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SUSTAINABLE HARVEST

BIOENERGY POTENTIAL FROM AGROFORESTRY AND NITROGEN-FIXING WOOD CROPS IN AFRICA

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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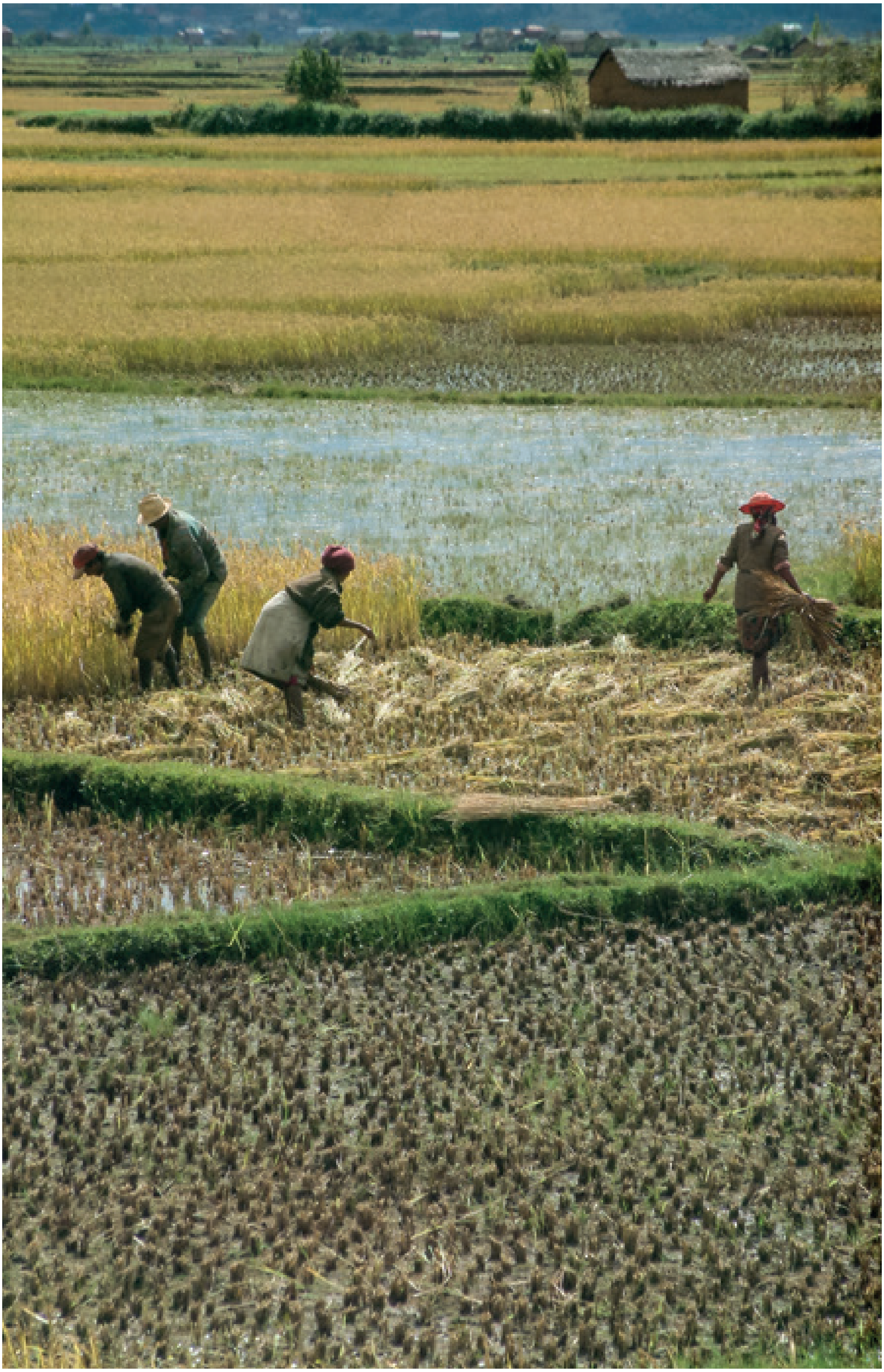
ABBREVIATIONS: NITROGEN-FIXING WOOD SPECIES

AAL	*Acacia albida*
AGE	*Acacia gerrardii*
ANI	*Acacia nilotica*
ASE	*Acacia senegal*
ATO	*Acacia tortilis*
CCU	*Casuarina cunninghamiana*
CCA	*Calliandra calothyrus*
CEQ	*Casuarina equistefolia*
CLA	*Conocarpus lancifolius*
CME	*Croton megalocarpus*
GRO	*Grevillea robusta*
GSE	*Gliricidia sepium*
LLE	*Leuceana leucocephala*
SSE	*Sesbania sesban*
TIN	*Tamarindus indica*

ABBREVIATIONS: GENERAL

Ac	Maximum active incoming photosynthetically active radiation (PAR) on a clear day
bc	Gross dry matter production rate (rate of photosynthesis) of a crop on a perfectly clear day
Bg	Gross biomass production
Bn	Net biomass production
bna	Average rate of biomass production
bnm	Net maximum rate of biomass production
bo	Gross dry matter production rate (rate of photosynthesis) of a crop on a completely overcast day
C	Charcoal
CEC	Cation exchange capacity
CH_2O	Carbohydrate
CIMMYT	International Maize and Wheat Improvement Center
CO_2	Carbon dioxide
COMACO	Community Markets for Conservation
CRU TS	Climate Research Unit Time Series database
ct	Temperature dependent proportionality constant of maintenance respiration
D	Dye
EJ	Exajoules
F	Fraction of daytime when the sky is overcast
FAO	Food and Agriculture Organization of the United Nations

Fb	Firebreak
FM	Fournier index
Fo	Fodder
Fr	Fruit
G	Gum
GAEZ	Global Agro-Ecological Zones
GIS	Geographic Information System
GLADIS	Global Land Degradations Information System
H	Hedge
ha	Hectare
HI	Harvest index
HWSD	Harmonised World Soil Database
IIASA	International Institute for Applied Systems Analysis
IRENA	International Renewable Energy Agency
kg	Kilogram
LAI	Leaf area index
LGP	Length of growing period
M	Manure
Mha	Million hectares
MJ	Megajoules
Mt	Million tonnes
O	Oil
Or	Ornamental
P	Pulp (wood)
PAR	Photosynthetically active radiation
Pl	Plywood, board, etc.
Pm	Maximum rate of photosynthesis
R	Respiration losses
r	Respiration rate
Rg	Incoming shortwave radiation
S	Shading
SEforALL	Sustainable Energy for All
SRWC	Short rotation woody crop
T	Timber
Tv	Vertic Arenosol
Wb	Windbreak
Yp	Potential yield
Yr	Year
ZARI	Zambia Agricultural Research Institute



EXECUTIVE SUMMARY

The world's population continues to grow, requiring increased amounts of food and fuel. Agroforestry systems, in which naturally fertilising nitrogen-fixing wood crops are planted alongside food crops, have the potential to boost fuel and food supply simultaneously. This study estimates the potential in Africa, based upon a systematic evaluation of yields for 15 short rotation woody crops (SRWCs).

While location-specific yields for such woody crops are not available from agricultural databases, such yields can be estimated from available data on soil and climate. First the *constraint-free* biomass production potential can be calculated based upon simple biophysical processes such as photosynthesis and respiration, as a function of temperature, precipitation and solar irradiation data. This constraint-free yield is then reduced by climate and soil constraints to arrive at the net *theoretical* yield potential. Finally, the *technical* yield potential is calculated by excluding unsuitable lands such as cities, roads, industrial infrastructure, undisturbed forest and environmentally protected areas.

The technical yield potential of the nitrogen-fixing wood species evaluated ranges between 2 tonnes per hectare (t/ha) and 16 t/ha in different parts of Africa. Potential *yields* are highest on agricultural lands, of which 95% are suited to SRWC production. Potential *production*, considering both yields and available area, is greatest on grasslands, even though just 30% of these are suited to SRWC production. Some SRWCs can also achieve high yields per hectare on sparsely vegetated or "marginal" land.

Total land suited to SRWCs in Africa is some 555 million hectares (Mha). If planted with the SRWC species with greatest potential in each place, in an agroforestry context where the wood crop occupies 20% of each hectare in rows interspersed with food crops on the other 80%, this land could yield 684 million tonnes (Mt) of wood per year with a primary energy potential of roughly 13 exajoules (EJ). However, this yield would be obtained only once the wood crops were mature, after 5 to 7 years.

Five of the wood species are suited to annual coppicing, which ensures high yields for interplanted food crops by allowing almost all available sunlight to reach them. The wood yields are substantially reduced because the leaf area for photosynthesis is reduced when the plants are cut back each year. But the wood crops' nitrogen-fixing ability and resulting boost to food yields remains unimpaired. For maize, a staple food crop grown on 24 Mha of agricultural land in Africa, intercropping of SRWCs with annual coppicing on 15 Mha could boost output by 22 Mt or over 60% while providing 3 Mt of wood.

1. INTRODUCTION

Access to energy is essential for rural economic growth, improved food production, health and education. Indeed, one of the Sustainable Development Goals agreed by the United Nations is Sustainable Energy for All (SEforALL). Achieving this goal, which calls for universal access to modern energy by 2030, will be challenging in much of the developing world. This is especially true in sub-Saharan Africa, where five-eighths of the population still lack access to electricity (World Bank, 2017).

As part of ensuring energy access, SEforALL calls for doubling the renewable share of energy supply by 2030. The International Renewable Energy Agency (IRENA) has found through its REmap modelling programme that bioenergy accounts for half of the cost-effective potential for doing so (IRENA, 2016). Indeed, global bioenergy use has increased over the last three decades (IRENA, 2015), driven by the desire to reduce energy costs and carbon emissions by displacing fossil fuels (World Energy Council, 2016). But expansion of bioenergy has been slowed by a perceived conflict between food and fuel production, which has often made it difficult for governments and development agencies to support investment. Bioenergy for energy access must therefore be developed in a way that does not reduce food access.

Despite the magnitude of the challenge, innovative solutions are emerging, some of which show great promise in terms of their replicability, scalability and multiple sustainable benefits. These solutions increasingly involve trees, or more particularly agroforestry. In addition to their role in the production of firewood and charcoal, trees have the potential to contribute to more “modern” energy systems. Tree-based systems can produce electricity and bioenergy at scales suitable for home and industry use, whilst also producing biofertilisers for crops and fodder for livestock, all of which combine to improve livelihoods, food security and economic development. As agroforestry supply chains develop for eventual use in heat and power plants, they can serve some of the 2.7 billion people worldwide who rely upon solid fuel, mostly woody biomass, for cooking and heating.

One key agroforestry approach is combining nitrogen-fixing wood crops and food crops with wood and food crops planted in alternating rows. The short rotation woody crops (SRWCs) provide natural fertiliser for the food crops, substantially boosting their yields. More food is thus produced while wood is obtained as a bonus, reducing pressure to collect wood unsustainably from forests.

This approach, producing both food and energy, provides additional income streams for the rural poor and small-holder farmers. It also puts a brake on land degradation, helps preserve forest, stores carbon in the soil and reduces carbon emissions to the atmosphere by displacing fossil fuels. With aggressive pursuit of such an approach leading to rapid increase in food yields, food needs could, furthermore, be met on less land than before, freeing up land for other food or energy crops.

Research shows that by enhancing soil productivity through a mix of trees and food crops (Lal *et al.*, 2016), agroforestry systems can double or even triple food output compared with non-fertilised food production (Sileshi *et al.*, 2008). Because such systems improve soil moisture levels and reduce soil erosion, they also hold great promise for restoring degraded lands (Hillbrand, 2017). Furthermore, such systems have considerable potential for carbon sequestration (FAO, 2011).

Among the most successful agroforestry projects so far is one that has reached more than 200 000 smallholder farmers in Zambia. It involves planting a nitrogen-fixing wood crop, gliricidia, alongside a traditional staple food crop, maize. The approach has been shown to nearly double maize yields while providing a sustainable source of local wood supply, greatly improving farmers' livelihoods. Although maize is widely grown throughout Africa, the yield as recently as the year 2000 was just 10% to 25% of the continent's rain-fed (unirrigated) potential (FAO and IIASA, 2013). This raises the question of how much additional food and fuel might be produced if the approach could be applied more widely.

Answering this question depends on understanding the yields of nitrogen-fixing wood crops in each place and the potential of such wood crops to enhance the yield of neighbouring food crops. However, spatially explicit data on local wood crop yields are not readily available from public sources. The Global Agro-Ecological Zones (GAEZ) model of International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization of the United Nations (FAO), created in 2012, assesses the growth potential of 23 different food crops, taking local climate and soil conditions into account (FAO and IIASA, 2012). It also includes locally differentiated yields for grass species that are suited to bioenergy production. However, it does not cover short-rotation wood species applied for agroforestry (FAO, 2017).

Hence, IRENA devised a method to estimate local wood crop yields from publicly available data about local soil and climate conditions. A model was developed to do so, building upon a methodology described by FAO and IIASA (1991). The model was used to answer four main analytic questions:

1. What are the main factors that determine the yield of SRWCs?
2. What SRWCs are suitable for agroforestry systems in Africa?
3. Which areas are suitable for the growth of SRWCs 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 land area that is suitable for growing it (Wicke *et al.*, 2011). In addressing the first two questions, pertaining to wood yields, the model offers insights into which wood crops can be most productively cultivated. In answering the third and fourth questions, on where wood crops can be grown and how they can boost food crop yields, the model then shows how much extra food and fuel could be produced.

2. BACKGROUND

An agroforestry approach has provided benefits to small farmers at scale in a real-life setting. Examining this is useful in order to understand why the potential for food and fuel from agroforestry is worth assessing. Such an examination also provides basis information on the processes affecting plant growth and how agroforestry can promote these processes in a wide range of ecosystems.

2.1 Agroforestry experience with gliricidia and maize

One of the nitrogen-fixing wood crops with which there is a growing body of experience is gliricidia. Gliricidia is native to Central America and Mexico but has been widely introduced throughout the tropics due to its high productivity and adaptability. It thrives on an annual rainfall of 600 to 3 500 millimetres. It grows rapidly, repels various pests, produces excellent fodder for livestock, provides mulch to enrich the soil with organic carbon and fertilising nitrogen, and mines plant nutrients such as phosphorus, potassium and magnesium from deeper layers of soil. It can readily be intercropped with food crops, thereby boosting their yields, and it tolerates aggressive annual coppicing. It is also an extremely good fuelwood, producing 19.8 megajoules per kilogramme (MJ/kg) and burning slowly with little smoke or sparks.

In Africa, where gliricidia was first introduced in the 17th century, the nitrogen-fixing crop is increasingly used to boost the yields of staple maize crops. Particularly in Zambia and neighbouring countries, gliricidia intercropping has a proven positive impact on maize yields within 3 years of planting. A social enterprise called Community Markets for Conservation (COMACO) is promoting such gliricidia use in Zambia. Large-scale wood supply chains have developed that could form the basis for future supply to heat and power plants.

The use of gliricidia to boost food and energy output has demonstrated a host of benefits:

- ***Social benefits*** include increased income and employment, empowerment of rural communities, and increased participation in projects by women, the elderly and the disabled.
- ***Economic benefits*** include improved agricultural productivity with greater food and livestock output, production of biofertiliser and biochar, increased rural business opportunities and job creation, foreign exchange savings from reduced use of fossil fuel, and development of rural infrastructure in off-grid and marginalised areas.
- ***Environmental benefits*** include reduced carbon emissions with increased sequestration of atmospheric carbon, reduced land degradation with increased forest coverage, reduced soil erosion, enrichment of soil nutrients, and reduced use of chemical fertilisers.

Agroforestry approach: Gliricidia with maize

In Zambia, COMACO promotes alley intercropping of gliricidia with existing maize crops. Gliricidia trees are grown in rows 4 metres apart, with rows of maize in between. Each tree is planted in a large hole or "basin" 30 cm deep, and trees are spaced at 1-metre intervals. Once the stand of gliricidia is established, it can be harvested each year at the end of the 8-month dry season, allowing the maize to grow unimpeded alongside it during the 4-month rainy season. Roughly 1500 gliricidia trees are typically planted per hectare.

Photograph: COMACO

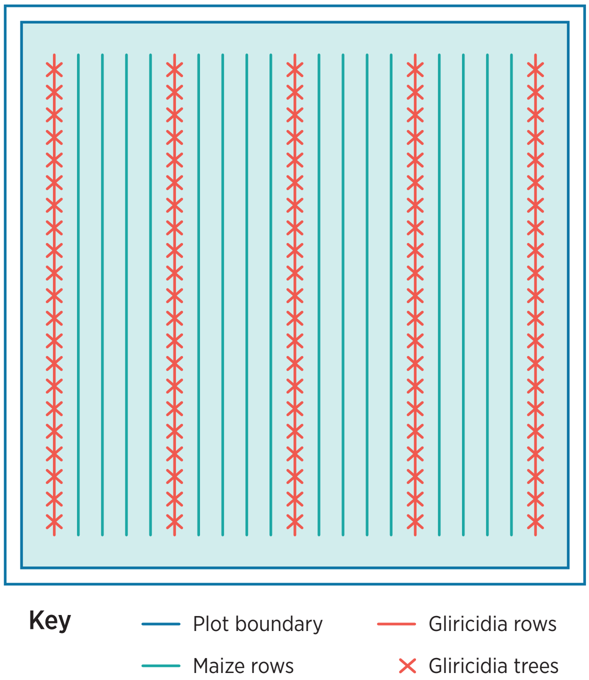
Scale of implementation

COMACO's approach is expanding rapidly in seven districts of Zambia, mostly in the Eastern Province, with increasing support from the Zambian government and other stakeholders. Plantings have increased more than sevenfold, from roughly 5 million trees in 2010 to 38 million in 2017. On average, nearly half the trees planted (48%) have survived, though survivorship was much lower in certain years. On a cumulative basis, more than 47 million gliricidia trees were producing wood as of 2017. The average participating farm plot had about 350 trees on about a quarter of a hectare of land.

Impacts on crop yields and livelihoods

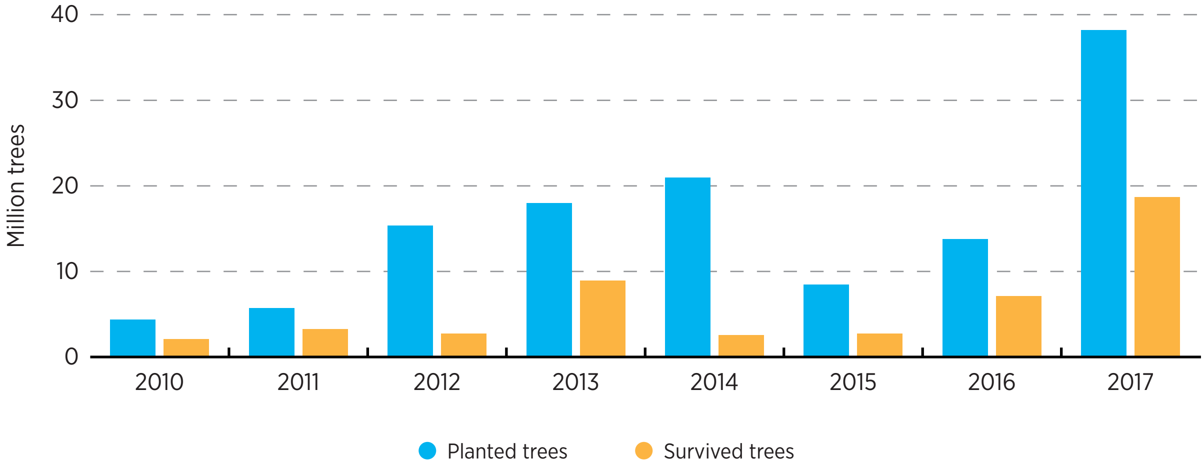
Agroforestry with gliricidia has empowered farmers and women in Zambia by doubling their maize yields, providing wood for their cooking and heating needs, and boosting their incomes.

