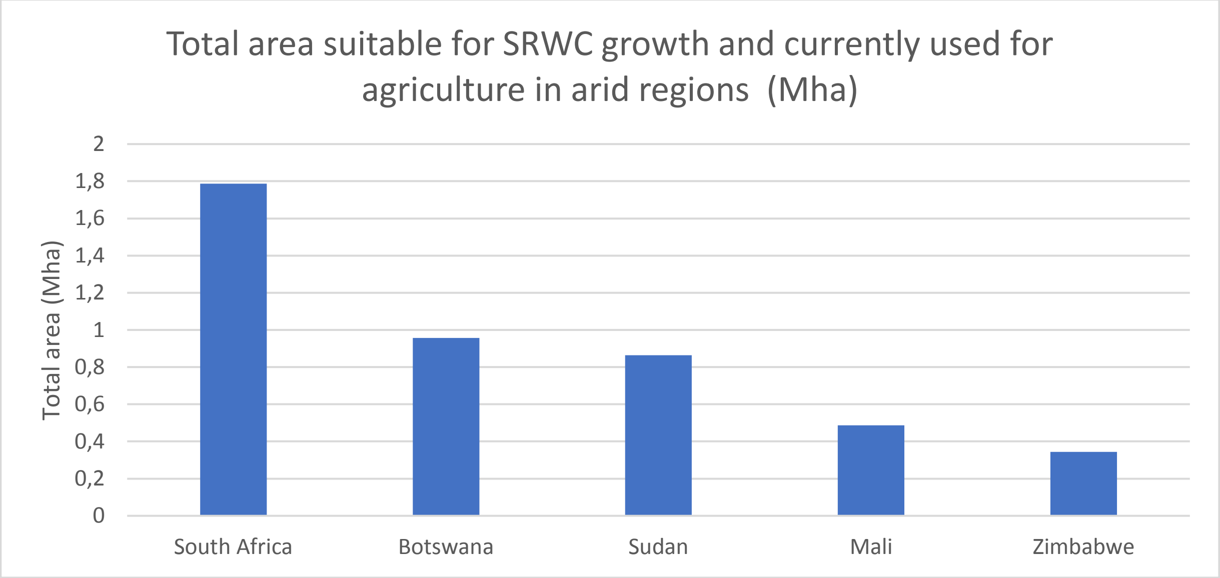


Figure 5.12; Total area suitable for SRWC growth and currently used for agriculture in arid regions. Own production

5.3.2 Benefits of agroforestry systems for food production on degraded lands

As stated before, the implementation of agroforestry systems has many positive effects on its environment. The improvement of the quality of the soil, reduction of the erosion and increased water availability are tree benefits of agroforestry systems that are essential in order to restore degraded lands (Hillbrand, 2017).

This research shows that 26,2 Mha of sparsely vegetated- and 14,05 Mha of bare lands are suitable for the production of nitrogen-fixing short rotation woody crops. Meaning that these regions have the potential to be restored by the implementation of agroforestry systems. As mentioned before, for this research it is assumed that 20% of the available land is used by SRWC production in agroforestry systems and 80% for food crops. Meaning that the implementation of agroforestry systems in these areas can potentially cause an increase of 21 Mha and 11.2 Mha available land for food production on sparsely vegetated and bare lands respectively.

Figure 5.13 shows the top 10 countries that have the largest potentially available land for food crop production after restoration by agroforestry systems.

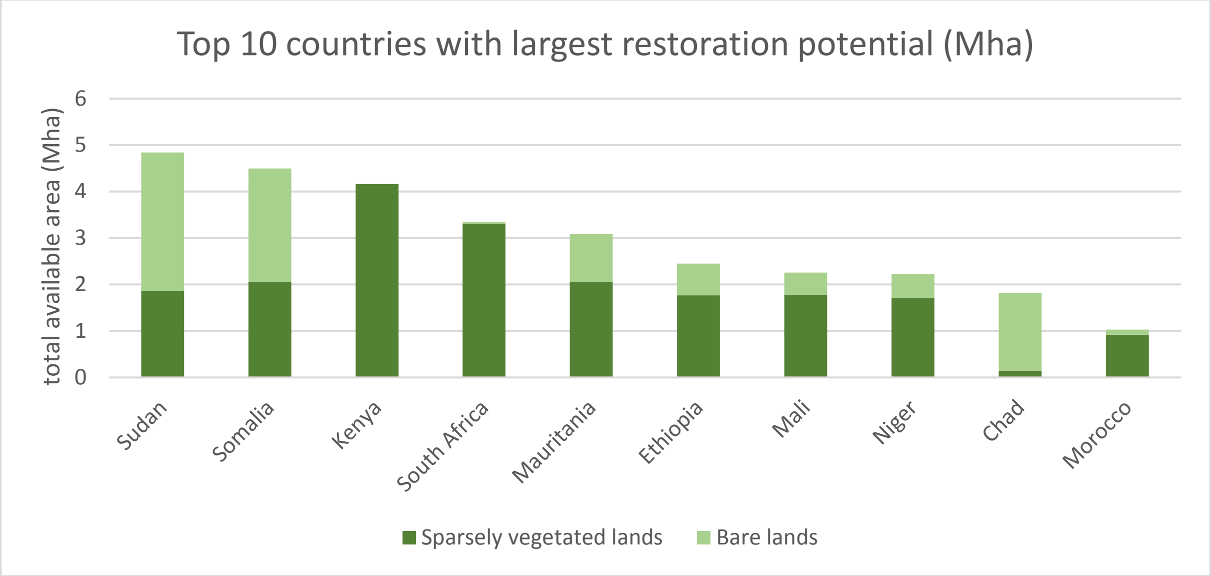


Figure 5.13; Top 10 countries with largest restoration potential. own production

6 Conclusion

The demand for food, feed, fibre and fuel has increased of the last few decades and it is expected that because of that, there will be an increase of land scarcity in the future for Africa. Agroforestry is a system were woody perennial crops share land with food crops and by doing so, multiple benefits can occur. Agroforestry improves among other things the soil quality, in particular when nitrogen-fixing trees are used. The root systems of the three cause an increase of water availability in the soil and a reduction of the topsoil erosion. As a result of these benefits, the efficiency of food crop production increases sustainably and thereby compensates the yield losses that are caused by land sharing. The total biomass production per hectare increases and lands are therefore used more efficiently. Another effect of those benefits is that agroforestry systems are also used for the restoration of degraded lands.
In other words, agroforestry systems, can play a role in reducing the expected increase of land scarcity by improving land use efficiency and increasing the total arable land. Therefore, the aim of this research is to provide insight on the yield potential of short rotation woody crops for bioenergy production in Africa, while taking local soil and climate conditions and agroforestry practices into account.

The technical yield potential is calculated for 15 nitrogen – fixing SRWCs separately. This analysis shows that all 15 species are suitable to grow in Africa, but there are differences in production potential between those species, due to the differences of climate and soil suitability. The total suitable land for the production of SRWC ranges between 195 Mha (Calliandra Callothyrus) and 423 Mha (Tamarindus Indica). On average the total available land is 355 Mha consisting out of 158 Mha agricultural lands, 184 Mha Grasses and Shrubs, 10 Mha Sparsely Vegetated lands and 4 Mha Bare Lands. Meaning that on average 62% of the total arable lands and 20% of the total pasture lands in Africa are suitable for SRWC production. The constraint of length of growing period has the most impact on the total available suitable land for a species.
The mean yield per hectare ranges from 1.8 and 7.8 t/ha. However the maximum achievable yield is 16.1 t/ha and for some species the maximum achievable yield is 4 times larger than the mean yield, indicating that the achievable yields are dependent of the location. Sesbania Sesban and Leuceana Leucocephala are the two species that achieve the highest maximum and mean yields, which can be explained by the fact that they have the highest photosynthetic production rate.
The highest total biomass production potential is achieved by Leuceana Leucocephala with a total of 411 Mt per year in Africa.

The maximum yield potential analysis shows that selecting the right species in an area is of importance for the total production of SRWCs in agroforestry systems in Africa. First of all, the analysis shows that only 10 of the 15 species preferred to use, because they achieve higher yields or produce more products than the other species. Secondly, some species can grow in areas, where other species are not able to grow. Therefore, selecting the right species results in a larger area that is suitable to grow SRWCs on compared with choosing only one species. After the maximalisation analysis, the total suitable area is 555 Mha, which means an increase of 56% compared with the 355 Mha of the average suitable land. In particular, the agricultural lands are better used by picking the right species. The analysis shows that 240 Mha of agricultural lands becomes suitable for SRWC production, meaning that 95% of the total arable land is suitable for SRWC production in agroforestry systems in Africa. As a result of an increase of the total suitable land and by selecting only the species with the highest yields, the total production potential of SRWCs is 684 Mt per year in Africa.

The food production in Africa can increase due to SRWCs in agroforestry system by land use intensification and the restoration of marginal lands. Since 95% of total arable land in Africa is suitable for SRWC production, land use intensification has the largest potential for improved food production. There is an area of 5 Mha of agricultural lands that have less than 60 growing days per year and since agroforestry can improve the water availability, these regions are in particular extra interesting to implement these systems.

A total of little more than 40 Mha of sparsely vegetated- and bare lands are suitable to implement agroforestry systems. Meaning that by restoring these degraded lands, potentially an area of 32 Mha can become available for food production.

To conclude, this research has developed a method that is able to calculate the technical yield potential of short rotation woody crops in agroforestry systems, while taking local soil and climate conditions into account. The results show that choosing the right species is of importance since the species differ from climate and soil suitability. Some species have a higher yield potential in wet and warm regions, while other species are performing better in dry areas. There is a large technical potential for SRWC production, which can also help improve the food production in Africa.

7 Discussion

The aim of this research is to calculate the yield potential of SRWCs in agroforestry systems while taking local soil and climate conditions into account. The results are supposed to help local farmers and decisionmakers to choose the best performing species that can grow on their lands. In order to make this calculation, a seven step method has been developed. First the theoretical upper limit of biomass production has been calculated, based on a method described in the Agro-Ecological Zones project of the FAO (1978). The theoretical upper limit is then reduced by limitations imposed by the local climate and soil conditions. These limitations are based on expert opinions, which are derived from the a report of the FAO and IIASA (1991). At last limitations due to land use systems have been applied, resulting in the technical yield potential.

In order to give a good advice to farmers and decisionmakers on which species to choose, the results should be reliable. In order to improve the reliability and validity a few aspects in the method should be further analysed in further research.

First of all, the constraint free biomass production is based up on main principles of plant growth; photosynthesis and respiration. The model uses temperature, water availability and solar irradiation as the three main input variables to calculate the constraint free biomass production. However, carbon dioxide is another essential element in plant growth (Bruhn, 2002), but is almost completely neglected in this research. The values of gross biomass production on overcast days (BO) and on clear days (BC) given by de Wit (1965) are taking carbon dioxide into account, but it is not a variable on itself. Since carbon dioxide is only a little present in the atmosphere, a small change in concentration has a large effect on plant growth (Backlund, Janetos, & Schimel, 2008). It could also give more insight on the carbon sequestration, which is one of the main benefits of SRWCs in agroforestry systems (Amedie, 2013).

Secondly, the climate and soil suitability has been based on ratings given by the experts of the FAO (1991). This research shows that the climate and soil suitability have a substantial limiting effect on the theoretical yield potential. However, it is not clear which experts gave these ratings and on what base these rating were given. Also the ratings itself is something that could be discussed. The possible scores ranged between 0%, 25%, 50%, 75% and 100% and is relatively rough compared with other research. The Global Agro-Ecological Zones report, which is based on the same methodology from 1978, presents more subtle ratings on similar topics, ranging between 10%, 30%, 50%, 70%, 90% and 100% (FAO, 2017b). So in other words, the suitability scores used in this research should be re-evaluated in the future, to validate the results.

Thirdly, in the sixth step of the method, it is assumed that in agroforestry systems only 20% of the total suitable land is used for SRWC production and 80% for food crop production. However it is not realistic to assume that for each location the same land share ratio is valid. The share of trees depends on the function and design of the system. For example, agroforestry systems with the function to produce timber woods have a relatively larger share of SRWCs than agroforestry systems with the function of food production (Unruh, Houghton, & Lefebvre, 1990).

The input data is another important factor in the quality of the calculated yield potentials. Since the aim of this research was to provide insight on the local effects of climate and soil conditions, it is therefore of importance to use data with the highest resolution as possible. In this research the technical yield potential is calculated based on a resolution of 30 arc-seconds, however the temperature-, precipitation- and LGP data have a coarser resolution and are for that reason resampled into a 30- arc seconds resolution. Also the data of the gross biomass production of a given crop on a clear day (BC) and overcast day (BO) given by De Wit (1965) have a course resolution since this data is given per 10 degrees latitude. The values of BC and BO are essential in the calculation of the constraint free biomass potential and the climate and soil data are necessary for the suitability analyses, therefore the quality of the results can be greatly improved by using data with a higher resolution.