Figure 2.1 Gliricidia alley-cropping with maize in Zambia – field layout



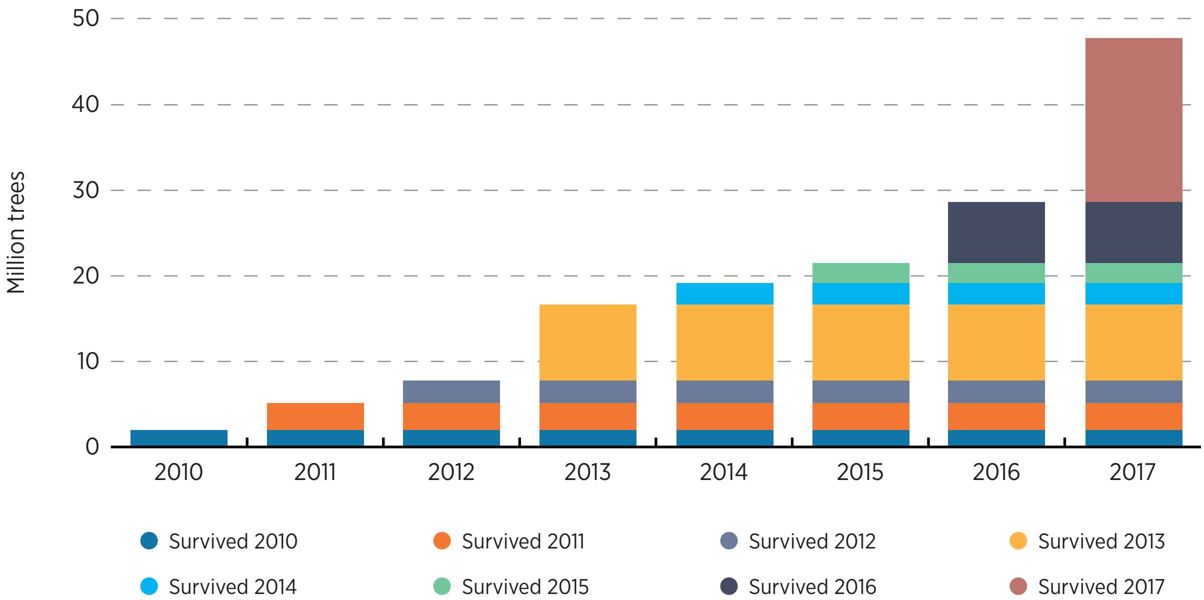
Source: ICRAF

Figure 2.2a Gliricidia planting and survival in Zambia, 2010-2017



Source: COMACO data

Figure 2.2b Cumulative number of gliricidia trees in Zambia, 2010-2017



Source: COMACO data

- ***Empowerment of farmers and women:*** More than 167 400 small-scale farmers, of whom 52% are women, actively participate, including in decision-making and teaching.
- ***Increased food yields:*** Participating farmers obtain average maize yields of more than 2 tonnes per ha, compared to 0.97 tonnes among non-COMACO farmers in the same areas.
- ***Improved food security:*** 80% of households registered with COMACO were considered to be food secure in 2016, compared to 34% in 2001 and 43% in 2003.
- ***Increased income:*** The average annual income per household reached USD 348 in 2016, more than quadrupling from its level of USD 79 in 2003.
- ***Reduced fertiliser costs:*** Typical participating farmers who have introduced gliricidia alley intercropping practices on 0.5 ha are saving about USD 80 to USD 120 annually on fertiliser.

- **_Efficient cooking:_** More than 70 000 fuel-efficient cookstoves have been distributed to member households, which typically harvest enough prunings for all their cooking and heating needs.
- **_Beekeeping:_** Members are trained in beekeeping, and 10 000 beehives have been established.
- **_Efficient extension service:_** The average annual cost of support to member farmers has declined from USD 25 in 2003 to USD 16 in 2016, while maintaining increased crop yields and incomes.
- **_Diversification of livelihoods:_** COMACO farmers have diversified their food and income sources, improving their resilience to climate change, extreme weather events and food shortages.

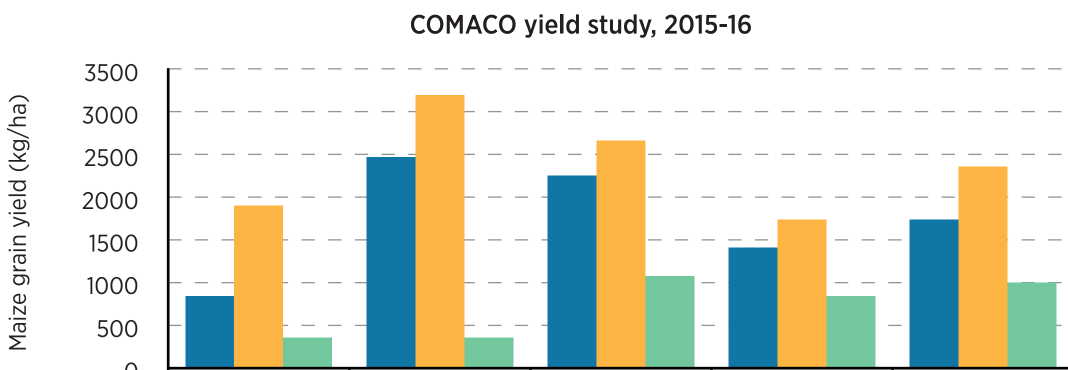
In April 2016, a joint research trial was undertaken by International Maize and Wheat Improvement Center (CIMMYT), Zambia Agricultural Research Institute (ZARI) and COMACO to assess the impact of gliricidia-based agroforestry on small-scale farmer maize yields.

- Yields for farming with three different treatments (without fertiliser, with organic fertiliser, and for natural fertilisation with nitrogen-fixing gliricidia) were compared for four clusters with different combinations of soil type (fertile or sandy) and tree age (two or four years).
- Data were drawn from a sample of ten randomly selected farmers for each of the resulting 12 combinations of treatments and clusters, involving a total of 120 farmers.
- Within each cluster, there were 30 separate plots, with 3 plots near each other in each of 10 locations to minimise variation in soil and other extraneous factors that might affect growth.

As shown in Figure 2.3, gliricidia was found to improve maize yields for the four different soil-age clusters by a simple average of 78% (CIMMYT, ZARI and COMACO, 2016). So gliricidia nearly doubled average maize yields *on each hectare* even though the food crop was sharing land with the wood.

Gliricidia nearly doubled average maize yields

Figure 2.3a Average maize yield for fields unfertilised, fertilised or with gliricidia (kg/ha)



	2 year loam	2 year sandy clay	4 year loam	4 year sandy clay	Overall average
Gliricidia/maize	805	2458	2239	1401	1726
Maize fertilized	1825	3155	2639	1708	2332
Maize unfertilized	354	1656	1029	832	968

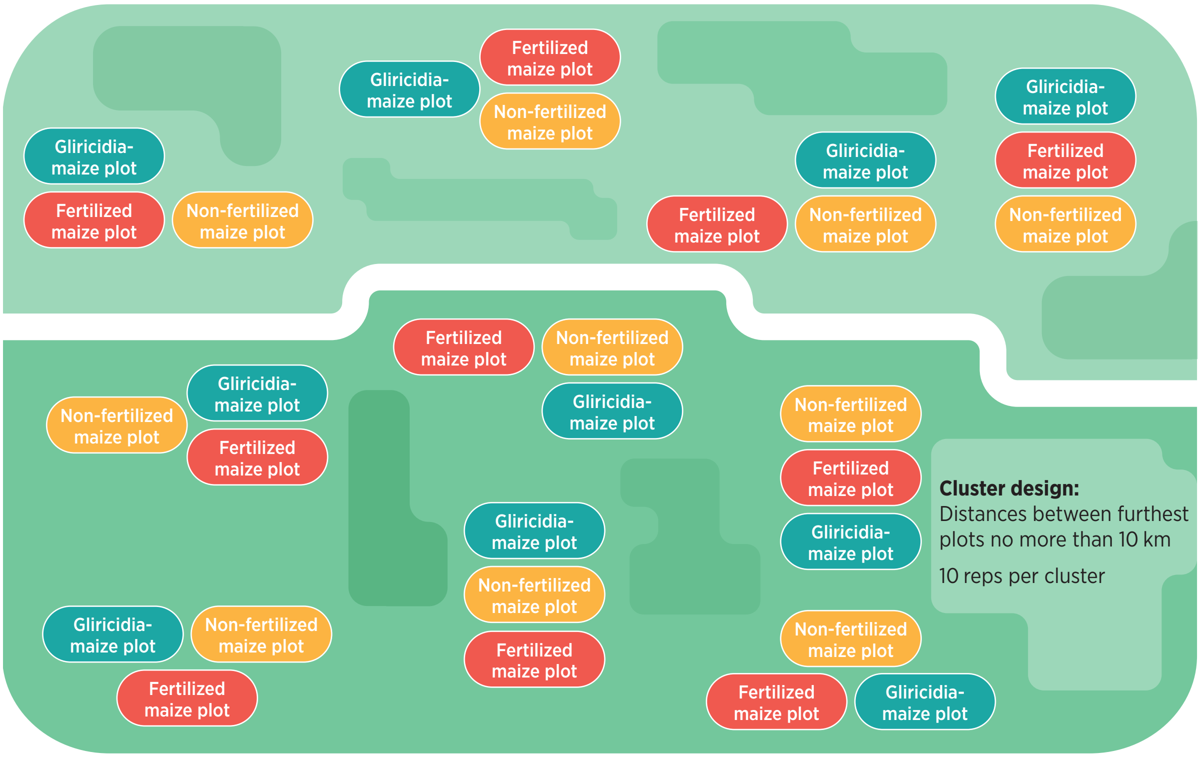
Source: CIMMYT, ZARI and COMACO (2016)

Figure 2.3b Maize yield increase from planting with gliricidia or fertiliser, by soil type

	2 year loam	2 year sandy clay	4 year loam	4 year sandy clay	Overall average
Maize with gliricidia	127%	48%	118%	68%	78%
Maize with fertiliser	416%	90%	156%	105%	141%

Source: CIMMYT, ZARI and COMACO (2016)

Figure 2.3c Comparison of yields on adjacent plots with gliricidia and with or without fertiliser



Source: CIMMYT, ZARI and COMACO (2016)

2.2 Environmental factors affecting plant growth

Biophysical processes of plant growth

To estimate how local climate and soil conditions affect crop yields, the biophysical processes that affect plant growth need to be understood (Holding and Streich, 2013). Plant growth is determined by three biophysical processes: photosynthesis, respiration and transpiration (Whiting, 2014).

Photosynthesis is a two-step process by which plants convert light, water and carbon dioxide into oxygen, sugar and energy (Raven, 2013). In the first step, involving *light* reactions, incoming solar radiation initiates a chemical reaction within the plant cell where oxygen and energy for the second step is released (Holding and Streich, 2013). In the second step, involving *dark* reactions, released energy is stored by what are called Rubisco enzymes into three-carbon molecules (Holding and Streich, 2013). These enzymes are essential to plant growth and consume nitrogen, which must be supplied to the soil.

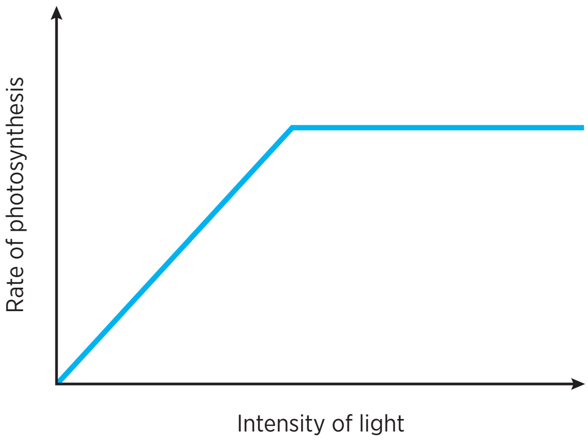
Respiration is often called the opposite reaction to photosynthesis (Holding and Streich, 2013). During the respiration process, plants convert oxygen from the atmosphere and sugars from photosynthesis into water, carbon dioxide and energy for growth and development (Whiting, 2014). A distinction can be made between respiration for plant maintenance and for biomass production. The energy needed for a plant to repair and maintain its cell tissue is released by maintenance respiration (Bruhn, 2002).

Transpiration is the evaporation of water molecules out of the plant and 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 by the roots of the plant, which thereby enhances plants' nutrient uptake (Sterling, 2004).

Climate factors affecting plant growth

Solar radiation is considered essential for the growth of any crop. Photosynthetically active radiation (PAR) ranges from 400 to 700 nanometres in wavelength. Biomass production is generally proportionate to incoming PAR (Pashiardis, Kalogirou and Pelengaris, 2017). That is because 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 and the rate of photosynthesis is shown in Figure 2.4.

Figure 2.4 Rate of photosynthesis versus light

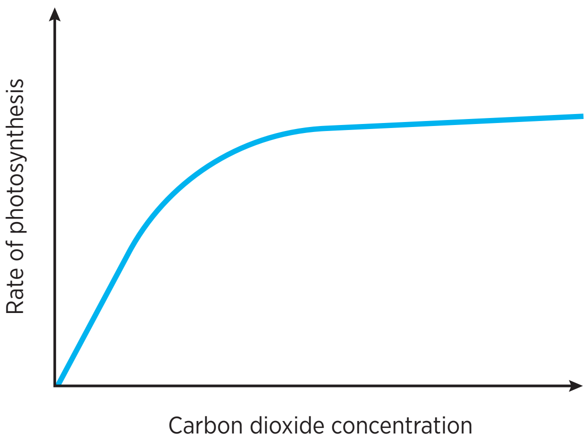


Source: RSC (2014)

Carbon dioxide (CO_2) is also an important factor in the processes of photosynthesis. A greater concentration of CO_2 will increase the rate of the dark reactions and thereby the overall rate of photosynthesis, as shown schematically in Figure 2.5 (RSC, 2014).

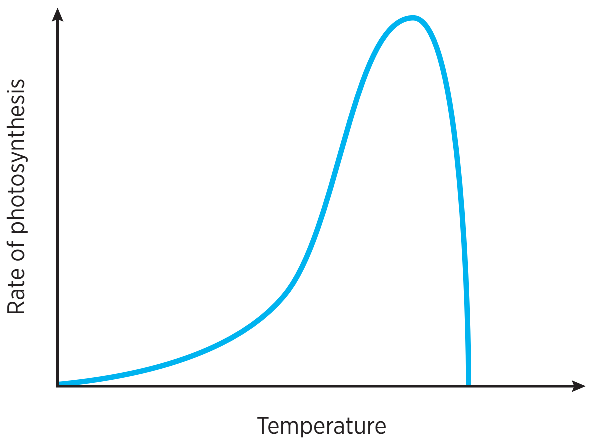
Temperature is another factor that plays an important role in plant growth. In the dark reactions of photosynthesis, plants use enzymes that work more efficiently as temperature rises (Amedie, 2013). The rate of photosynthesis roughly doubles for every increase of 10°C up to an optimum temperature, above which it drops sharply, as shown in Figure 2.6 (RSC, 2014).

Figure 2.5 CO_2 concentration and rate of photosynthesis



Source: RSC (2014)

Figure 2.6 Temperature and rate of photosynthesis



Source: RSC (2014)

Water is essential for a plant to survive and plays several roles in plant growth. It makes up 90% of the matter in plant cells (Singh, 2007). It serves as both reactant and solvent for chemical reactions that occur in photosynthesis and respiration (Kramer and Boyer, 1995). Minerals are transported and distributed from the roots by water due to the hydraulic lift effect of transpiration (Whiting, 2014). Water also regulates plant temperature (Kramer and Boyer, 1995). Since photosynthesis, respiration and transpiration processes all depend on water (Chavarria and dos Santos, 2012), lack of water reduces plant productivity. But excessive water in the soil also slows plant growth (Douglas *et al.*, 2003) as it limits oxygen and nutrient uptake (Taylor, 2006; García, Mendoza and Pomar, 2008).

Soil factors affecting plant growth

Soil provides the water and nutrients that plants need to grow (Hewitt, 2004). Water and nutrient uptake is affected by soil slope and requires a soil texture that allows roots to develop (Walter, 1973).

Nutrients are essential for plant growth. The three most important are nitrogen, potassium and phosphorus (Kramer and Boyer, 1995). Nitrogen is responsible for development of plant foliage, which undertakes most of the plant's photosynthesis and energy production. However, nitrogen is prone to leaching from the soil. Potassium is important because it makes a plant more resistant to drought and disease. Phosphorus promotes the development of the plant's root system (Crouse, 2018).

Soil texture is an important factor in plant development (Walter, 1973). The texture of a soil relates to the proportions of sand, silt and clay within it (Cornell University, n.d.). The clay share is important because clay is negatively charged and thus can hold on to nutrients that are positively charged through the Cation Exchange Capacity (CEC) mechanism (Ketterings, Reid and Rao, 2007). Clay is also important due to its 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). Therefore, in general, the smaller the grain size, the more suitable the soil (FAO and IIASA., 2012). However, when pores between grains are too small, water is unable to move through the soil profile, resulting 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 (Ministry of Environment and Natural Resources, 2016). In general, steeper slopes have fewer nutrients and less water available due to the runoff induced by rainfall (Fischer *et al.*, 2012).

2.3 Agroforestry and plant growth

Benefits of agroforestry for ecosystems

Agroforestry systems can benefit a wide range of different types of ecosystems by improving soil quality, reducing the impact of erosion and increasing water availability (Hillbrand, 2017).

Soil quality: Agroforestry systems improve soil quality through more intensive nitrogen cycling than conventional agricultural systems. The amount of nitrogen leaving the system is lower, and the rate of transfer of nitrogen within the system is higher (Tsonkova *et al.*, 2012). The deeper rooting systems of some SRWCs are able to take up nitrogen from deeper soil layers and return it to the surface soil (Allen *et al.*, 2004). SRWC cultivation can thus help restore nitrogen-poor soils and maintain the fertility of agricultural land without additional fertilisation (Tsonkova *et al.*, 2012).

Erosion control: SRWCs in agroforestry systems can help reduce 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 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 plant growth and can limit growth if not sufficient (Walter, 1973). SRWCs can supply neighbouring crops with water due to hydraulic lift of the deeper root system. In this process, water is absorbed up from deeper soil layers and released into the upper layer (Burgess *et al.*, 2001).

Types of agroforestry management systems

Different agroforestry systems have different impacts on climate and soil factors that affect crop growth. Nair (1993) has defined three major types of agroforestry systems, as detailed in Table 2.1.

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.

Table 2.1 Agroforestry system types and characteristics

System type	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 establishment of plantations
Alley cropping	Woody species in hedges; agricultural species in alleys between hedges
Multilayer tree gardens	Multispecies, multilayer dense plant associations with no organised planting arrangements
Multipurpose trees on crop lands	Trees scattered haphazardly or according to some systematic patterns
Plantation crop combination	Integrated multistory mixtures of plantation crops
Home gardens	Intimate multistory 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 irregularly or arranged in 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**
Home gardens involving animals	Intimate multistorey combination of various trees, 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

Source: Nair (1993)

3. INPUT DATA

3.1 Species overview

This study assesses yields for 15 nitrogen-fixing SRWC species. The FAO and IIASA have grouped these species into six classes as shown in Table 3.1. An important distinction among species is the optimum temperature for photosynthesis. Some species perform better under cooler conditions with the optimum temperature ranging between 15°C and 20°C. Others function better in warmer conditions with mean optimum temperatures between 20°C and 30°C. Within those two groups, a further distinction can be made based on the maximum rate of photosynthesis, Pm. Three classes of Pm have been identified by the FAO and IIASA (1991):

- low rate: Pm = 5-10 kg CH_2O per hectare per hour
- medium rate: Pm = 10-20 kg CH_2O per hectare per hour
- high rate: Pm = 20-30 kg CH_2O per hectare per hour.

Table 3.1 Classification of species by Pm and temperature

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 CH_2O/ha/hr)	*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 CH_2O/ha/hr)	*Casuarina cunninghamiana*	*Casuarina equisetifolia*
HIGH RATE OF PHOTOSYNTHESIS (Pm = 20-30 kg CH_2O/ha/hr)	*Sesbania sesban*	*Leucaena leucocophala*
		Sesbania sesban

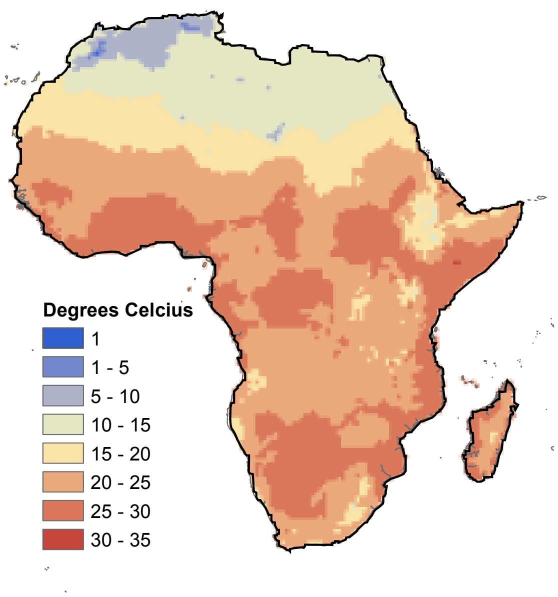
Source: FAO and IIASA (1991)

3.2 Climate data

The calculation of yield potential for SRWCs is based on four climatic variables: temperature, precipitation, the length of growing period (LGP) and solar radiation.

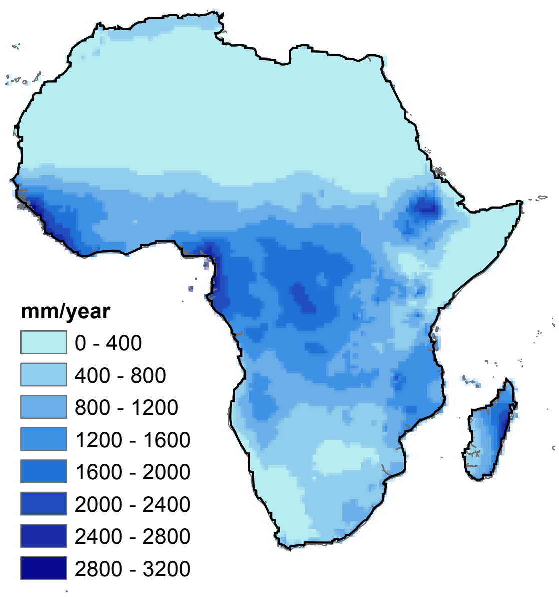
The temperature and precipitation data for the yield calculation can be obtained from the Time Series database of the Climate Research Unit (CRU TS) which contains monthly temperature and precipitation data for the period of 1950-2016 with a resolution of 30 arc-minutes. The latest database version, CRU TS 4.01, which revises and extends the earlier version, CRU TS 2.1, is used for the present analysis.

Figure 3.1 Average temperature in Africa, 1950-2016



Based on: Harris *et al.* (2014)

Figure 3.2 Average precipitation in Africa, 1950-2016



Based on: Harris *et al.* (2014)

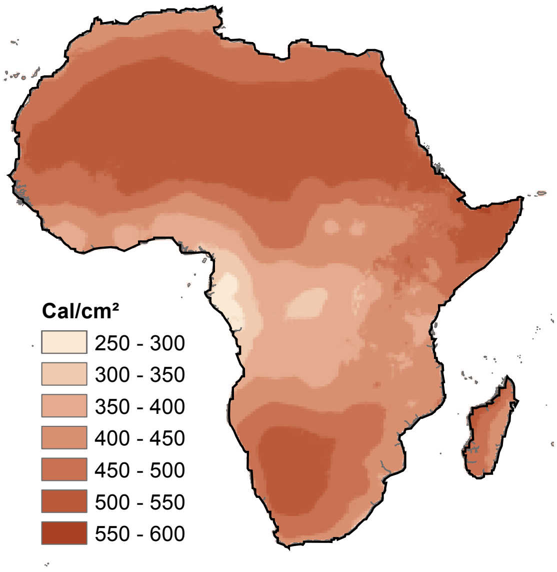
The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

The **solar radiation** data come from the WorldClim V2 database compiled by Hijmans and Fick (2017), which provides a detailed, 30 arc-seconds gridded monthly average solar radiation map for 1970-2000 and somewhat less detailed data for a more extended period, as shown in Figure 3.3.

The availability of moisture content in the soil can be expressed as the **length of growing period** (LGP). This is the number days per year when precipitation exceeds half of the potential evapotranspiration. LGP data are taken from the Global Agro-Ecological Zones (GAEZ) report by FAO and IIASA (2012). Figure 3.4 shows LGP for each 5 arc-minute-sized raster layer.

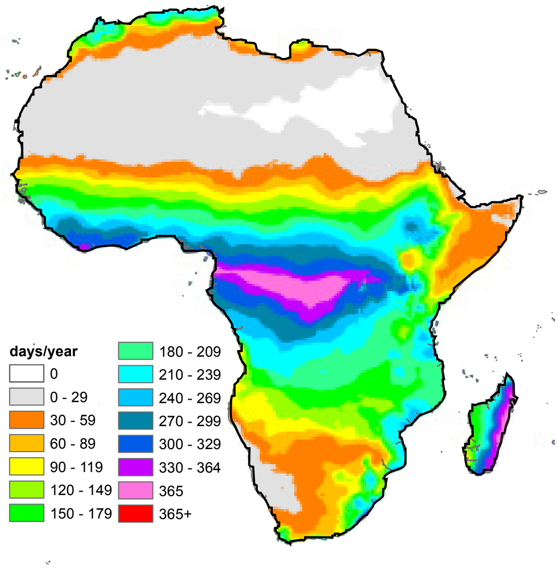
The temperature, precipitation and LGP data are interpolated into a 30 arc-second raster. To minimise information loss, a cubic interpolation method was applied within Arcmap 10.5. This method calculates the value of each pixel by fitting a smooth curve based on the surrounding 16 pixels.

Figure 3.3 Average insolation in Africa, 1950-2016



Based on: Harris *et al.* (2014)

Figure 3.4 Length of Growing Period (LGP) in Africa



Source: FAO and IIASA (2012)

The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

3.3 Soil data

A soil's suitability for a species can be evaluated from data on its physical and chemical composition, texture and slope. The Harmonized World Soil Database (HSWD) provides such data. The information in this database is stored as 30 arc-seconds in a Geographic Information System (GIS) raster, which is linked to an attribute database in Microsoft Access format containing harmonised soil profile data (FAO and 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, 2015). To identify which soils are present in a certain region, the FAO has classified all soils based on their physical and chemical composition into "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). For Africa, the soil unit data provided by the Harmonised World Soil Database (HWSD) are divided between FAO74 and FAO90 data, as shown in Figure 3.5 (FAO/IIASA/ISRIC/ISS-CAS.JRC, 2009).

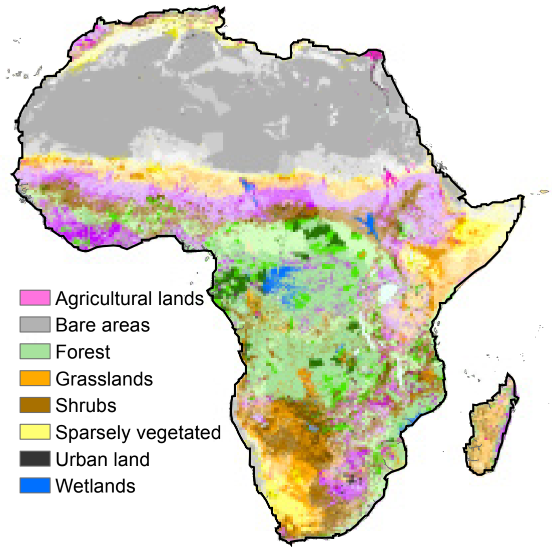
Land use system data

The study's data on land use systems in Africa are derived from the Global Land Degradations Information System (GLADIS) analysis. Based on satellite imagery, eight main land cover types have been recognised. These land covers are divided into 41 different land use systems, based on statistics and other data layers, with eight main systems, as shown in Figure 3.6 (Ministry of Environment and Natural Resources, 2016). The raw data have a resolution of 5 arc-minutes. To provide greater resolution, it was resampled into 30 arc-seconds using the Arcmap 10.5 cubic interpolation resample tool. Although the associated area varies with location, the greater resolution makes specific data available for about every square kilometre.

Figure 3.5 Soil unit classification in Africa

Source: FAO/IIASA/ISRIC/ISS-CAS.JRC (2009)

Figure 3.6 Land use systems in Africa



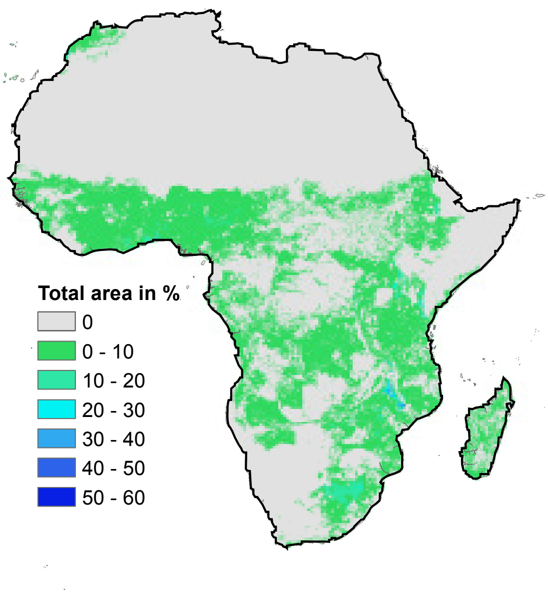
Source: Ministry of Environment and Natural Resources (2016)

The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

3.4 Maize data

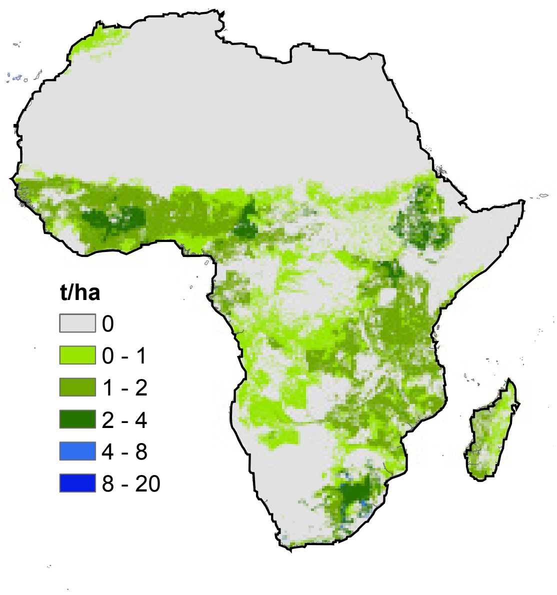
Over the past 30 years, the FAO and IIASA have developed the GAEZ database. This database contains, among other things, global information about actual achieved yields and production of main crop commodities for the year 2000. One of the main crop commodities that has been analysed in the GAEZ database is maize. The database provides information on maize production areas and their yields. The data are presented in a raster format, which can be utilised by the Arcmap 10.5 programme. The resolution of the raster is 5 arc-minutes, which means that each square in the raster is roughly 10 000 ha (or 10 km x 10 km) in size. Most of the squares have a value for maize cultivation of less than 10%, so that less than 1 000 ha in the square is used for maize production. Figure 3.7 shows the area used for rain-fed maize production in Africa. Figure 3.8 shows the maize yield achieved in this area.

Figure 3.7 Rain-fed maize production area in Africa, 2000



Source: GAEZ database (2018)

Figure 3.8 Rain-fed maize yield in Africa, 2000



Source: GAEZ database (2018)

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4 METHOD

In the present study, the yield potential of SRWC in agroforestry systems in Africa is calculated, taking account of local soil and climate conditions. A distinction is made between theoretical and technical yield potential. The theoretical potential is the upper limit of biomass production allowed by soil and climate conditions. The technical potential is the portion of theoretical potential that is available within suitable land use systems (Smeets *et al.*, 2007). These potentials were calculated using the following seven-step procedure, shown in Figure 4.1.

Step 1: **Maximum constraint-free yield potential calculation:** To calculate the theoretical yield potential, the upper limit of SRWC production was analysed. The methodology for this calculation was derived from the fuelwood productivity annex of FAO's Agro-Ecological Zones report on Kenya (FAO and IIASA, 1991). With the use of temperature and solar radiation data, the constraint-free yield was calculated.

Step 2: **Climate suitability analysis:** This step analysed the suitability of the local climate for SRWC production. For each species, the temperature and LGP suitability was mapped. The suitability analyses are based on FAO and IIASA (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 FAO and IIASA (1991). The slope suitability is based on FAO and IIASA (2012).

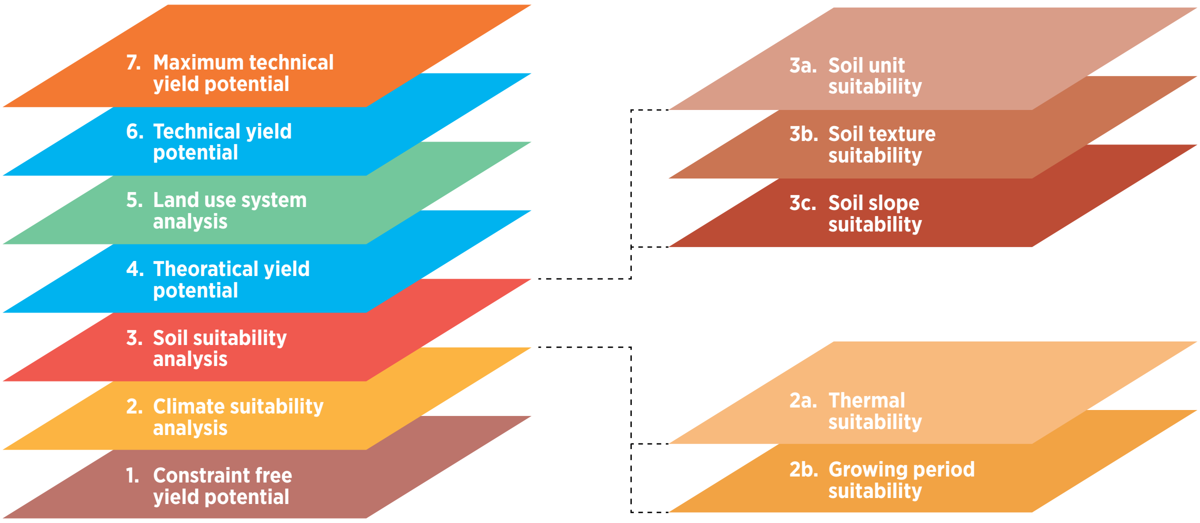
Step 4: **Theoretical yield potential calculation:** Steps 1, 2 and 3 provide the information necessary for the theoretical yield potential calculation. In Step 4, the maximum constraint-free yield potential (from Step 1) is reduced by climate constraints (from Step 2) and soil constraints (from Step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

Step 5: **Land use system limitations:** The areas 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 analysed all available land uses for SRWC production in Africa.

Step 6: **Technical yield potential calculation:** The land use systems identified in Step 5 were excluded from the theoretical yield potential calculation. The remaining yield potential was 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 SRWCs was known. In most areas the climate and soil conditions meet the requirements of multiple different species. As a result, some areas have multiple species that will achieve the same technical yield potential per hectare. To calculate the maximum yield potential, species preference was based on the quantity of utilisation options of the SRWC.

Figure 4.1 Schematic overview of the seven-step method



4.1 Constraint-free yield potential

The first step in defining the theoretical yield potential is to calculate the constraint-free biomass production potential (Smeets *et al.*, 2007). To do so, this study uses a methodology developed by the GAEZ project undertaken by the FAO and IIASA. This methodology calculates the yield potential using basic eco-physiological principles as explained in this chapter.

Gross and net biomass production

As explained in Chapter 2, Section 1, a plant's biomass production depends on processes of photosynthesis and respiration. The following equations show how gross biomass production (through photosynthesis) is reduced by losses through respiration (FAO and IIASA, 1991):

- *Bn = Bg – R* (1)

where:

» Bn = Net biomass production

» Bg = Gross biomass production

» R = Respiration losses.

The rate of which a plant produces biomass can therefore be expressed as:

- *bn = bg – r* (2)

where:

» bn = rate of net biomass production

» bg = rate of gross biomass production

» r = respiration rate.

The net maximum rate of biomass production (bnm) depends mainly on the rate of gross biomass production bg (rate of photosynthesis). Since photosynthesis occurs in the leaves of the plants, bnm is achieved when the soil surface is completely covered by the crop. A more developed plant has more leaves and grows faster. The plant growth rate over time, as shown in Figure 4.2, has the shape of a normal distribution curve. The GAEZ model assumes that the average rate of biomass production (bna) over the whole growing period is half of the maximum growth rate (FAO and IIASA, 1991):

- *Bn = 0.5 bnm x LGP* (3)

where:

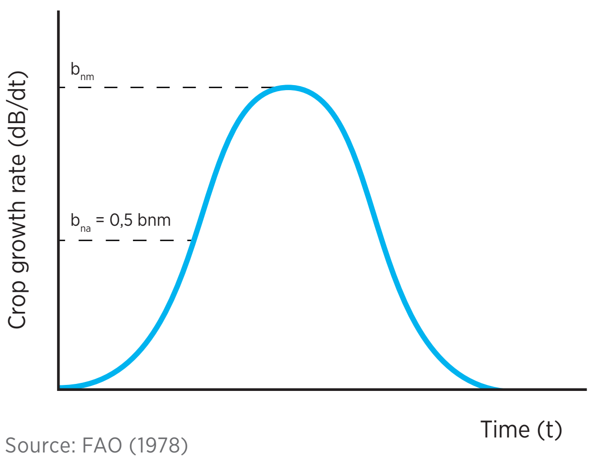
» Bn = Net biomass production

» bnm = maximum rate of net biomass production

» LGP = length growth period in days.

As explained above, LGP depends on the availability of moisture. If the maximum rate of biomass production is known, the net biomass production can be calculated (FAO and IIASA, 1991). Equation 2 shows that the rate of net biomass production

Figure 4.2 Crop growth rate over time



Source: FAO (1978)

depends on the rate of gross biomass production and the respiration loss. So to calculate the net biomass production, the maximum rate of gross biomass production (bgm) and associated respiration loss need to be known.

Maximum rate of gross biomass production

Since photosynthesis is the main process of biomass production, the maximum rate of gross biomass production (bgm) depends on the maximum rate of photosynthesis (Pm). Pm in turn depends on incoming photosynthetically active radiation (PAR) and temperature.

The bgm each 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 (FAO and IIASA, 1991). De Wit (1965) presents the daily gross photosynthesis rate for completely overcast days (bo) and for very clear days (bc), as shown in Table 4.1. With the use of those values and the fraction of the daytime when the sky is overcast, bgm can be calculated as follows (FAO and IIASA, 1991):

- *bgm = F x bo + (1-F) bc* (4)

where:

» F = fraction of the daytime 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 per ha per day) (data from 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 per ha per day) (data from de Wit, 1965).

The fraction of daytime 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 and IIASA, 1991). De Wit (1965) has estimated the total amount of PAR on a very clear day (Ac) for the 0°, 10°, 20°, 30° and 40° northern latitudes, shown in Table 4.1. The present study assumes that these values are equal for the corresponding southern latitudes and that on a totally overcast day, only 20% as much PAR reaches the surface compared to a perfectly clear day. Since the PAR is 50% of incoming shortwave radiation, the fraction of daytime when the sky is overcast (F) is calculated as follows (FAO and IIASA, 1991):

- *F = (Ac – 0.5Rg) / 0.8 Ac* (5)

where:

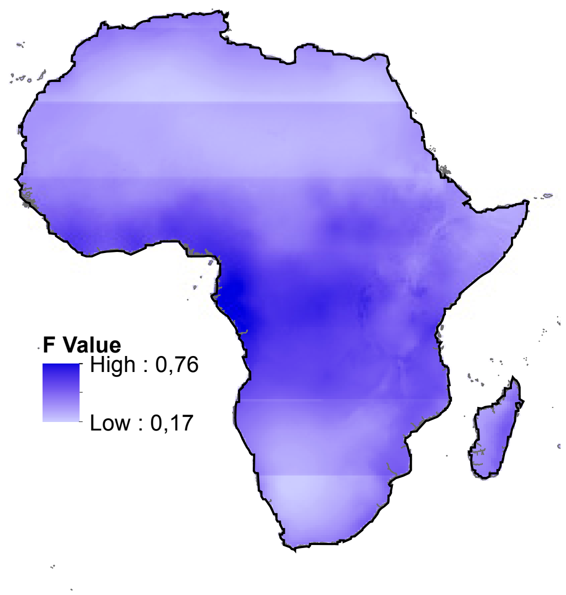
» F = fraction of daytime when the sky is overcast

» Ac = maximum incoming PAR on a clear day (de Wit, 1965)

» Rg = incoming shortwave radiation.

De Wit (1965) has calculated the values of bo and bc for plants with a photosynthesis rate of 20 kg CH_2O/ha/h. However, as stated before, the rate of photosynthesis depends on temperature. The

Figure 4.3 *F* value for Africa



Based on: Equations from FAO and IIASA (1991)

The boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

technical annex of the report by FAO and IIASA (1991) gives the relationship between temperature and rate of photosynthesis for the six adaptability classes, shown in Table 4.2. Based on actual case studies, FAO adjusts the bgm equation (Equation 4) for different photosynthesis rates as follows (FAO, 2017).

When *Pm* is greater than 20 kg CH_2O/ha/h, *bgm* is given by the equation:

- *bgm = F (0.8 + 0.01 Pm) bo + (1 - F) (0.5 + 0.025 Pm) bc* (6)

When *Pm* is less than 20 kg CH_2O/ha/h, bgm is calculated according to:

- *bgm = F (0.5 + 0.025 Pm) bo + (1 - F) (0.05 Pm) bc* (7)

Table 4.1 Values for Ac, bo and bc in northern latitudes

	Values of Ac, bc and bo												
North latitude		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

Source: De Wit (1965)

Table 4.2 Relationship between temperature and rate of photosynthesis (kg CH_2O/ha/hr)

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

Source: FAO and IIASA (1991)

Respiration loss

As Equation 2 shows, respiration loss is the other factor that is needed to calculate the net rate of biomass production. Respiration includes both growth respiration and maintenance respiration.

McCree (1974) shows that growth respiration is a linear function of the rate of gross biomass production (bg) and maintenance respiration is a linear function of net biomass that has already been accumulated (*B*) (FAO and IIASA, 1991). The equation of the respiration rate associated with the maximum rate of biomass production is therefore:

- $rm = k\ bgm + c\ Bm$ (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 between the two crop groups. At 30°C, factor *c* equals 0.0283 for a legume crop and 0.0108 for a non-legume crop (McCree, 1974). The temperature dependence of *c* for both crop groups is modelled with a quadratic function:

- $ct = c30\ (0.0044 + 0.0019\ T + 0.0010\ T^2)$ (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, synthesising and maintaining biomass that is richer in protein ends up being costlier in energy terms.

So if we know Bm, the net biomass that has accumulated when a plant reaches its maximum biomass production rate, then rm can be calculated. The GAEZ model (FAO, 2017) assumes that when a crop reaches the bgm rate, half of the 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 and IIASA, 1991):

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

where:

- » Bm = net biomass accumulated at the time of maximum rate of net biomass production
- » bnm = maximum rate of net biomass production
- » LGP = length of growing period.

Net biomass production

According to the equation of the rate of net biomass production (Equation 2), the maximum rate of net biomass production can be calculated by combining equations for gross biomass production (Equation 6) and respiration (Equation 8). Therefore, the maximum rate of net biomass production can be formulated as follows (FAO and IIASA, 1991):

- *bnm = 0.72 bgm / (1 + 0.25 ct * LGP)* (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.