Another point of discussion is that the technical yield potential should not be mistaken for the actual yield potential. In order to calculate the actual yield potential, the economic- and implementation potential should be analysed as well (Smeets et al., 2007).
The economic potential is the fraction of the technical potential that is considered as economically viable (Smeets et al., 2007). In order to calculate the economic potential of an area, the costs and benefits should be known. There are many different factors that influence the costs of SRWC production that differ per location. For example the costs for labour and machinery varies per region (Eppler, 2007). Also the terrain itself influences the economic viability, for example, hard and rocky soils are more difficult to work on than softer soils (Fischer et al., 2012). This research shows that the yield potential of SRWCs differs per species and location, the benefits are therefore also region dependent.
The implementation potential is the fraction of the economic potential that can be implemented while taking institutional and social constraints into account (Smeets et al., 2007). The local support of the government and community is vital for the success of the implementation of agroforestry systems (Hillbrand, 2017). Literature shows that the public acceptance of changing the traditional agricultural systems can be a bottleneck in some areas (Ordonez et al., 2014).

This research provides insight on the potential effects of SRWCs in agroforestry systems on the food production in Africa. A major benefit of agroforestry systems is an increase of food production due to more efficient growth of the food crops. Literature shows that food crop production can double or even triple in agroforestry systems (Sarvade et al., 2014). This research shows that 95% of the total arable lands and 30% of the pasture lands are suitable for the implementation of agroforestry systems. Therefore the potential increase of food production due to land use intensification is enormous for Africa. However, it is not realistic to expect that these potentials are fully used in the future, since only the technical yield potential has been calculated.
There is also an indirect benefit from more efficient land use, which is not included in this research. Since more food is produced by the same land, less lands might be necessary to meet the demands for food, therefore land can become available for the production of other crops such as energy crops.

The second major benefit of agroforestry systems is the ability of the restoration of degraded lands. This research shows that more than a total of 40 Mha of Sparsely Vegetated lands and Bare lands are suitable for SRWCs production. In most areas the yield per hectare is relatively low, which is expected with these type of land use system classification. However, in some areas of these marginal lands, the yield potential of SRWCs is relatively high. In particular, Kenya has a relatively large area of Sparsely Vegetated lands where yields of 4 tons per hectare per year or higher can be achieved. These contradictions can be explained when looked into the causes of land degradation.

Land degradation can be divided into biophysical factors and unsustainable land use and management practices (Ministry of Environment and Natural Resources, 2016). The biophysical factors that influence the land degradation are described as the water availability in the soil, the topographic features of the terrain and soil chemical composition (Ministry of Environment and Natural Resources, 2016). All of these factors are included in the methodology of this research. So therefore it is likely that the regions are degraded by unsustainable land use management. For that reason, it is of extra importance that a implementation potential analysis is done before implementing agroforestry in these regions.

So in other words, this research shows that there is a large potential of food and wood production in agroforestry systems in Africa. However, there are still some improvements to make on the method of this research. It is therefore advised to do a validation study with local sample plots in different regions in Africa.

8 Appendix

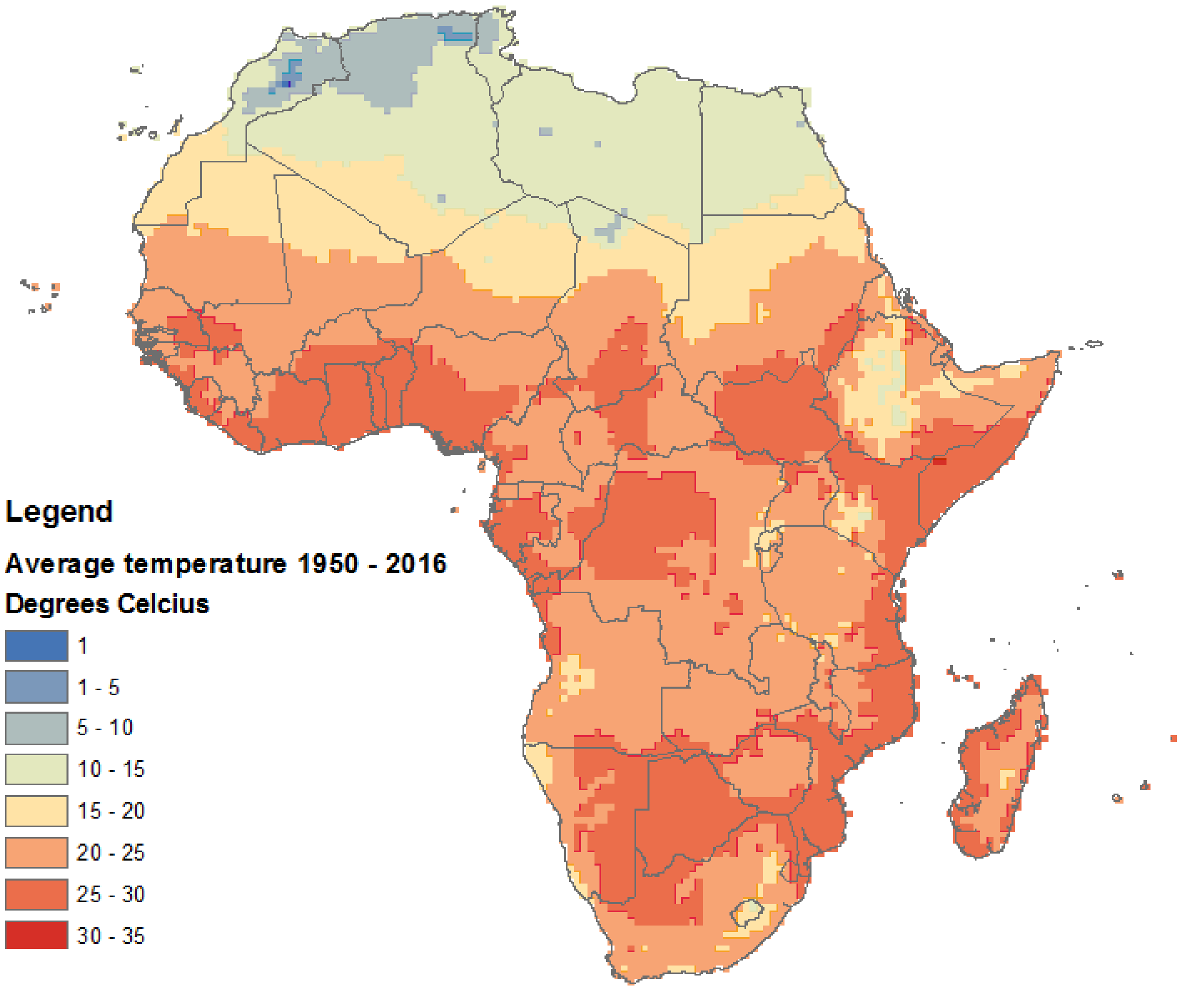


Figure A1.1. Average Temperature in Africa, 1950-2016 (Degrees Celsius)