Knowing bnm, the net biomass production can be calculated by using Equation 3 (FAO and IIASA, 1991). The net biomass production (*Bn*) for a crop growing *N* days can be derived as:

- *Bn = (0.36 bgm x L) / (1/N + 0.25 ct)* (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 = number of days the crop grows
- » ct = maintenance respiration, dependent on crop and temperature per Equation 9.

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

- *Yp = Hi x Bn* (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 of different short rotation wood crops depends mainly on air temperature and length of growing period (LGP) as diagrammed in Figure 4.4. This study applies a method for assessing climate suitability described in the GAEZ report annex (FAO and IIASA, 1991) with updated data sets.

Thermal suitability

As explained in Chapter 2, Section 1, temperature can affect photosynthesis, respiration and transpiration and therefore plays an important role in biomass production. 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.

Length of growing period suitability

The availability of water plays a key role in biomass production. The availability of moisture in the soil can be expressed by the LGP. This is the total number of days per year when precipitation exceeds half the potential evapotranspiration (FAO and IIASA, 1991), so that more water is added to the soil than evaporates. Dry periods and demand for water differ by species of SRWC (FAO and IIASA, 1991); some plants are more drought resistant than others (Singh, 2007). The Agro-Ecological Zones report (FAO and IIASA, 1991) provides information on the LGP SRWCs require (Table 4.4).

Figure 4.4 Climate suitability schematic overview

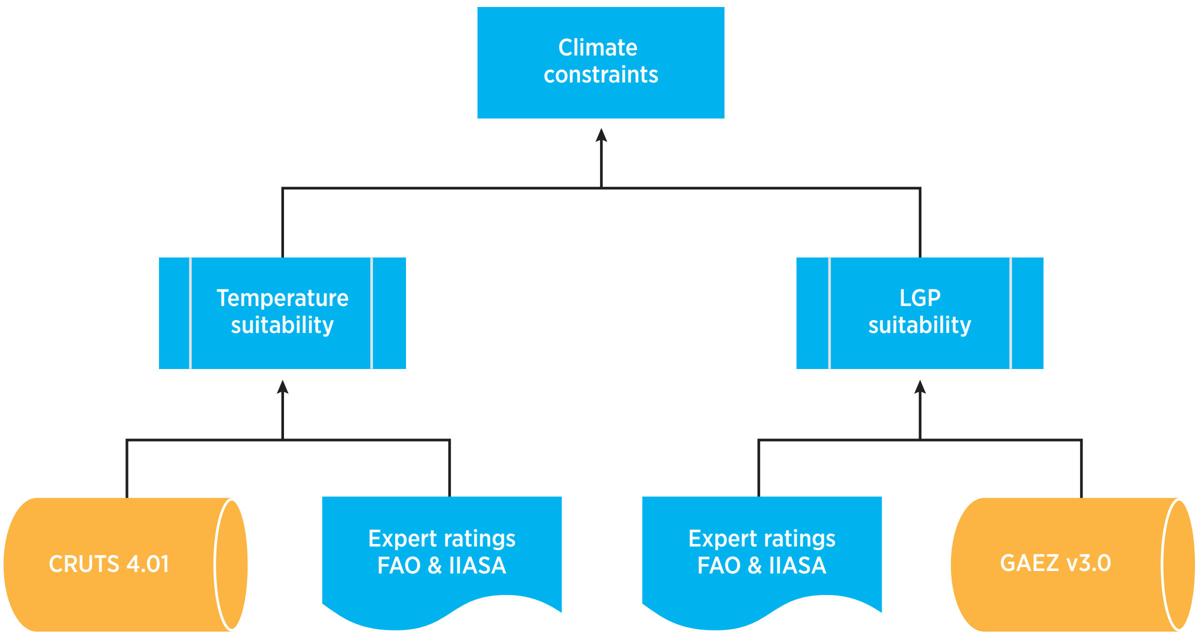


Table 4.3 Thermal suitability by species

		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**	**15.0 - 17.5**	**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%

Source: FAO (1991)

Table 4.4 LGP suitability for all species

	Length of Growing Period (LGP) (days per year)														
Species	**0**	**01 – 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 +**
AAL			■	■	■	■	■	■	■						
AGE					■	■	■	■	■	■	■				
ANI			■	■	■	■	■	■	■	■					
ASE			■	■	■	■	■	■	■						
ATO			■	■	■	■	■	■	■	■					
CCA								■	■	■	■	■	■	■	■
CEQ					■	■	■	■	■	■	■				
CCU						■	■	■	■	■	■	■	■	■	■
CLA			■	■	■	■	■	■	■	■					
CME						■	■	■	■	■	■				
GSE							■	■	■	■	■	■	■	■	■
GRO						■	■	■	■	■	■	■	■	■	■
LLE						■	■	■	■	■	■	■	■	■	■
SSE						■	■	■	■	■	■	■	■	■	■
TIN			■	■	■	■	■	■	■	■					

4.3 Soil suitability

The edaphic suitability analysis consists of the soil unit, soil texture and soil slope suitability. The first volume of the GAEZ report provides a soil unit and soil texture suitability rating for all mentioned SRWC species (FAO and IIASA, 1991). The soil slope suitability analysis is based on the ratings given by experts in the latest GAEZ report as shown in Figure 4.5 (FAO and IIASA, 2012).

Soil unit suitability

FAO and IIASA (1991) provide expert ratings of soil unit suitability for all SRWC species mentioned above. Soil units are given a rating or S1, S2, S3, S4 or NS and are weighted in the same way thermal suitability is weighted. The expert ratings are based on the FAO74 classification. However, HWSD soil unit data use a mix of FAO74 and FAO90 classifications. So, to apply the expert ratings, the present study converts soil unit data from FAO90 to FAO74 based on the study by Dewitte *et al.* (2013).

Soil texture suitability

As explained above, the texture of the soil influences SRWC biomass production. Soil fertility generally improves as grains of soil get smaller and worsens as grains of soil get larger. So all soil units with a coarse texture have their suitability rating reduced by one step (FAO and IIASA, 1991).

The HWSD provides information on the texture of the soil, giving soil a score of 3, 2 or 1, where 3 means coarse, 2 means medium-coarse and 1 means fine (FAO and IIASA, 2009). This is the case for all types of soil units, except for Andosols (Q, Qa, Qc, Qf, Qkc, Ql) and Vertic Arenosol (Tv) (FAO and IIASA, 1991). The area in Figure 4.6 that is outlined in red, toward the lower left point of the triangle, shows which soil textures limit biomass growth (FAO and IIASA, 2012).

Figure 4.5 Soil suitability schematic overview

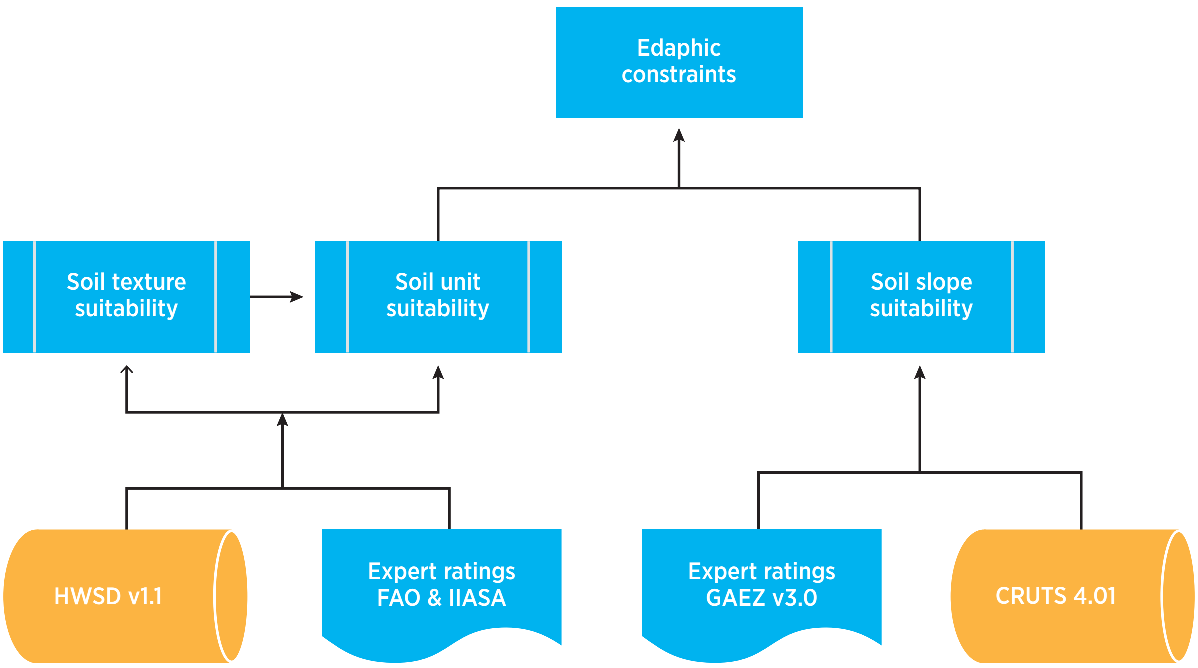
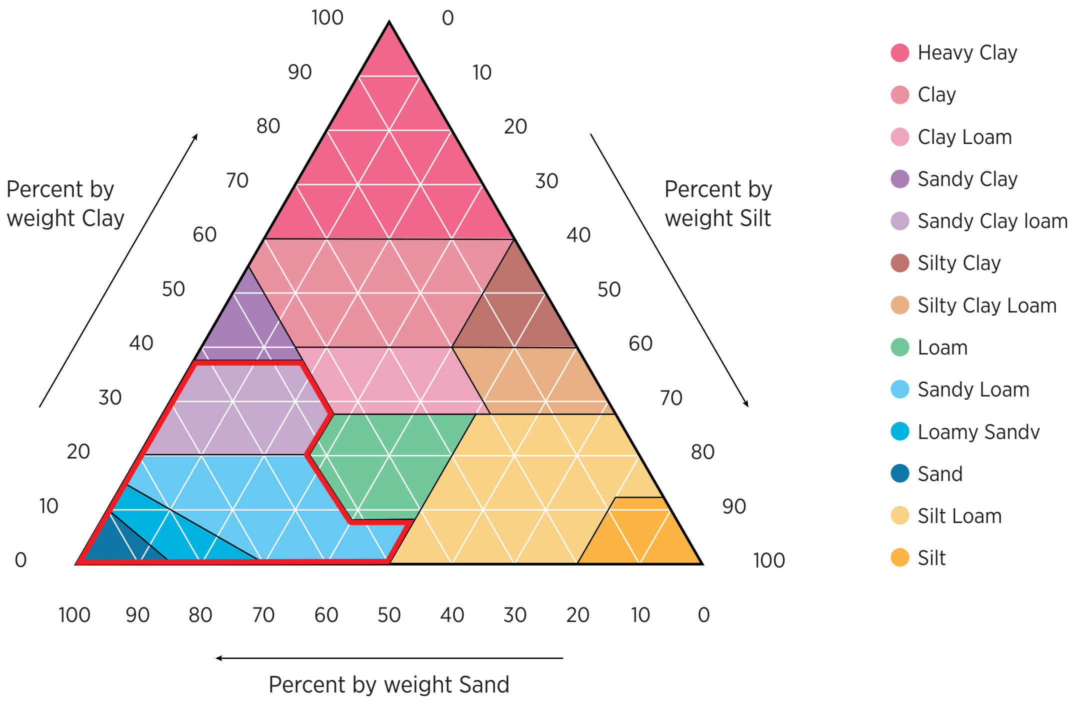


Figure 4.6 Coarse diagram of soil texture



Source: FAO and IIASA (2012); red outline of coarse soils added

Soil slope limitation

As explained earlier, terrain slope affects the growth potential of biomass. This is mainly due to the maximum angle at which a tree can grow and the loss of fertilisers and topsoil caused by runoff (Kramer and Boyer, 1995). FAO and IIASA (1991) set the maximum angle at which a plant may grow at 45%.

Rainfall, in particular the intensity of rainfall, is an important causation factor in runoff (FAO, 2017). Monthly rainfall data are available, but they do not directly address rainfall intensity. To account for 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 and IIASA, 2012) as follows:

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

» where P_i = precipitation in month *i*.

Based on the FM, FAO and IIASA (2012) have produced suitability ratings for a set of slope gradient classes. Table 4.5 provides an overview of the scores given by slope gradient.

Table 4.5 Slope suitability by slope gradient class

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%

Source: FAO and IIASA (2012)

4.4 Theoretical yield potential

The theoretical yield potential, or upper limit of biomass production as reduced by climate and soil constraints, can be calculated by the findings in steps 1, 2 and 3. 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 by the shares of climate and soil suitability.

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

where:

» Y_{th} = 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 local 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 are derived from the *Land Degradation Assessment in Drylands* report (Biancalani *et al*., 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 excluded from the theoretical yield potential map encompasses 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.

The remaining land use systems that are considered suitable for biomass production are:

- agricultural lands
    - crops, large-scale irrigation with moderate or higher livestock density
    - crops and moderately intensive livestock density
    - crops and high livestock density
    - agriculture – large-scale irrigation
    - rain-fed 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 – low livestock density
- barren areas
    - barren areas – unmanaged
    - barren areas – low livestock density
    - barren areas – moderate livestock density.

In agroforestry systems, SRWCs are planted alongside food crops and are therefore sharing the arable land. This research assumes that 20% of total suitable lands can be used for SRWC production in such systems, meaning that the remaining 80% can be used for food production.

4.6 Technical yield potential

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

- $Y_{te} = Y_{th} * LUS$

where:

- Y_{te} = technical yield potential (t/ha)
- Y_{th} = theoretical yield potential (t/ha)
- LUS = land use systems suitability (percentage).

The various steps to derive the technical yield potential from the unconstrained yield potential and technical yield potential are nicely Illustrated by the contrasting examples of *Sesbania*, a high-performing wood species in wet conditions, and *Acacia*, a high-performing wood species in dry conditions. The method starts with the unconstrained yield potential (Figure 4.7).

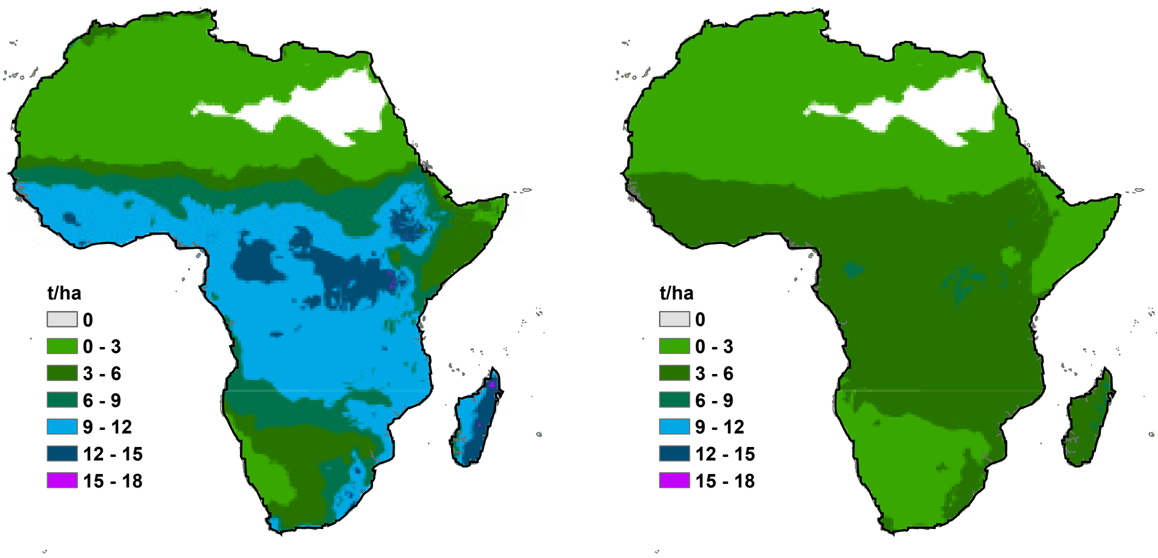
The yield potential is then controlled for climatic variables of temperature (Figure 4.8), growing period (Figure 4.9) and soil conditions (Figure 4.10) to arrive at a theoretical yield potential.

Figure 4.10 shows *theoretical* yield potential, after the application of climate and soil constraints. Figure 4.11 then filters for the availability of suitable lands to arrive at *technical* yield potential.

Figure 4.7 Unconstrained yield potential for *Sesbania* and *Acacia*

Constrain free production - Sesbania Sesban

Constrain free production - Acacia - Senegal

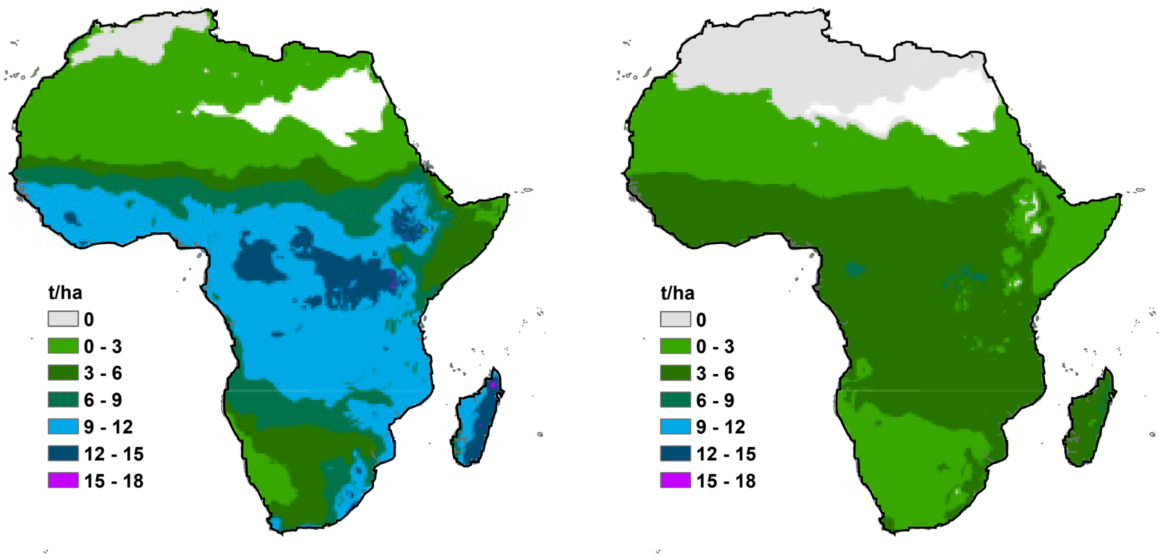


The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Figure 4.8 Temperature suitability constraint on *Sesbania* and *Acacia* yield

After Thermal Suitability - Sesbania Sesban

After Thermal Suitability - Acacia - Senegal

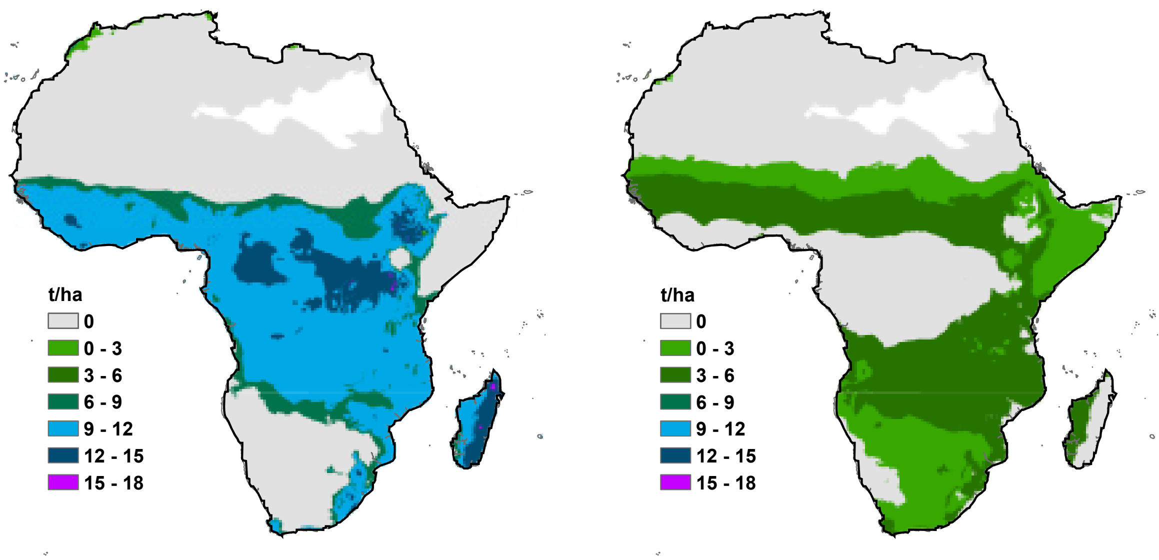


The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Figure 4.9 Length of Growing Period (LGP) constraint on *Sesbania* and *Acacia* yields

After LGP Suitability - Sesbania Sesban

After LGP Suitability - Acacia - Senegal

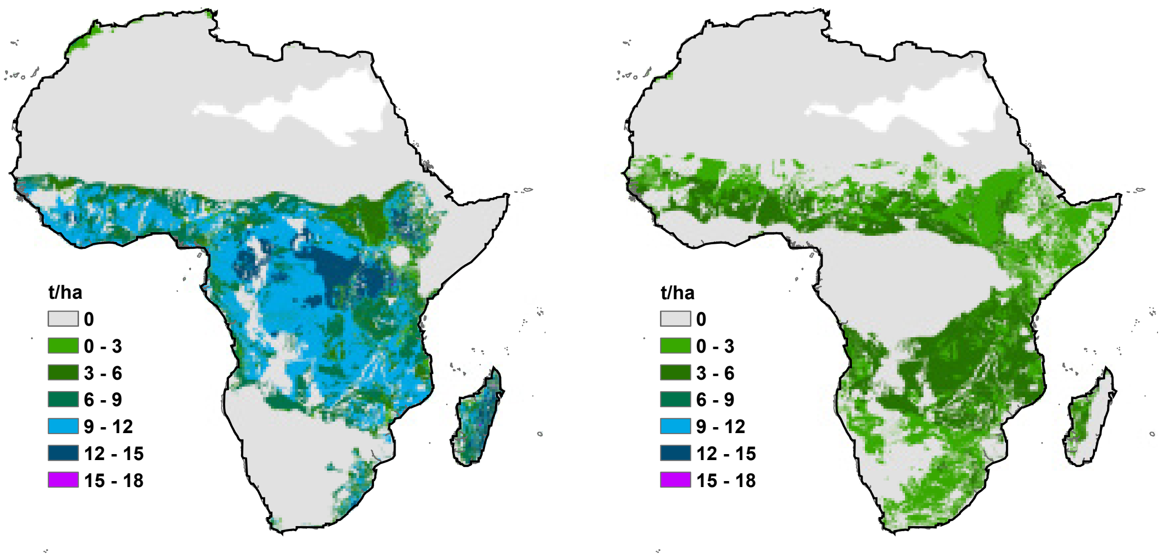


The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Figure 4.10 Soil suitability constraint on yields for *Sesbania* and *Acacia*

After Soil Suitability - Sesbania Sesban

After Soil Suitability - Acacia - Senegal

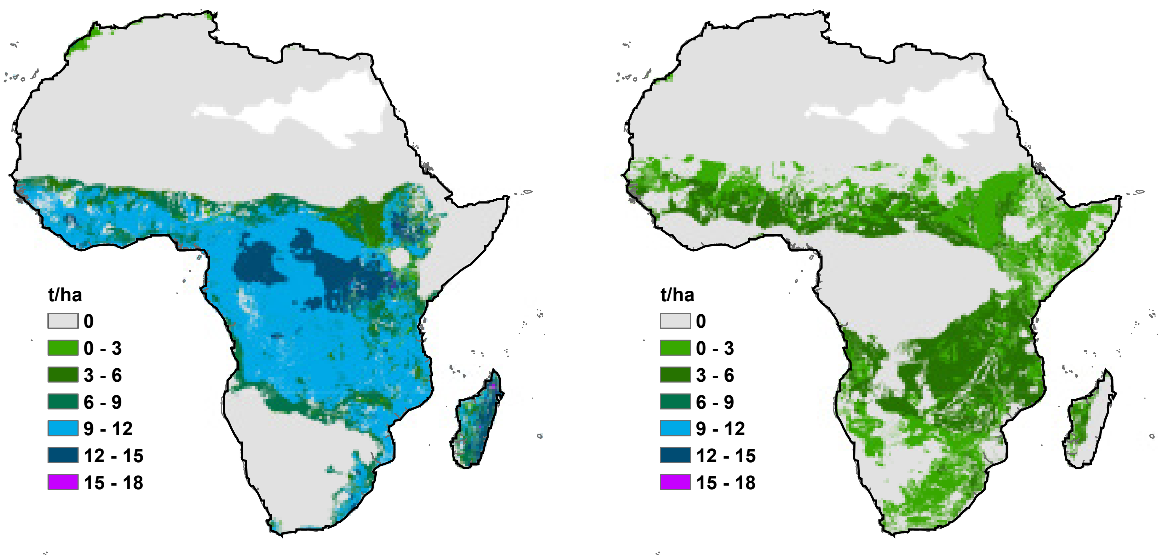


The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Figure 4.11 Technical yield potential for *Sesbania* and *Acacia* after applying land use constraints

Technical Potential - Sesbania Sesban

Technical Potential - Acacia - Senegal



The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

4.7 Selecting the highest yielding species

Once the suitable and available land for SRWC production is known, the last step of the analysis is to calculate the maximum achievable technical yield potential. Using Arcmap 10.5, technical potential maps were made, one for each SRWC species. The maps were then compared to select the species with the greatest biomass production potential in each area. In places where multiple species are equally productive, the species with the highest number of possible uses was selected. Table 4.6 lists the main uses to which species may be put and ranks the species in order of preference by number of potential uses.

Table 4.6 Preferred species based on utilisation options

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

Key

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
S = shading
Sb = shelterbelt
T = timber
Wb = windbreak

Source: FAO (1991)

4.8 Extra maize produced due to agroforestry practices

One of the major benefits of combining short rotation woody crops with food crops, as already noted, is the more efficient growth of the food crops. Such a combination can substantially increase biomass production without increasing land use.

Much of the literature on agroforestry practices is about woody crops combined with maize, a staple food crop. This raises the question of how much extra maize could be produced using agroforestry practices in Africa. Estimating this first requires identifying areas of current maize production that are also suited to agroforestry with SRWCs. An assumption must then be made about the effect of SRWCs on maize yields Finally, the extra maize that could be produced through agroforestry can be calculated.

Current maize production in Africa

To estimate the production growth of maize, a maize production baseline was identified. The GAEZ database provides detailed information on the areas that were used for maize growth and on the maize yields that were achieved in those areas for Africa in the year 2000. These data are therefore used for the base year of the calculations. By multiplying the maize yield per hectare with the area that is used for maize production, total maize production can be calculated:

» *Total maize production (t) = Maize yield (t/ha) x Area used for maize production (ha).*

To identify areas of maize cultivation that are also suitable for annually coppiced SRWCs, the GAEZ dataset can be superimposed upon the SRWCs dataset produced using Arcmap 10.5.

Increase of maize yield and output with agroforestry

To quantify the extra food that can be produced using agroforestry practices, the effect of agroforestry practices on maize yields must be estimated. However, only a few studies are available that assess how maize yields are boosted by agroforestry management systems. Moreover, many geographically specific factors affect the impact on maize yields. Among these are local soil and climate conditions, the type of woody crop that is intercropped with maize, and accepted harvesting practices. Reported values for increased maize yields therefore vary widely. The present study hypothesises that in typical circumstances, maize production will approximately double when planted alongside SRWC.

Potential maize production, including in agroforestry systems, is then calculated as follows:

Total maize produced =
Maize produced on soils not suitable for agroforestry +
(Maize produced on soils that are suitable for agroforestry) x (increase in maize yield per ha).

5 RESULTS

This study aims to provide insight on the performance of short rotation woody crops in agroforestry systems, taking account of local soil and climate conditions. Findings are reported in three parts:

1. Total available land and associated yields per hectare are analysed for each SRWC species.
2. Maximum yield potentials are mapped for Africa as a whole and assessed for four main land types: agricultural lands, shrub and grasslands, sparsely vegetated lands, and barren lands.
3. The potential effect of SRWCs in agroforestry systems on food production is evaluated.

5.1 Technical yield potential for all nitrogen-fixing species

Figure 5.1 shows the amount of suitable land available for each main SRWC in Africa, after climate, soil and land use restrictions are applied.

Due to differences in soil and climate suitability among the species, the total suitable area varies from 195 Mha for *Calliandra calothyrus* up to 423 Mha for *Tamarindus indica*. The average SRWC assessed has a suitable growing area of 355 Mha, of which somewhat less than half (158 Mha) is on agricultural land, somewhat more than half (184 Mha) is on shrub and grassland, and much smaller amounts are on sparsely vegetated or barren lands. The average suitable range for SRWCs comprises 62% of Africa's farmland (Slade *et al.*, 2011) and 20% of its pasture land (Slade *et al.*, 2011).

Figure 5.1 Land available for different nitrogen-fixing wood species in Africa

The total suitable area for SRWCs on sparsely vegetated lands and bare lands varies substantially by species. Only SRWCs that can tolerate a shorter growing period can practically be raised on such lands. For example, *Tamarindus indica* (TIN) has a greater range of suitable area than *Calliandra calothyrus* (CCA) after the LGP constraint is applied, as shown in Figure 5.2.

The mean yields per hectare that SRWCs achieve on suitable lands in Africa are shown in Figure 5.3. Most species have a relatively low mean biomass production per hectare, around 2 t/ha, which implies that the vast majority of the suitable area is not very productive. However, the range between minimum and maximum yields achieved for each species is relatively wide, which means that the productivity is location-dependent and may be high in some places even though it is low on average. Locational dependency is greatest for *Acacia gerrardii, Causarina cunninghamiana, Croton megalocarpus* and *Grevillea robusta,* whose maximum yield is almost four times greater than the mean.

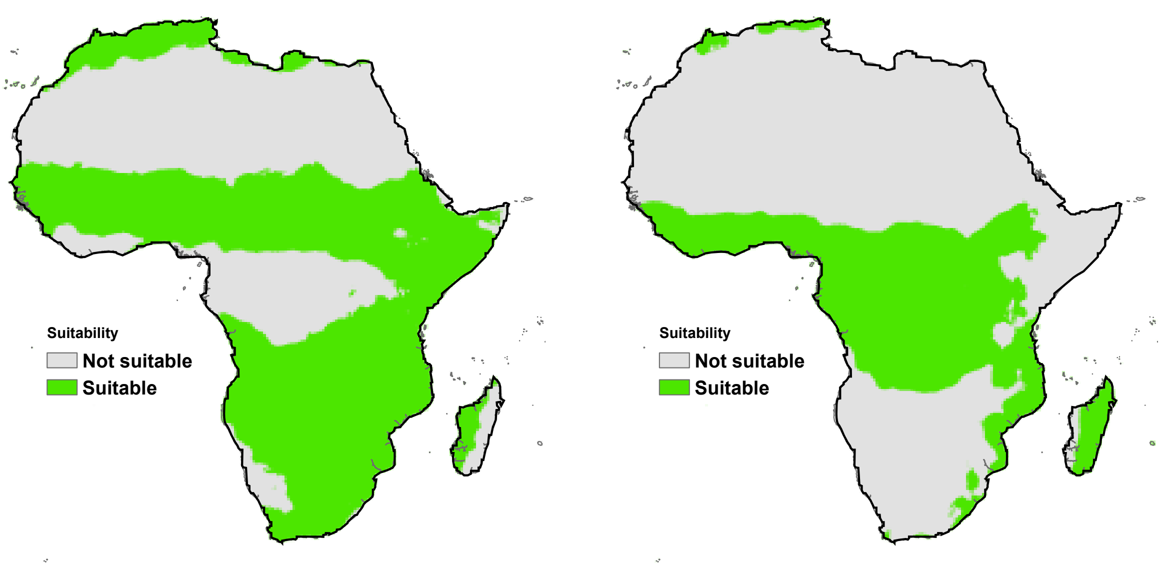
The main reason for different yields across species is different photosynthetic productivity. *Leuceana leucocephala* (LLE) and *Sesbania sesban* (SSE), in the class with the highest photovoltaic productivity, achieve the highest maximum and mean yields per hectare. *Casuarina cunninghamiana* (CCU) and *Casuarina equisetifolia* (CEQ), in the medium photovoltaic productivity class, achieve the third and fourth highest maximum yields, though mean yield of CCU is notably low due to poor thermal suitability. Other species, grouped in the lowest productivity class, achieve the lowest mean yields.

Using data on total suitable land area and mean yield per hectare, while assuming SRWCs take up 20% of each plot when planted together with food crops, production potential in agroforestry systems can be calculated for each species, shown in Figure 5.4. Most production potential comes from grasslands and agricultural lands. The most productive species is *Leuceana leucocephala* due to its high yields in agricultural lands. The average production potential for an individual species is 171 Mt per year.

Figure 5.2 LGP constraints on *Tamarindus indica* and *Caliandra colothyrus*

Suitable area after LGP suitability - TIN

Suitable area after LGP suitability - CCA



The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Figure 5.3 Mean yields of nitrogen-fixing wood species in Africa

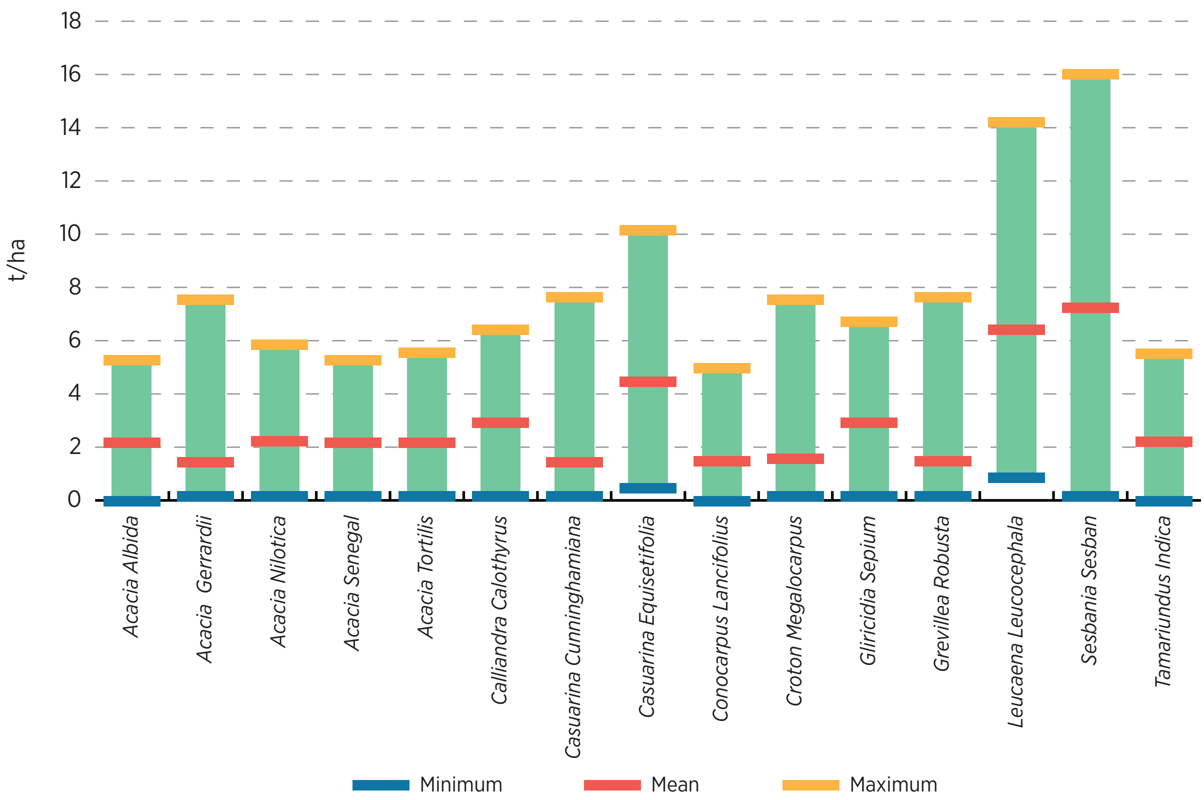
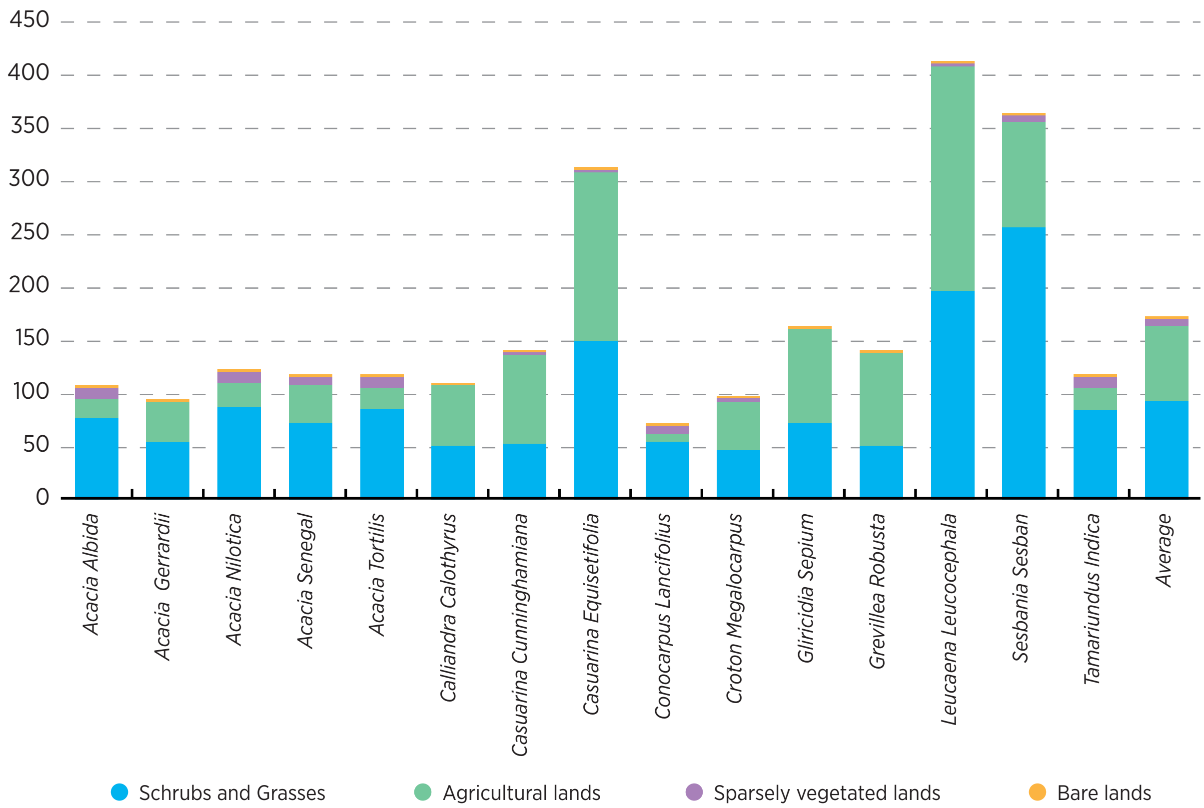


Figure 5.4 SRWC production in African agroforestry by species

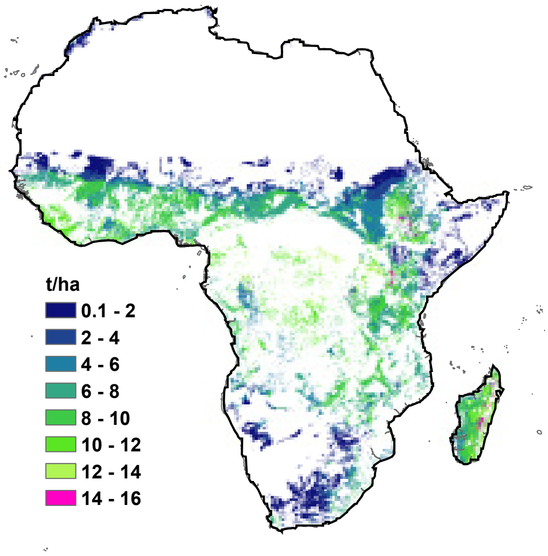


5.2 Selection of the most suitable species

By superimposing the maps of yield potential for nitrogen-fixing wood species, it is possible to evaluate which one has the highest yield in each location, as shown in Figure 5.5. The biomass potential of the best-performing species in Africa ranges from 0.1 t/ha 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 and land use systems and are therefore excluded from the analysis. The highest yields are achieved in Kenya, Ethiopia and Madagascar. Large areas of Sudan, Mali and South Africa have a relatively low yield; these areas have a low number of LGP days and are therefore classified as sparsely vegetated and bare lands.

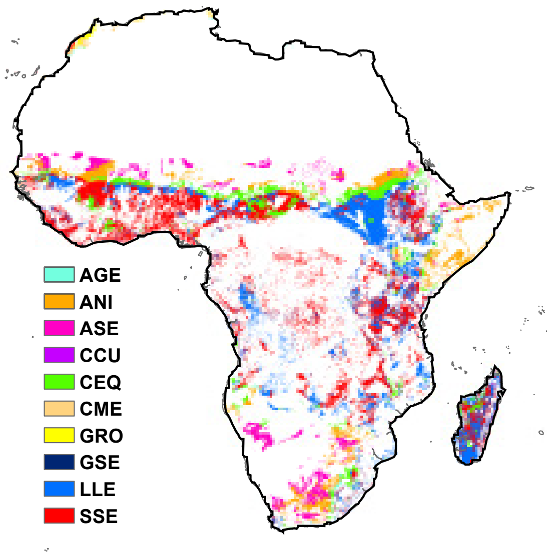
The species that achieve these yields are shown in Figure 5.6. Five species do not appear on the map because the other ten species achieve higher yields or provide material inputs to more products.