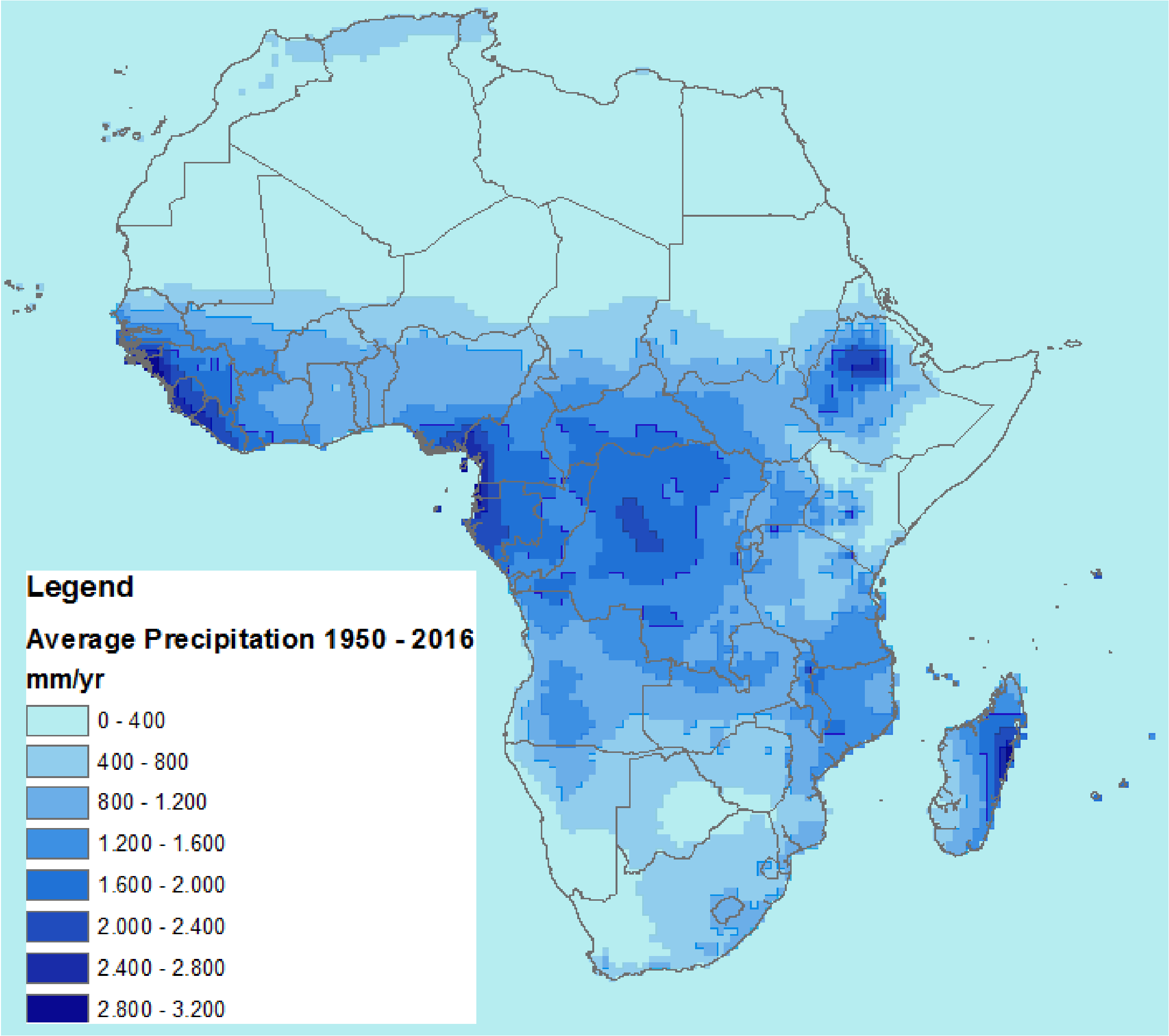


Figure A1.2. Average Precipitation in Africa, 1950-2016 (millimetres per year)