Figure 5.5 Maximum technical yield potential for SRWCs in Africa



Source: FAO/IIASA/ISRIC/ISS-CAS.JRC (2009)

Figure 5.6 Best-performing SRWC species in each part of Africa



Source: Ministry of Environment and Natural Resources (2016)

The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

- *Sesbania sesban* (SSE) and *Leuceana leucocephala* (LLE) are the two most striking species on the map. They have high yields per hectare due to their high photosynthesis rate. Differences in soil suitability explain most of the distribution between these two species; soils in eastern Africa are generally more suitable for LLE, while the soils in west Africa tend to be more suitable for SSE.
- *Casuarina equisetifolia* (CEQ) belongs to the second-best productivity class and is more drought resistant than SSE and LLE. It therefore achieves the highest yields in areas that do not meet the LGP-suitability criteria of SSE and LLE.

- *Acacia senegal* (ASE), *Acacia gerrardii* (AGE) and *Acacia nilotica* (ANI) belong in the lowest productivity group and are more prevalent in areas that have a short growing period. They also have a higher preference rank than other drought-resistant species.
- *Grevillea robusta* (GRO) and *Croton megalocarpus* (CME) are the dominant SRWC species in north Africa, which is relatively cold and thus not conducive to the growth of most other species.
- *Gliricidia sepium* (GSE) achieves the highest yield in west Congo. Some other species such as ASE achieve a similar yield per hectare but have fewer potential uses.

To clarify the potential for SRWC production in agroforestry systems, the potential is separately evaluated below for each of four main land use systems: agricultural land, grassland, sparsely vegetated land and barren land. Tables show the suitable land available and associated potential output for each land type. They distinguish among three levels of yield: low (less than 4 t/ha), medium (4 to 8 t/ha) and high (more than 8 t/ha). A figure is also provided for each land use type to show the ten countries with greatest SRWC potential on such land. Wood is assumed to take up 20% of the available land in a mixed agroforestry system on each type of land, with food crops taking up the rest.

Agricultural land production potential for SRWCs in Africa

Table 5.1 shows the agricultural land area suited to SRWCs and associated production potential in agroforestry systems by species. In all, SRWCs could be raised on some 48 Mha of agricultural lands in Africa, producing 325 Mt of wood per year. The largest share of available land has a mean yield above 8 t/ha and covers 19.27 Mha. With a total production potential of 219 Mt per year, *Sesbania sesban* (SSE) is the best-performing species 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 species with 65 Mt per year. Together they are responsible for 88% of the total production potential. *Acacia nilotica* and *Casuarina equisetifolia* have the greatest potential low-yield areas because they are the most drought resistant.

Figure 5.7 shows the ten African countries with the greatest SRWC production potential on agricultural lands. Nigeria has the greatest potential, at nearly 40 Mt per year, followed by Ethiopia, United Republic of Tanzania, Mali and the Democratic Republic of Congo. Half of the production potential of *Casuarina equisetifolia* (CEQ) is in Chad and Sudan.

Grasslands production potential for SRWCs in Africa

Table 5.2 shows the shrub and grassland area suited to SRWCs as well as the associated production potential in agroforestry systems by species. In all, SRWCs could be raised on some 55 Mha of grasslands in Africa, producing 349 Mt of wood yearly. *Sesbania sesban* is once again the species with the greatest potential, followed by *Leuceana leucocephala*. In areas with low yields, *Acacia senegal* has the greatest potential.

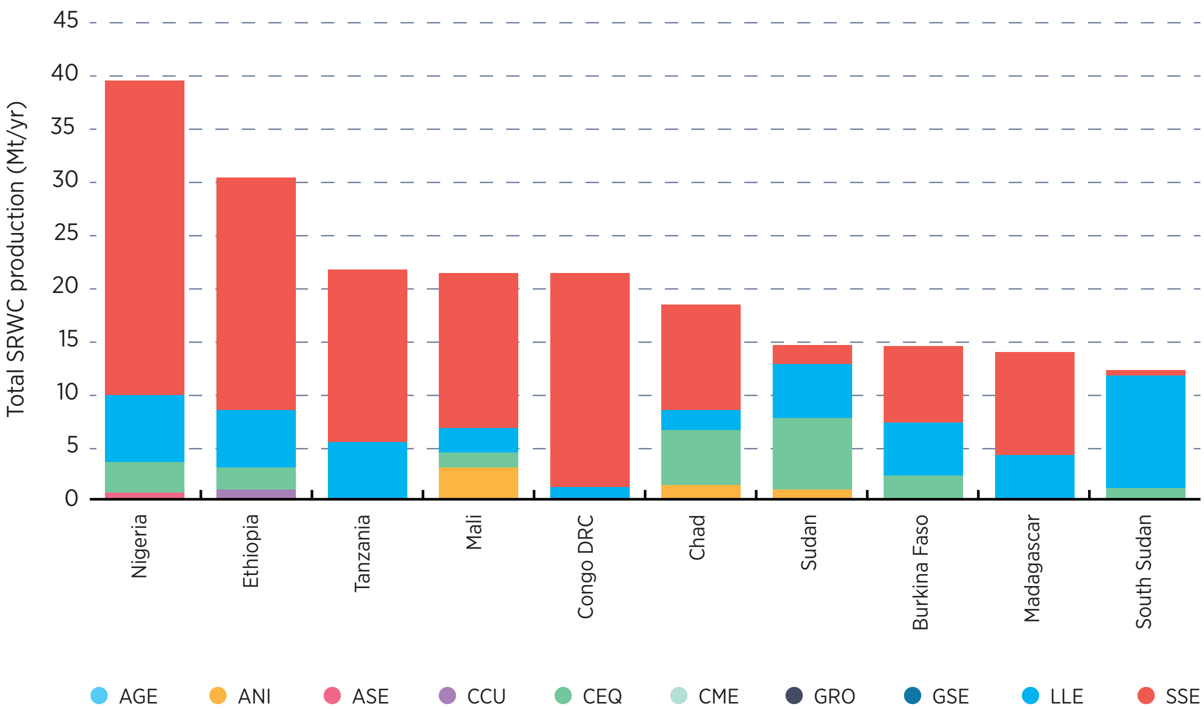
Figure 5.8 shows the ten African countries with the greatest SRWC production potential on shrubland and grassland. Madagascar is by far the best-performing country with a potential of more than 60 Mt per year; in addition, the climate and soil conditions are relatively good for the production of LLE and SSE. As the figure shows, the minimal achieved mean yield per hectare is 8 t/ha or higher in Madagascar.

Table 5.1 Performance of nitrogen-fixing wood species on agricultural lands

	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**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area

Figure 5.7 African countries with greatest SRWC production potential on agricultural lands



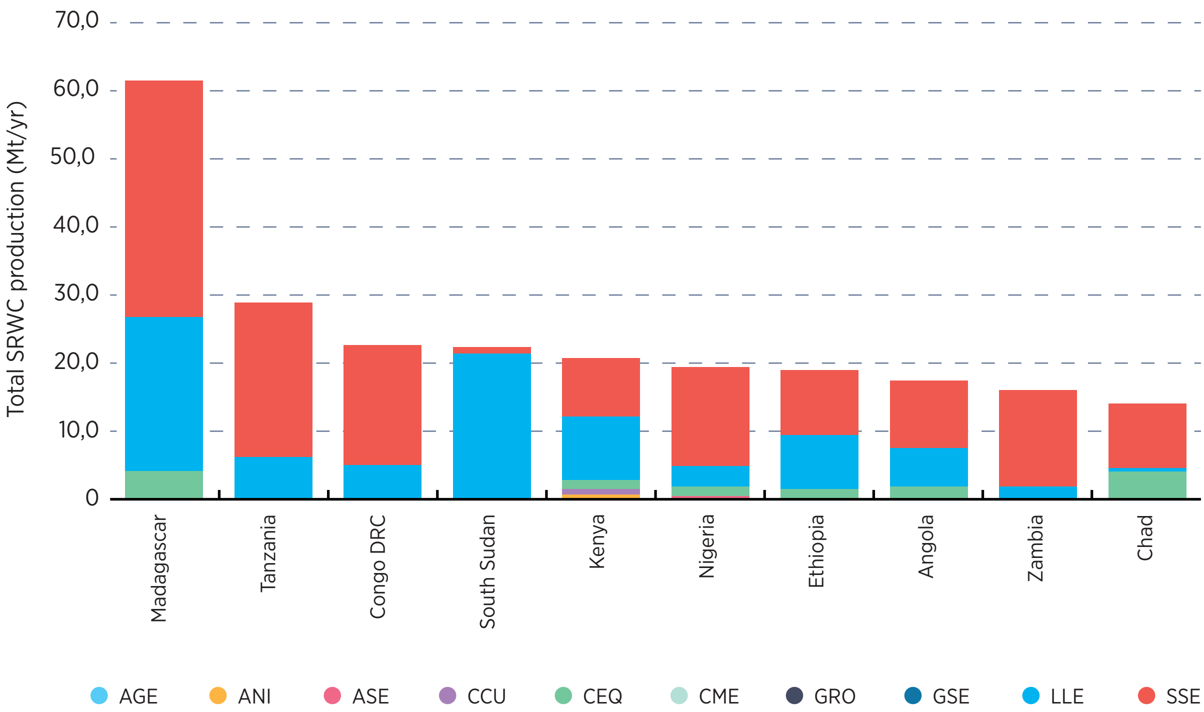
Note: "Congo DRC" is an abbreviation for Democratic Republic of the Congo.
Note: "Tanzania" is an abbreviation for United Republic of Tanzania.

Table 5.2 Performance of nitrogen-fixing wood species on grasslands

	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**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area

Figure 5.8 African countries with greatest SRWC production potential on grasslands



Note: "Congo DRC" is an abbreviation for Democratic Republic of the Congo.
Note: "Tanzania" is an abbreviation for United Republic of Tanzania.

Table 5.3 Performance of nitrogen-fixing wood species 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**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area

Figure 5.9 African countries with greatest SRWC potential on sparsely vegetated lands

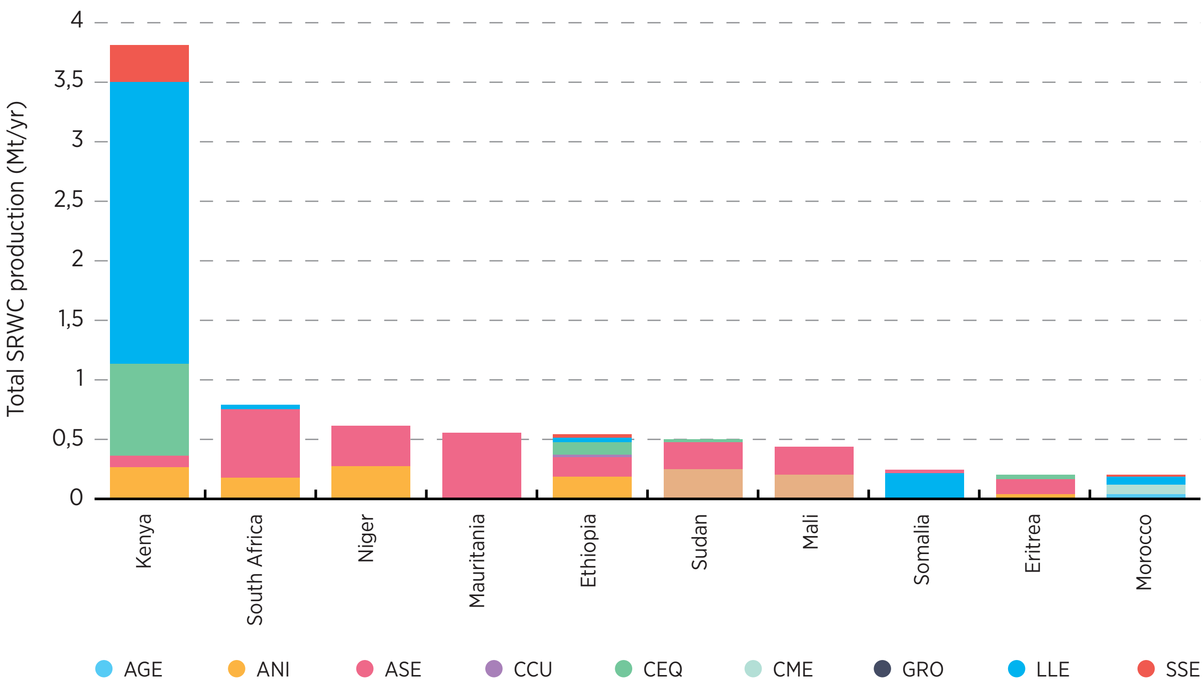
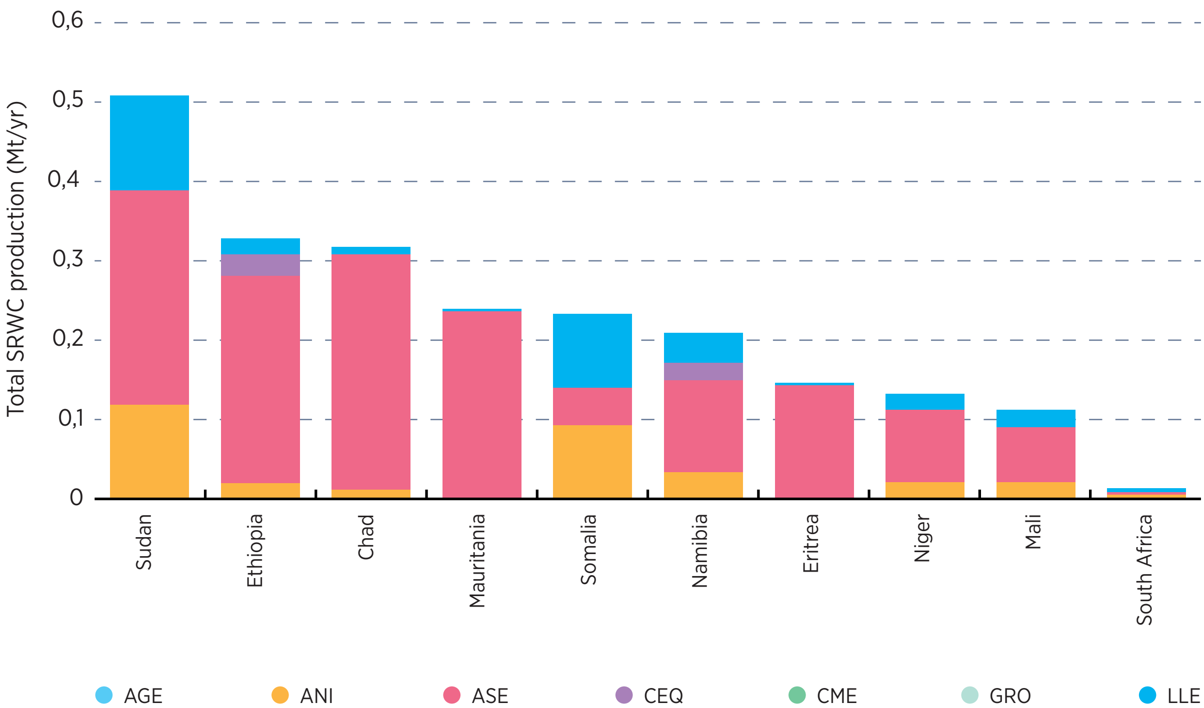


Table 5.4 Performance of nitrogen-fixing wood species on barren lands

	Barren 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**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area

Figure 5.10 African countries with greatest SRWC potential on barren lands



Sparsely vegetated lands production potential for SRWCs in Africa

Table 5.3 shows the sparsely vegetated land area suited to SRWCs and associated production potential by species. In all, SRWCs could be raised on some 5.2 Mha of sparsely vegetated lands in Africa, producing 8.0 Mt of wood per year. *Acacia nilotica* (ANI) has the most suitable land, while *Leucaena leucocephala* (LLE) has the greatest production potential. LLE could achieve greater production than ANI with less than half as much land because its mean yield is over three times higher (2.4 t/ha vs 0.7 t/ha). *Gliricidia sepium* (GSE) is the only species that has no potential on sparsely vegetated lands.

Figure 5.9 shows the ten African countries with the greatest SRWC production potential on sparsely vegetated lands. Kenya has by far the greatest potential, including 90% of the potential for LLE and CEQ. Both of these species can reach mean yields of more than 4 t/ha, indicating that the climate and soil conditions are reasonably good in these areas even though they are sparsely vegetated. *Acacia senegal* is the best-performing species in sparsely vegetated areas for other countries.

Barren lands production potential for SRWCs in Africa

Table 5.4 shows the barren land area suited to SRWCs and associated production potential by species. In all, SRWCs could be raised on some 2.8 Mha of barren lands in Africa, producing 2.3 Mt of wood per year. Two-thirds of the production potential is for *Acacia senegal* (ASE) at a low yield of less than 1 t/ha.

Figure 5.10 shows the ten African countries with greatest SRWC production potential on barren lands. The top nine account for 95% of the potential. Sudan has the most potential, about 0.5 Mt per year.

5.3 Selection of the most suitable wood species for growing with annual food crops

Food crops like maize require unimpeded access to sunlight for optimal growth. As wood crops mature, access to sunlight can be restricted by their expanding leaf cover. To avoid this situation, a typical strategy is to coppice the wood crops on an annual basis. With intercropping of gliricidia and maize in Zambia, for example, the gliricidia is harvested each year at the end of the 8-month dry season, allowing the maize to grow in full sunlight during the 4-month rainy season, and the maize is then harvested so that food yields are not affected by further growth of the trees.

However, not all SRWCs can be coppiced in this fashion, as not all are able to sprout and grow again easily once they are cut down. Among the 15 nitrogen-fixing species examined, experience has shown that five are suitable for annual coppicing. These are *Gliricidia sepium, Leuceana leucocephala, Acacia nilotica, Acacia senegal and Calliandra calothyrus* (FAO and IIASA, 1991; Sileshi, 2018).

With yearly coppicing, the crowns of the trees are less well developed than when the trees are fully grown. The leaf area index (LAI) of annually coppiced trees is therefore assumed to be reduced from 3.5 (as in the previous analysis) to 2.0. The output is reduced proportionately.

By superimposing the maps of yield potential for the five coppice-friendly SRWC species, it is possible to evaluate which one has the highest yield in each location, as shown in Figure 5.11. Since annual coppicing reduces the leaf area available for photosynthesis, it substantially reduces wood yields. The solid biomass potential of the best-performing species in Africa ranges from less than 1 t/ha to 3.5 t/ha with coppicing, instead of up to 16 t/ha without coppicing. Again, countries around the equator achieve the highest yields: in particular, Kenya, Ethiopia and Madagascar.

The species that achieve these yields are shown in Figure 5.12. *Calliandra callothyrus* doesn't appear because the other four species achieve higher yields or provide material inputs to more products.

- *Leuceana leucocephala* is the best performing coppice-friendly species. It has high yields per hectare due to its high photosynthesis rate.
- With fewer species included in the analysis, *Gliricidia sepium* is more often selected as the best performing species.
- *Acacia senegal* and *Acacia nilotica* are more drought resistant than *Leuceana leucocephala* and are therefore more dominant in the arid regions of Africa.

As for SRWCs in general above, the potential for coppice-friendly species is separately evaluated below for each of four main land use systems: agricultural land, grassland, sparsely vegetated land and barren land. The tables show the suitable land of each type and associated mean yield.

Figure 5.11 Maximum technical yield potential for coppice-friendly SRWC in Africa

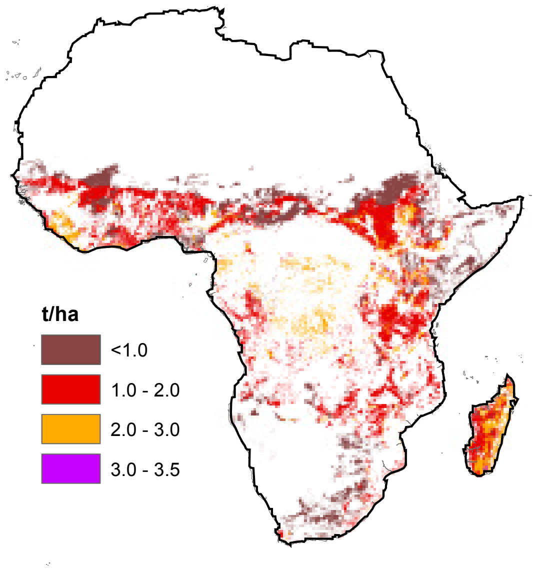
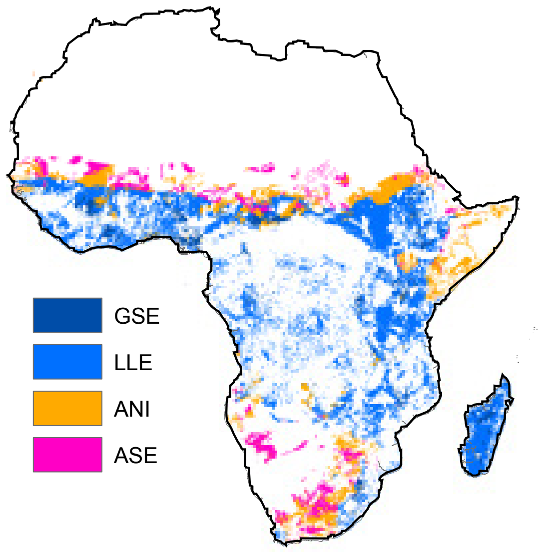


Figure 5.12 Best performing SRWC species with annual coppicing in each part of Africa



The boundaries and names shown on these maps do not imply any official endorsement or acceptance by IRENA.