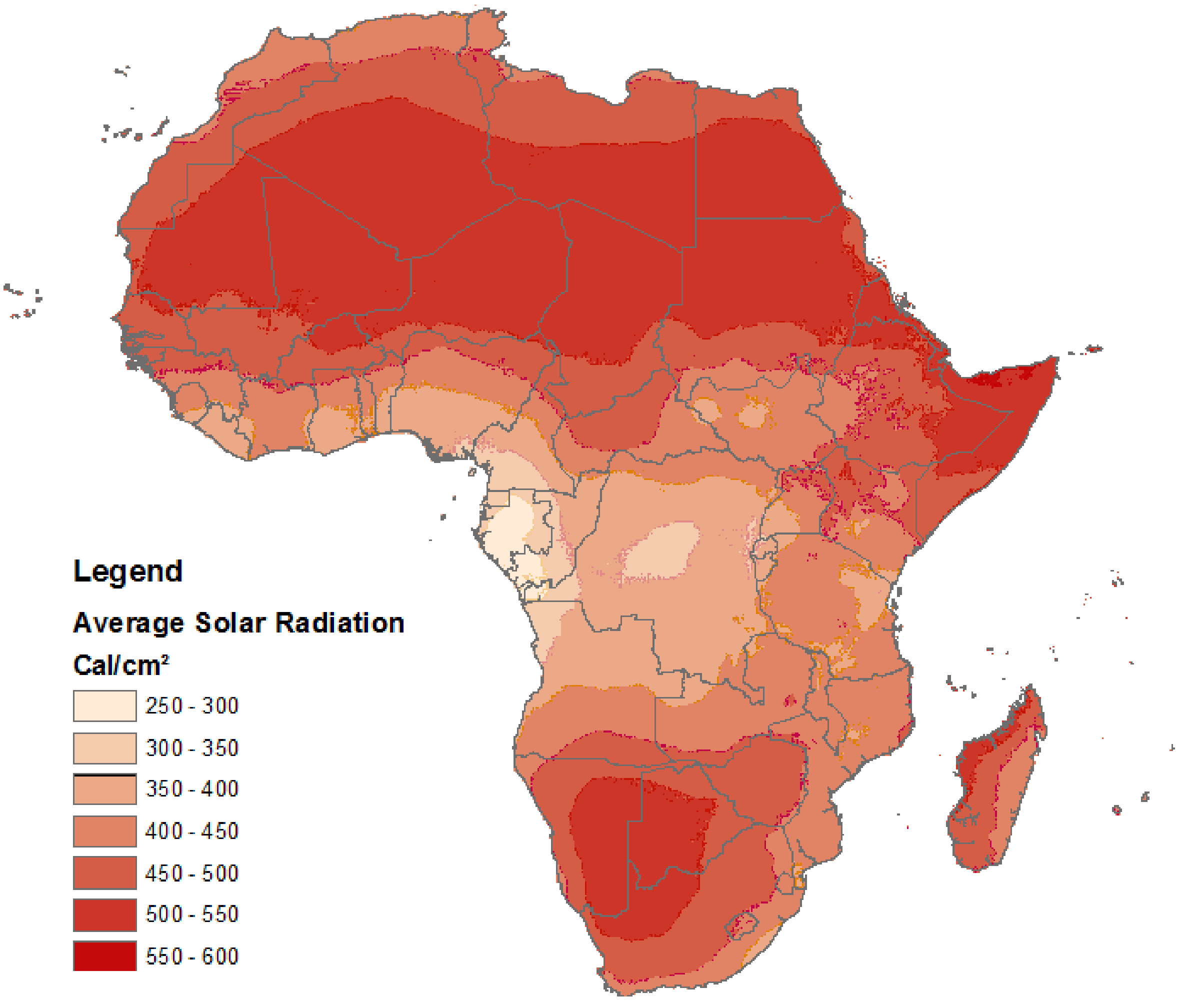


Figure A1.3. Average Insolation in Africa, 1950-2016 (Calories per square centimetre)

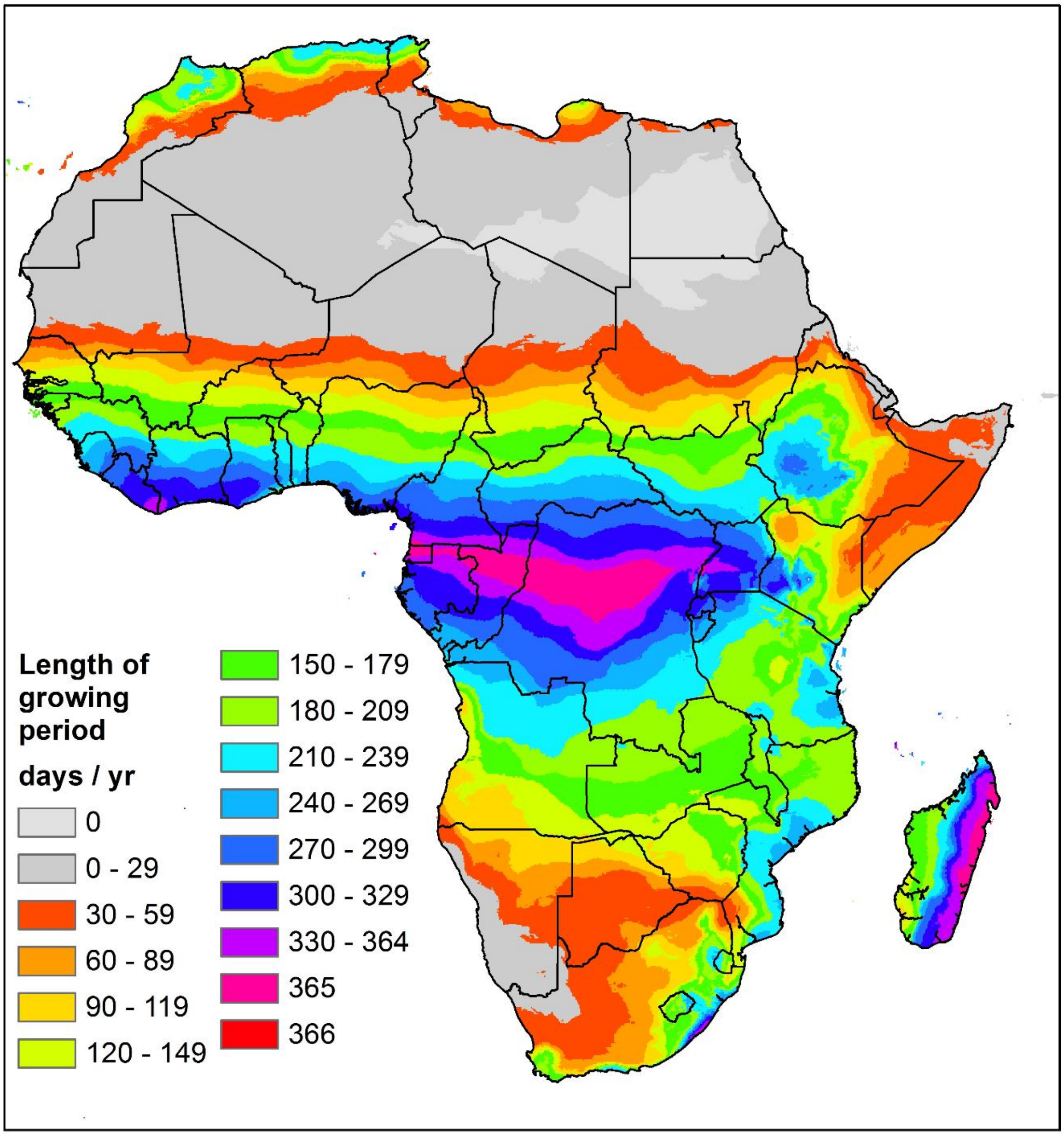


Figure A1.4 Length of growing period in Africa (days per year)