Agricultural lands' potential for SRWCs in Africa with yearly coppicing

Table 5.5 shows the agricultural land suited to SRWCs with good yearly coppicing ability, along with associated production potential in agroforestry systems by species. A total of 46.7 Mha of agricultural lands are found to be suitable for SRWC production with yearly coppicing. This could potentially produce some 59.8 Mt of wood per year. With the most suitable land, highest mean yield, and potential production of 47.8 Mt, *Leuceana leucocephala* is the best performing species. *Acacia nilotica* is the second best performing species, mainly due to its drought resistance.

Grasslands' potential for SRWCs in Africa with yearly coppicing

Table 5.6 shows the shrub and grassland area suited to SRWCs with annual coppicing ability, as well as the associated production potential in agroforestry. In all, SRWCs could be raised with annual coppicing on some 55 Mha of grasslands in Africa, producing 68 Mt of wood yearly. *Leuceana leucocephala* is once again the species with the greatest potential, followed by *Acacia nilotica*.

Table 5.5 Performance of coppice-friendly SRWCs on agricultural lands

Agricultural lands			
Species	**Total suitable area (Mha)**	**Mean yield (t/ha)**	**Total production (Mt)**
GSE	2.7	0.8	2.3
LLE	29.9	1.6	47.8
ANI	10.4	0.7	7.4
ASE	3.7	0.6	2.3
Total	**46.7**	**1.3**	**59.8**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area.

Table 5.6 Performance of coppice-friendly SRWCs on grasslands

Shrubs and grasslands			
Species	**Total suitable area (Mha)**	**Mean yield (t/ha)**	**Total production (Mt)**
GSE	3.7	0.9	3.2
LLE	34.5	1.6	54.8
ANI	9.5	0.7	6.3
ASE	6.9	0.6	4.0
Total	**54.7**	**1.2**	**68.3**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area.

Sparsely vegetated lands' potential for SRWCs in Africa with yearly coppicing

Table 5.7 shows the sparsely vegetated area suited to SRWCs with yearly coppicing and the corresponding production potential. SRWCs could be raised with yearly coppicing on some 4.9 Mha of sparsely vegetated lands in Africa, producing 1.9 Mt of wood per year. The best performing species are *Acacia senegal*, *Leuceana leucocephala* and *Acacia nilotica*. *Leuceana* achieves the highest yields, but has less suitable land available than the *Acacia* species, which are more drought resistant.

Barren lands' potential for SRWCs in Africa with yearly coppicing

Table 5.8 shows the barren land suited to SRWCs and associated production potential by species. In all, SRWCs could be raised on some 2.2 Mha of barren lands in Africa, producing 1.3 Mt of wood per year. *Acacia senegal* is once again the best performing species. While *Gliricidia* and *Leuceana* have the highest mean yields on barren lands, very little area on such lands is suited to them.

Table 5.7 Performance of coppice-friendly SRWCs on sparsely vegetated lands

Sparsely vegetated			
Species	**Total suitable area (Mha)**	**Mean yield (t/ha)**	**Total production (Mt)**
GSE	0.0	1.5	0.0
LLE	0.4	1.6	0.6
ANI	2.5	0.2	0.6
ASE	2.0	0.4	0.7
Total	**4.9**	**0.4**	**1.9**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area.

Table 5.8 Performance of coppice-friendly SRWCs on barren lands

Barren lands			
Species	**Total suitable area (Mha)**	**Mean yield (t/ha)**	**Total production (Mt)**
GSE	0.0	0.9	0.0
LLE	0.0	1.6	0.0
ANI	0.6	0.7	0.4
ASE	1.6	0.6	0.9
Total	**2.2**	**0.6**	**1.3**

Note: Suitable land available for SRWCs is shown as 20% of suitable land area.

5.4 Potential boost to food and fuel production

Agroforestry systems can confer several benefits for local environments. They can improve soil quality, reduce soil erosion and increase available soil moisture (Young, 1990). Research shows that due to such benefits, agroforestry can achieve food yields similar to or greater than those obtained with artificial fertiliser (Sarvade *et al.*, 2014). In addition, the ecological benefits of agroforestry can also facilitate conversion of degraded lands into arable lands (Hillbrand, 2017). In this light, the potential can be evaluated for SRWCs to boost both food and fuel production.

More efficient land use

Agroforestry systems can substantially raise food yields per hectare in a developing country context, providing a boost similar to commercial fertiliser, which poor farmers cannot readily afford. As noted in the introduction above, intercropping of *Gliricidia* with maize in Zambia raised yields by 68% in sandy clay and 118% in loam after four years (CIMMYT, ZARI and COMACO, 2016*).* Compared with unfertilised 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). Interplanting *Acacia albida* with millet, yields can improve up to 600% (Charreau and Poulain, 1963). In view of such examples, it seems reasonable to suppose that SRWCs could typically double food yields.

As explained above, the total suitable land for SRWC production on agricultural lands in Africa is approximately 240 Mha. The total arable land in Africa is estimated at 253 Mha (Slade *et al.*, 2011). This means that almost 95% of the arable land is suitable for SRWC production in agroforestry systems.

Potential for food and fuel on arid lands

Since agroforestry systems raise the availability of water in the soil, they can lengthen the growing period and raise food production in arid areas (Ministry of Environment and Natural Resources, 2016). FAO and IIASA (2012) define arid areas as those with LGP of less than 60 days per year. Africa has 4.9 Mha of arid agricultural land that is suitable for SRWCs, including 1.8 Mha in South Africa. Figure 5.13 shows the African countries with the most suitable lands for agroforestry in arid areas.

Potential for food and fuel on degraded lands

Improved soil quality, reduced erosion and increased water availability are three benefits of agroforestry systems that are essential in order to restore degraded lands (Hillbrand, 2017). Some 26 Mha of sparsely vegetated lands and 14 Mha of barren lands are suitable for nitrogen-fixing SRWCs. Assuming that 20% of the suitable land plots were occupied by SRWCs, agroforestry systems could thus newly enable 21 Mha of sparsely vegetated land and 11 Mha of barren lands to produce food crops. Figure 5.14 shows the ten countries in Africa with greatest agroforestry land restoration potential.

Extra maize production on agricultural land

According to the GAEZ database, African farmers raised 34.2 Mt of maize on 23.9 Mha of land in the year 2000. Approximately 64% of the area used for maize production is also suitable for the growth of SRWCs. This means there is 15.3 Mha of maize land with practical potential for agroforestry.

Figure 5.13 Total agricultural area suitable for SRWC in arid countries of Africa

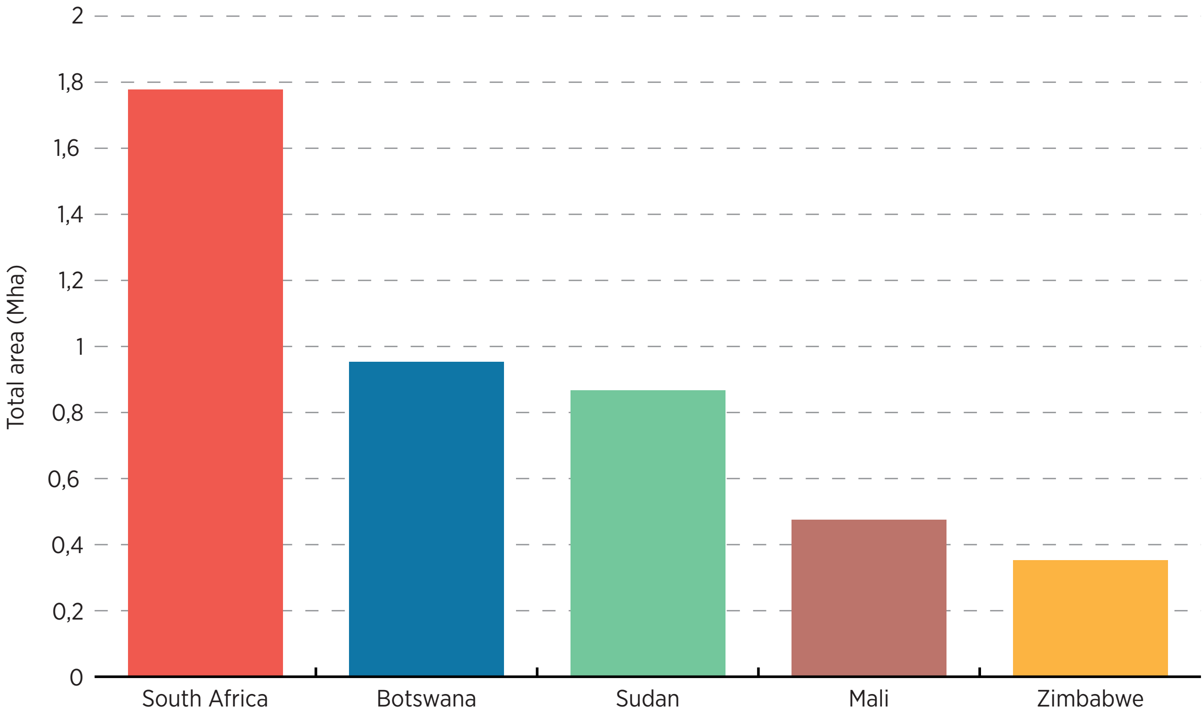


Figure 5.14 African countries with greatest land restoration potential

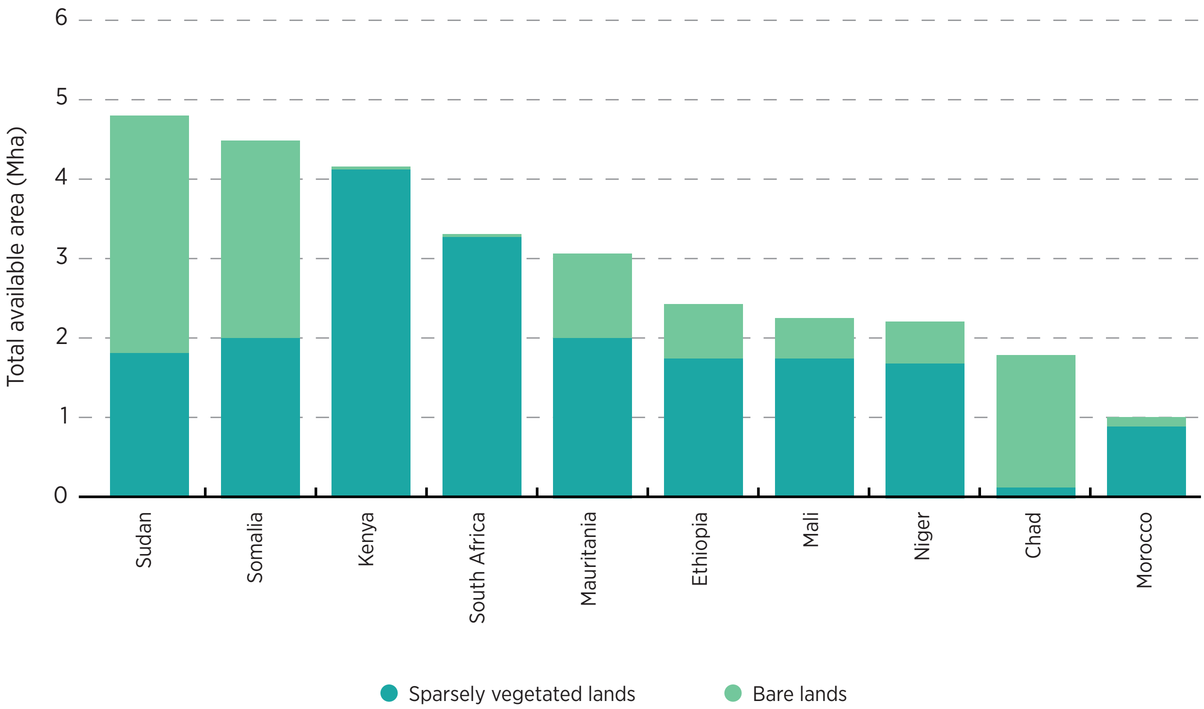


Table 5.9 shows how agroforestry could boost production of maize and wood in most countries of Africa. The first column shows actual maize production in 2000. The second column shows the share of land on which maize is grown that is also suited to SRWCs. The third and fourth columns show how much maize and wood could be produced if SRWCs were interplanted on all such maize land. Under the rough assumption that naturally fertilising SRWCs let maize yields per hectare double, maize output would be boosted by more than half, yielding some 21.6 Mt of extra maize and 2.9 Mt of wood.

Depending upon market prices, maize farmers might choose a different production mix. Because of increased yields, they could produce the same amount of maize as before by applying agroforestry to 61% of their land, or 9.4 Mha. Then they would be free to plant other food or energy crops on the 39% of the land left over, or 5.9 Mha. If they chose fast-growing wood or grass crops with a notional yield of 5 to 10 t/ha, there could be some 30 to 60 Mt of additional associated bioenergy feedstock potential.

Table 5.9 Potential wood and maize production through agroforestry in Africa

Country	Year 2000 without agroforestry	Area suitable for agroforestry practices (%)	Potential production with agroforestry practices	
	Maize produced (kt)		Maize produced (kt)	SRWC produced (kt)
Algeria	0.6	31%	0.6	0
Angola	414	60%	579	38
Benin	732	50%	1 221	87
Botswana	15	65%	26	2.9
Burkina Faso	495	75%	842	44
Burundi	124	33%	221	15
Cameroon	740	8%	1 179	29
CAR*	100	61%	111	1.4
Chad	88	75%	143	9
Congo	6	49%	11	1.3
Côte d'Ivoire	577	26%	904	30
DRC**	1 187	32%	1 541	103
Equatorial Guinea	0	0%	0	0
Eritrea	10	63%	17	0.3
Eswatini	105	12%	119	1.1
Ethiopia	2 828	62%	4 688	136
Gabon	26	31%	38	1.4
Gambia	23	72%	43	0.9
Ghana	997	61%	1 736	122
Guinea	326	17%	370	8
Guinea-Bissau	25	31%	36	1.6
Kenya	2 398	74%	4 321	298
Lesotho	125	51%	181	8
Liberia	1.0	53%	1.4	0.1
Madagascar	173	88%	332	62
Malawi	2 147	66%	3 893	299
Mali	383	87%	731	55
Mauritania	2.0	56%	3.2	0.1
Morocco	93	0%	93	0
Mozambique	1 128	26%	1 601	103
Namibia	15	23%	18	0.4
Niger	2.9	10%	3.7	0.1
Nigeria	4 742	56%	7 996	601
Rwanda	66	87%	126	12
Senegal	87	76%	161	6
Sierra Leone	9	62%	15	1.9
Somalia	72	61%	130	2.6
South Africa	7 235	44%	11 105	104
Sudan	10	62%	17	1.2
South Sudan	41	85%	78	10
Tanzania***	2 490	58%	4 274	292
Togo	499	63%	880	59
Uganda	1 120	42%	1 739	82
Zambia	937	61%	1 595	113
Zimbabwe	1 695	46%	2 780	156
Total	**34 291**	**64%**	**55 902**	**2 899**

*Central African Republic **Democratic Republic of the Congo ***United Republic of Tanzania

6 DISCUSSION AND CONCLUSIONS

Agroforestry practices in which nitrogen-fixing wood crops are planted alongside food crops hold substantial potential to increase both food and fuel production in Africa. The wood crops not only enhance soil nitrogen content, but also boost soil water retention and reduce soil erosion. Hence, they can boost food crop yields and produce wood for energy without requiring an increase in land use.

An algorithm can be applied to calculate technical yield potential for each square kilometre of the continent based on publicly accessible data on climate, soil, urban infrastructure and protected areas. In applying this algorithm to 15 nitrogen-fixing SRWCs, differences in climate and soil suitability evidently result in different production potentials for each species. Roughly three-fifths of the agricultural land and one-fifth of the pastureland in Africa are suitable for growing each species on average. However, selecting the highest-yielding species in each location, about 95% of the agricultural land and 30% of the pastureland is suitable. Some 555 Mha of land in Africa is suited to SRWC production, including 240 Mha of agricultural land. The technical potential for wood production on this land is some 684 Mt per annum, including 325 Mt on agricultural land, when plants reach maturity.

Of the land suited to SRWC production, 15 Mha is also suited to maize production. Based on a review of the limited literature, the introduction of SRWC on this land could roughly double maize yields per hectare. That could boost maize production by 22 Mt (from 35 Mt to 57 Mt) each year, while also providing 3 Mt of wood. However, this can be regarded as only a rough indication of potential until more detailed research can be done on the impacts of nitrogen-fixing wood crops on maize yields in different locations, with a variety of different climate and soil conditions and farming practices.

The method for calculating SRWC yields could also be refined in several respects to give farmers better advice on which wood species to consider planting. Firstly, the calculation of constraint-free biomass yields could add a variable for carbon dioxide concentration, which has a large effect on plant growth (Bruhn, 2002; Backlund, Janetos and Schimel, 2008). Secondly, the ratings of climate and soil suitability that are used to evaluate theoretical biomass yield potential could be updated and validated. Thirdly, yield potentials could be better calculated with higher-resolution input data for gross biomass production on clear and overcast days, which is key to constraint-free potential, as well as for temperature, precipitation and LGP, which affect species' climate suitability.

In terms of assessing additional potential for food and fuel production, it would be worthwhile to research how agroforestry systems may deviate from the present study's assumption that 20% of the land area is planted with wood and 80% with food. The share of trees depends on the function and design of the system. For example, agroforestry systems producing mainly timber wood have a larger share of SRWCs than those producing mainly food (Unruh, Houghton and Lefebvre, 1990).

Another vital step is to develop a better understanding of the economic potential for putting the technical potential in place. This depends not only on the benefits of SRWC production, which are apt to be greatest where yields are highest, but also on the costs of production, which vary according to local costs for labour and machinery (Eppler, 2007) and the difficulty of the terrain (FAO and IIASA., 2012).

Finally, the ability to put agroforestry systems in place depends upon local support and acceptance (Hillbrand, 2017). Public acceptance of change to traditional agricultural systems can be a bottleneck in some areas (Ordonez *et al.*, 2014). Success thus requires active engagement with stakeholders.

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GLOSSARY

Short rotation woody crops: Tree species that have been bred and selected to have extremely high rates of growth, allowing them to be harvested after a short growing period.[1]

Agroforestry: Land use systems or practices in which trees are deliberately integrated with crops and/or animals on the same land management unit.[2]

Nitrogen-fixing wood crops: Tree species that are able to fix nitrogen from the atmosphere into the root system of the tree.

Global agro-ecological zones: Global agro-ecological zones are geographical areas exhibiting similar climatic conditions that determine their ability to support rain-fed agriculture.[3]

Maximum rate of photosynthesis (Pm): The theoretical maximum speed at which the process of photosynthesis can occur within a plant.

Length of growing period (LGP): The total amount of days per year when precipitation exceeds half the potential evapotranspiration.[4]

Theoretical yield potential: The upper limit of biomass production allowed by soil and climate conditions.[5]

Technical yield potential: The portion of theoretical potential that is available within suitable land use systems.[5]

Climate suitability: The effects that temperature and water availability have on SRWC development.

Soil suitability: The effects that soil quality, soil texture and soil slope have on SRWC development.

Photosynthetically active radiation (PAR): The part of the incoming solar radiation that has wavelengths between 400 and 700 nanometres. This part of the spectrum activates the hotosynthesis process within plants.[6]

Land restoration: The process of assisting the recovery of an ecosystem that has been degraded. Restoration seeks to re-establish the pre-existing ecological structure and function.[7]

Marginal land: Land of low agricultural value due to soil, climatic or geographic constraints that limit productivity.

1 Derived from Genera Energy website: https://generaenergy.com/short-rotation-woody-crops/.

2 Leakey, R.R.B. (1996), "Definition of agroforestry revisited", Agroforestry Today, Vol. 8, No. 1, pp. 5-7. https://www.researchgate.net/publication/284100284_Definition_of_agroforestry_revisited.

3 See also FAO Forest Resources Assessment Programme (FRA) Terms and Definitions 2015, www.fao.org/docrep/017/ap862e/ap862e00.pdf.

4 HarvestChoice (2010), "Agro-ecological Zones of sub-Saharan Africa", International Food Policy Research Institute, Washington, DC and University of Minnesota, St. Paul, http://harvestchoice.org/node/8853.

5 FAO and IIASA (2012), Global Agro-ecological Zones (GAEZ): Model Documentation, 1-179.

6 Smeets, E.M.W. et al. (2007), "A bottom-up assessment and review of global bio-energy potentials to 2050", Progress in Energy and Combustion Science, Vol. 33, No. 1, pp. 56-106, https://doi.org/10.1016/j.pecs.2006.08.001.

7 ALS Association (2014), Environmental Factors, www.alsa.org/research/about-als-research/environmental-factors.html.

APPENDIX

YIELD POTENTIALS FOR 15 NITROGEN-FIXING WOOD SPECIES IN AFRICA

Maps in this report, including the present appendix, do not imply any official endorsement or acceptance by IRENA in regard to country names, borders, territorial claims or sovereignty.