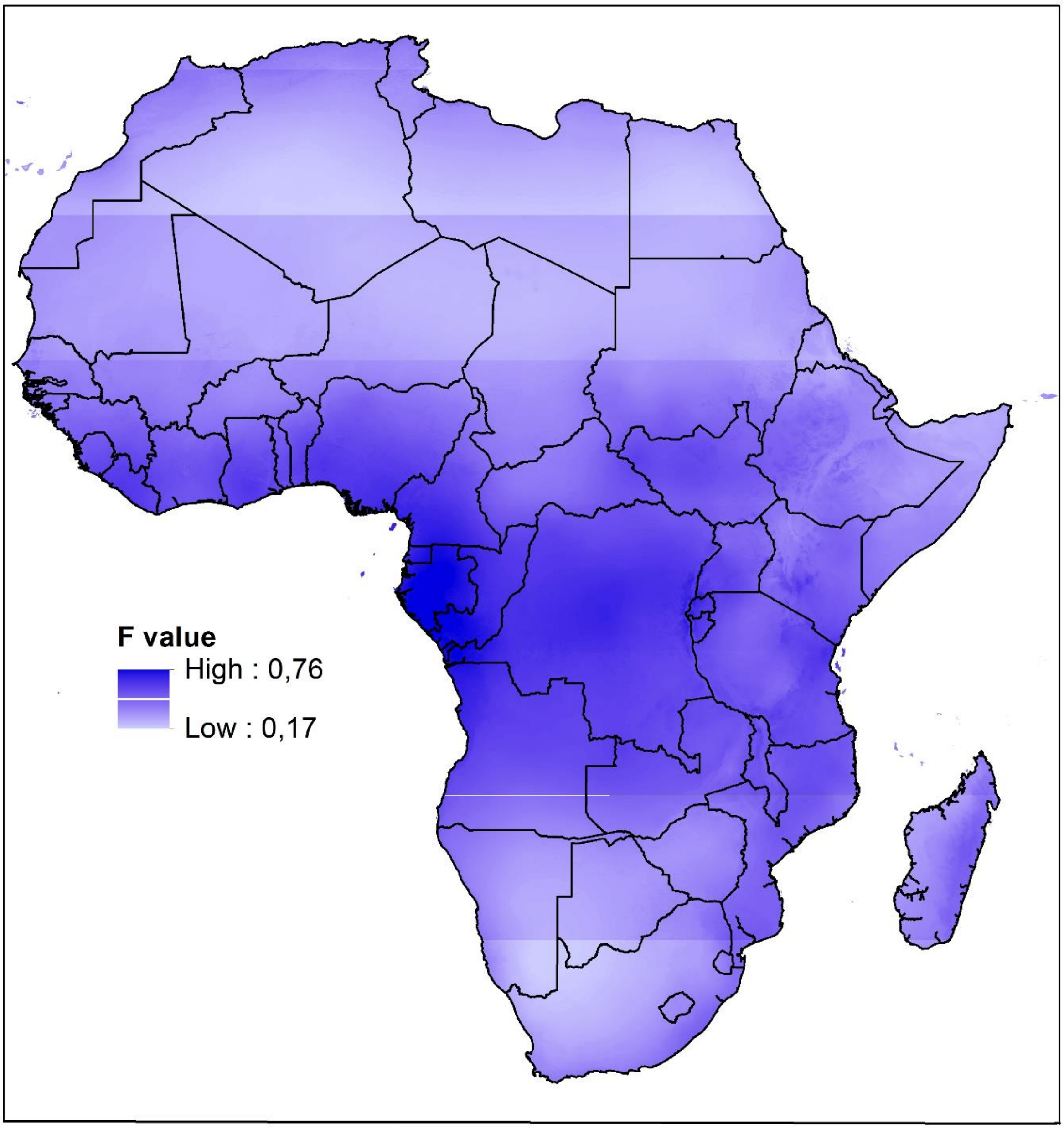


Figure A1.5 F value for Africa

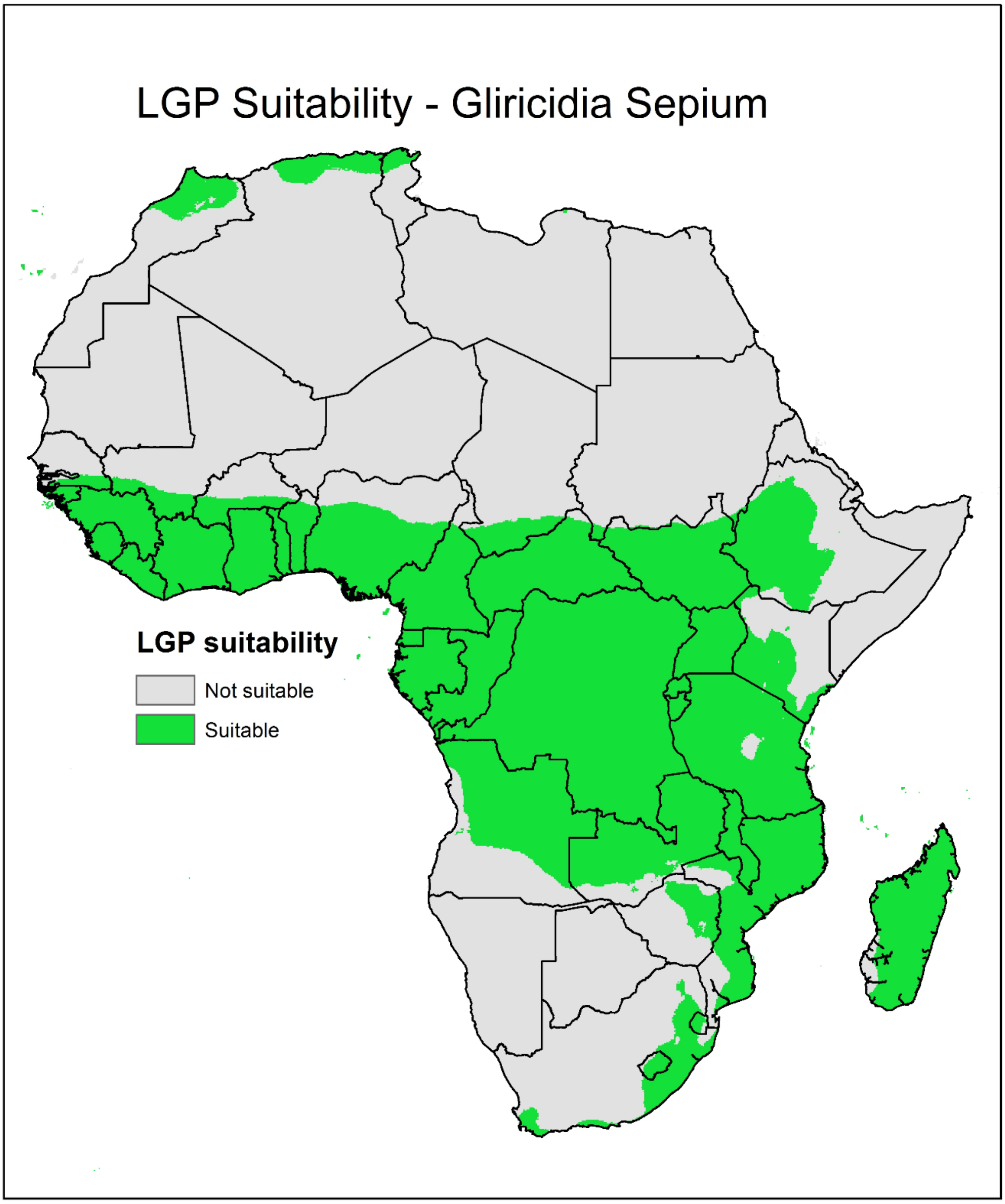


Figure A1.6. LGP suitability - Gliricidia Sepium

	Soil Unit Suitability															
Species	**A**	**Ac**	**Ag**	**Ah**	**Aic**	**Aif**	**Aio**	**Ao**	**Ap**	**Ath**	**B**	**Bc**	**Bd**	**Be**	**Bf**	**Bg**
Acacia Albida	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Acacia Gerrardii	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Acacia Nilotica	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Acacia Senegal	75%	75%	50%	75%	75%	50%	75%	75%	75%	75%	100%	100%	75%	100%	75%	75%
Acacia Tortilis	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	50%	75%	100%
Calliandra Calothyrus	75%	75%	50%	75%	75%	50%	75%	75%	75%	75%	100%	100%	75%	100%	75%	75%
Casuarina Cunninghamiana	75%	75%	50%	75%	75%	50%	75%	75%	75%	75%	100%	100%	75%	100%	75%	75%
Casuarina Equisetifolia	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Conocarpus Lancifolius	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Croton Megalocarpus	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Gliricidia Sepium	75%	75%	50%	75%	75%	50%	75%	75%	75%	75%	100%	100%	75%	100%	75%	75%
Grevillea Robusta	75%	75%	50%	75%	75%	50%	75%	75%	75%	75%	100%	100%	75%	100%	75%	75%
Leucaena Leucocophala	50%	50%	0%	50%	50%	50%	50%	50%	0%	50%	100%	75%	50%	100%	50%	0%
Sesbania Sesban	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%
Tamarindus Indica	50%	50%	50%	50%	75%	50%	50%	50%	0%	50%	100%	75%	75%	100%	50%	75%

Table A1.7a, soil unit suitability per specie. Source: FAO, 1991

Species	Bh	Bk	Bnc	Btc	Bte	Bv	C	Ch	Ck	E	Ec	Eo	F	Fa	Fh
Acacia Albida	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Acacia Gerrardii	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Acacia Nilotica	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Acacia Senegal	75%	0%	100%	100%	100%	75%	0%	0%	0%	0%	0%	0%	75%	0%	75%
Acacia Tortilis	50%	50%	75%	100%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Calliandra Calothyrus	75%	0%	100%	100%	100%	75%	0%	0%	0%	0%	0%	0%	75%	0%	75%
Casuarina Cunninghamiana	75%	0%	100%	100%	100%	75%	0%	0%	0%	0%	0%	0%	75%	0%	75%
Casuarina Equisetifolia	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Conocarpus Lancifolius	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Croton Megalocarpus	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Gliricidia Sepium	75%	0%	100%	100%	100%	75%	0%	0%	0%	0%	0%	0%	75%	0%	75%
Grevillea Robusta	75%	0%	100%	100%	100%	75%	0%	0%	0%	0%	0%	0%	75%	0%	75%
Leucaena Leucocophala	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Sesbania Sesban	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%
Tamarindus Indica	75%	100%	75%	75%	100%	75%	100%	100%	100%	0%	0%	0%	25%	0%	25%

Table A1.7b, soil unit suitability per specie. Source: FAO, 1991

Species	Fnh	Fnr	Fo	Fr	Fx	G	Gc	Ge	Gd	Gh	Gn	Gv
Acacia Albida	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Acacia Gerrardii	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Acacia Nilotica	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Acacia Senegal	75%	75%	75%	75%	50%	50%	0%	50%	25%	50%	50%	25%
Acacia Tortilis	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Calliandra Calothyrus	75%	75%	75%	75%	50%	50%	0%	50%	25%	50%	50%	25%
Casuarina Cunninghamiana	75%	75%	75%	75%	50%	50%	0%	50%	25%	50%	50%	25%
Casuarina Equisetifolia	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Conocarpus Lancifolius	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Croton Megalocarpus	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Gliricidia Sepium	75%	75%	75%	75%	50%	50%	0%	50%	25%	50%	50%	25%
Grevillea Robusta	75%	75%	75%	75%	50%	50%	0%	50%	25%	50%	50%	25%
Leucaena Leucocophala	25%	50%	25%	50%	25%	0%	0%	0%	0%	0%	0%	0%
Sesbania Sesban	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%
Tamarindus Indica	25%	50%	25%	50%	25%	50%	50%	50%	25%	0%	0%	25%

Table A1.7c, soil unit suitability per specie. Source: FAO, 1991

Species	H	Hg	Hh	Hnl	Hol	Hrl	Hth	Htl	Hvl	I	Ir	J	Jc	Je	Jt	K
Acacia Albida	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Acacia Gerrardii	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Acacia Nilotica	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Acacia Senegal	100%	50%	100%	100%	100%	100%	100%	100%	100%	0%	0%	100%	0%	100%	0%	0%
Acacia Tortilis	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Calliandra Calothyrus	100%	50%	100%	100%	100%	100%	100%	100%	100%	0%	0%	100%	0%	100%	0%	0%
Casuarina Cunninghamiana	100%	50%	100%	100%	100%	100%	100%	100%	100%	0%	0%	100%	0%	100%	0%	0%
Casuarina Equisetifolia	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Conocarpus Lancifolius	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Croton Megalocarpus	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Gliricidia Sepium	100%	50%	100%	100%	100%	100%	100%	100%	100%	0%	0%	100%	0%	100%	0%	0%
Grevillea Robusta	100%	50%	100%	100%	100%	100%	100%	100%	100%	0%	0%	100%	0%	100%	0%	0%
Leucaena Leucocephala	50%	0%	25%	75%	75%	75%	50%	50%	50%	0%	0%	100%	100%	100%	0%	100%
Sesbania Sesban	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%
Tamarindus Indica	50%	0%	25%	75%	75%	75%	50%	75%	50%	0%	0%	100%	100%	100%	0%	100%

Table A1.7d, soil unit suitability per specie. Source: FAO, 1991

Species	Kh	L	La	Lc	Lf	Lg	Lic	lif	Lio	Lk	Lnc	Lnf	Lo	Lv
Acacia Albida	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Acacia Gerrardii	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Acacia Nilotica	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Acacia Senegal	0%	100%	50%	100%	50%	50%	100%	75%	100%	0%	100%	50%	100%	75%
Acacia Tortilis	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Calliandra Calothyrus	0%	100%	50%	100%	50%	50%	100%	75%	100%	0%	100%	50%	100%	75%
Casuarina Cunninghamiana	0%	100%	50%	100%	50%	50%	100%	75%	100%	0%	100%	50%	100%	75%
Casuarina Equisetifolia	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Conocarpus Lancifolius	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Croton Megalocarpus	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Gliricidia Sepium	0%	100%	50%	100%	50%	50%	100%	75%	100%	0%	100%	50%	100%	75%
Grevillea Robusta	0%	100%	50%	100%	50%	50%	100%	75%	100%	0%	100%	50%	100%	75%
Leucaena Leucocophala	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Sesbania Sesban	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%
Tamarindus Indica	100%	100%	0%	25%	25%	50%	25%	25%	75%	100%	25%	25%	75%	50%

Table A1.7e, soil unit suitability per specie. Source: FAO, 1991

Species	M	Mo	Mvo	N	Nd	Ne	Nh	Nm	Nth	Nve	Nvm	O	Od	Q
Acacia Albida	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Acacia Gerrardii	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Acacia Nilotica	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Acacia Senegal	100%	100%	75%	100%	75%	100%	75%	100%	75%	75%	75%	0%	0%	0%
Acacia Tortilis	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Calliandra Calothyrus	100%	100%	75%	100%	75%	100%	75%	100%	75%	75%	75%	0%	0%	0%
Casuarina Cunninghamiana	100%	100%	75%	100%	75%	100%	75%	100%	75%	75%	75%	0%	0%	0%
Casuarina Equisetifolia	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Conocarpus Lancifolius	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Croton Megalocarpus	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Gliricidia Sepium	100%	100%	75%	100%	75%	100%	75%	100%	75%	75%	75%	0%	0%	0%
Grevillea Robusta	100%	100%	75%	100%	75%	100%	75%	100%	75%	75%	75%	0%	0%	0%
Leucaena Leucocophala	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	25%
Sesbania Sesban	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%
Tamarindus Indica	100%	100%	75%	75%	50%	75%	25%	50%	25%	50%	50%	0%	0%	0%

Table A1.7f, soil unit suitability per specie. Source: FAO, 1991

Species	Qa	Qc	Qf	Qk	Ql	R	Rc	Rd	Re	Rtc	S	Sg
Acacia Albida	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Acacia Gerrardii	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Acacia Nilotica	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Acacia Senegal	0%	0%	0%	0%	0%	75%	25%	50%	75%	25%	0%	0%
Acacia Tortilis	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Calliandra Calothyrus	0%	0%	0%	0%	0%	75%	25%	50%	75%	25%	0%	0%
Casuarina Cunninghamiana	0%	0%	0%	0%	0%	75%	25%	50%	75%	25%	0%	0%
Casuarina Equisetifolia	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Conocarpus Lancifolius	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Croton Megalocarpus	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Gliricidia Sepium	0%	0%	0%	0%	0%	75%	25%	50%	75%	25%	0%	0%
Grevillea Robusta	0%	0%	0%	0%	0%	75%	25%	50%	75%	25%	0%	0%
Leucaena Leucocophala	0%	25%	25%	25%	25%	75%	100%	50%	75%	25%	0%	0%
Sesbania Sesban	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%
Tamarindus Indica	0%	0%	0%	0%	0%	75%	100%	50%	75%	100%	0%	0%

Table A1.7g, soil unit suitability per specie. Source: FAO, 1991

Species	Sl	Sn	So	T	Th	Tn	Tv	U	V	Vc	Vp	W	Wd
Acacia Albida	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Acacia Gerrardii	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Acacia Nilotica	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Acacia Senegal	0%	0%	0%	75%	75%	75%	0%	0%	50%	50%	50%	50%	25%
Acacia Tortilis	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Calliandra Calothyrus	0%	0%	0%	75%	75%	75%	0%	0%	50%	50%	50%	50%	25%
Casuarina Cunninghamiana	0%	0%	0%	75%	75%	75%	0%	0%	50%	50%	50%	50%	25%
Casuarina Equisetifolia	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Conocarpus Lancifolius	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Croton Megalocarpus	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Gliricidia Sepium	0%	0%	0%	75%	75%	75%	0%	0%	50%	50%	50%	50%	25%
Grevillea Robusta	0%	0%	0%	75%	75%	75%	0%	0%	50%	50%	50%	50%	25%
Leucaena Leucocophala	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Sesbania Sesban	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%
Tamarindus Indica	0%	0%	0%	50%	50%	50%	0%	0%	50%	50%	50%	50%	25%

Table A1.7h, soil unit suitability per specie. Source: FAO, 1991

Species	We	Wh	Ws	Wve	X	Xh	Xk	Xy	Z	Zg	Zo	Zt
Acacia Albida	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Acacia Gerrardii	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Acacia Nilotica	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Acacia Senegal	50%	25%	0%	25%	0%	50%	0%	0%	0%	0%	0%	0%
Acacia Tortilis	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Calliandra Calothyrus	50%	25%	0%	25%	0%	50%	0%	0%	0%	0%	0%	0%
Casuarina Cunninghamiana	50%	25%	0%	25%	0%	50%	0%	0%	0%	0%	0%	0%
Casuarina Equisetifolia	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Conocarpus Lancifolius	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Croton Megalocarpus	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Gliricidia Sepium	50%	25%	0%	25%	0%	50%	0%	0%	0%	0%	0%	0%
Grevillea Robusta	50%	25%	0%	25%	0%	50%	0%	0%	0%	0%	0%	0%
Leucaena Leucocophala	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Sesbania Sesban	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%
Tamarindus Indica	50%	0%	0%	25%	75%	0%	75%	0%	0%	0%	0%	0%

Table A1.7i, soil unit suitability per specie. Source: FAO, 1991

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