Figure A-1: Yield potentials for *Acacia albida*

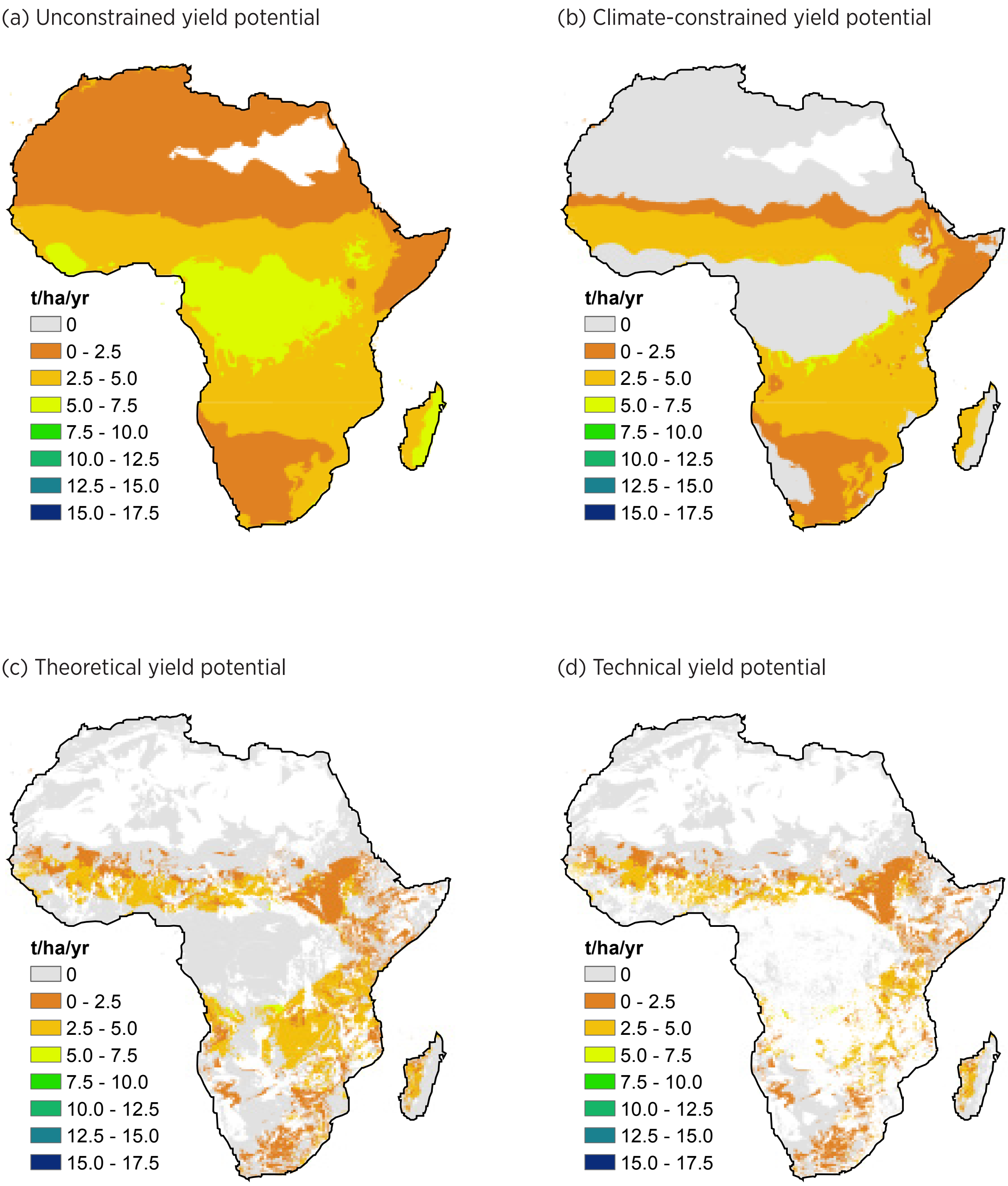
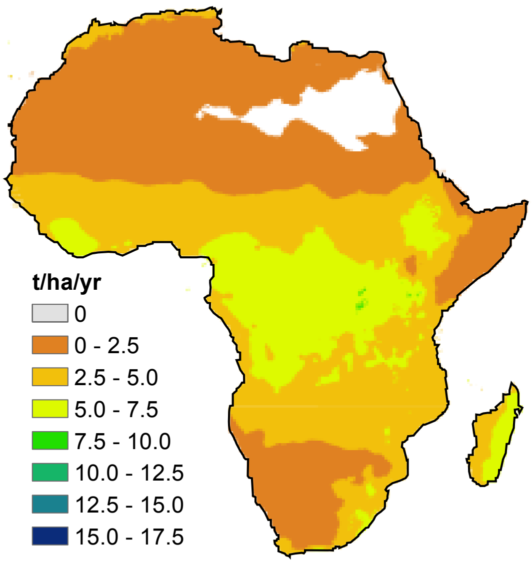
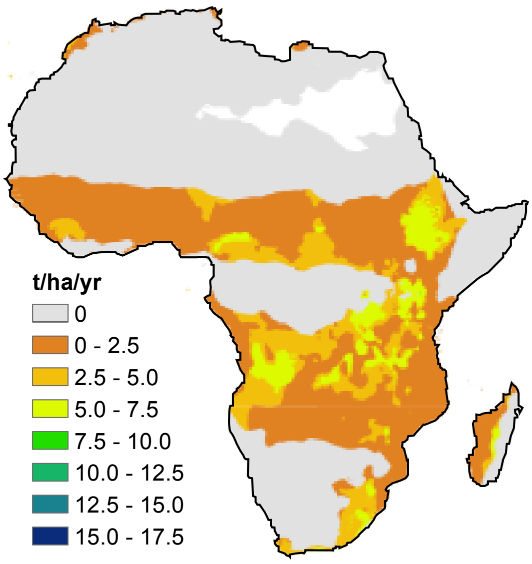


Figure A-2: Yield potentials for *Acacia gerardi*

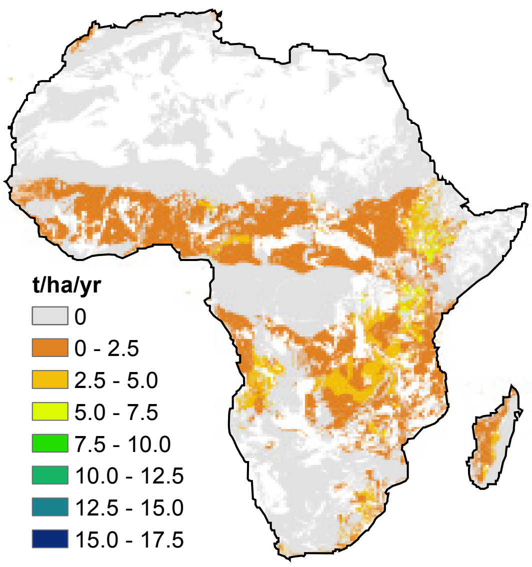
(a) Unconstrained yield potential



(b) Climate-constrained yield potential



(c) Theoretical yield potential



(d) Technical yield potential

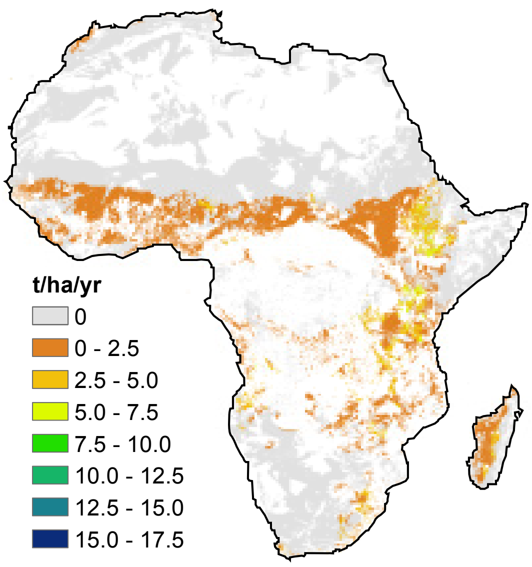


Figure A-3: Yield potentials for *Acacia nilotica*

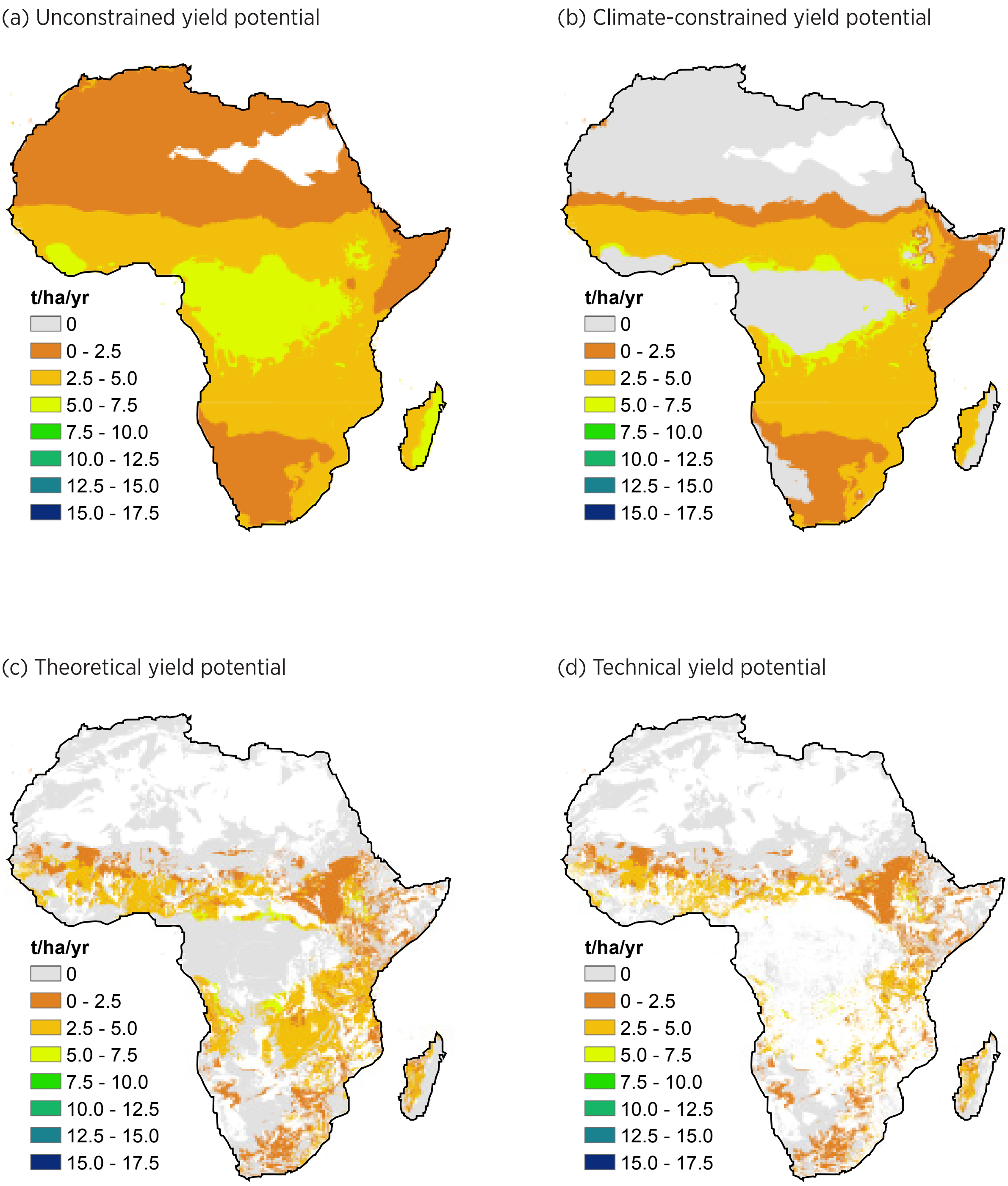


Figure A-4: Yield potentials for *Acacia senegal*

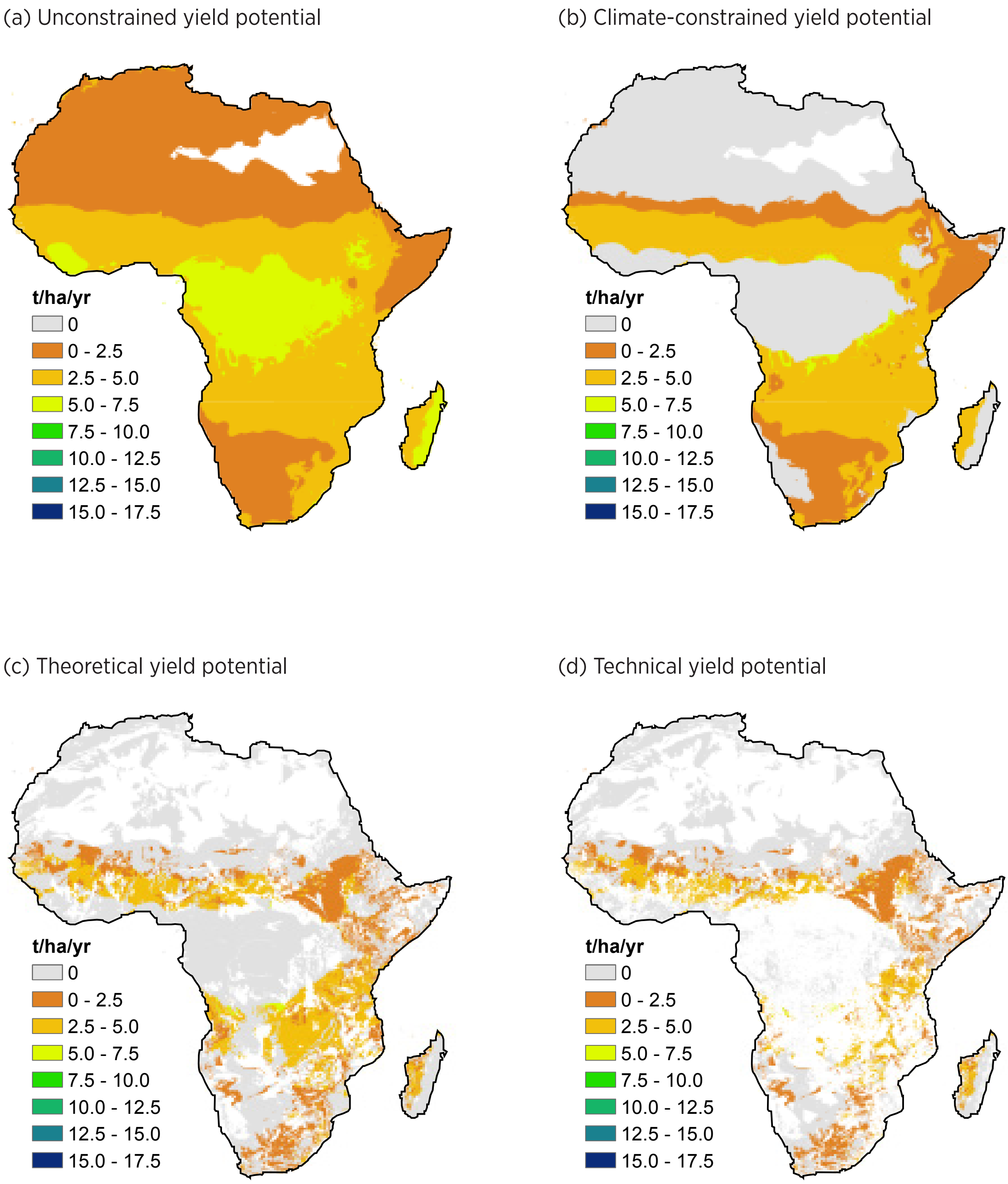
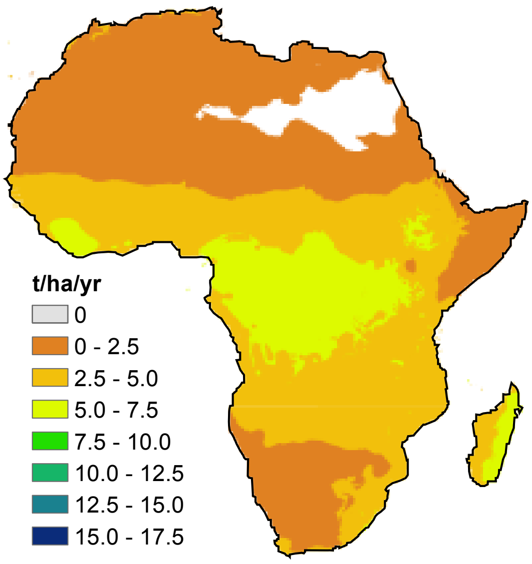
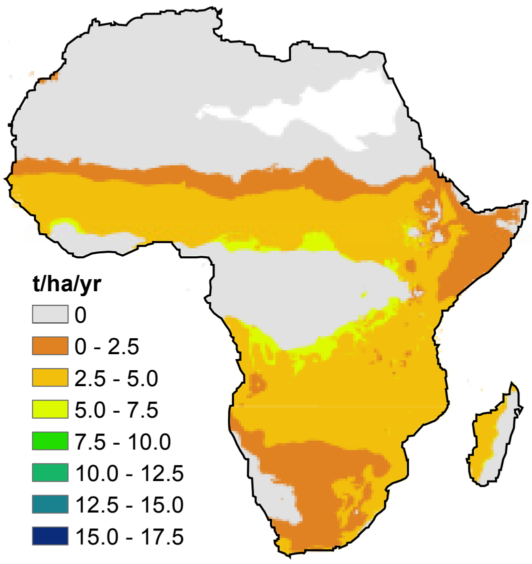


Figure A-5: Yield potentials for *Acacia tortilis*

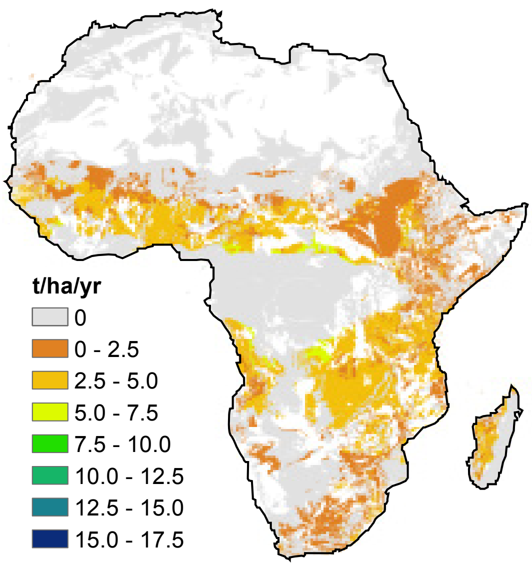
(a) Unconstrained yield potential



(b) Climate-constrained yield potential



(c) Theoretical yield potential



(d) Technical yield potential

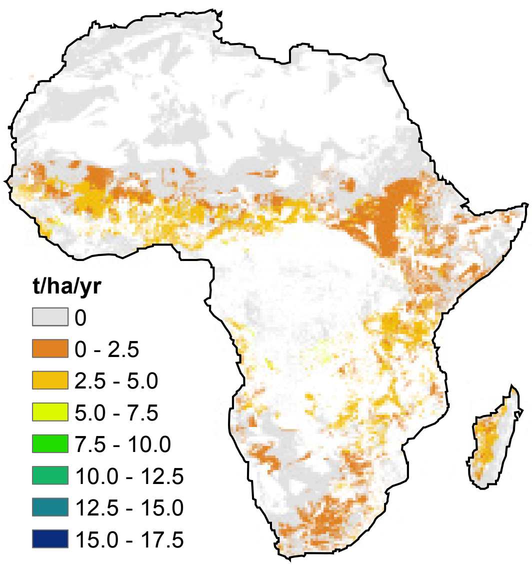
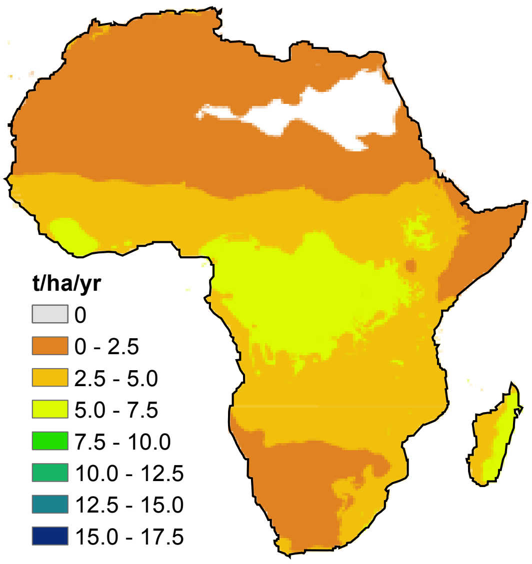
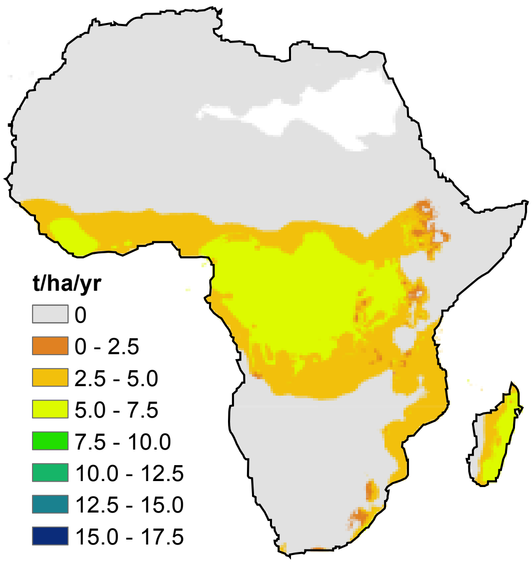


Figure A-6: Yield potentials for *Calliandra calothyrus*

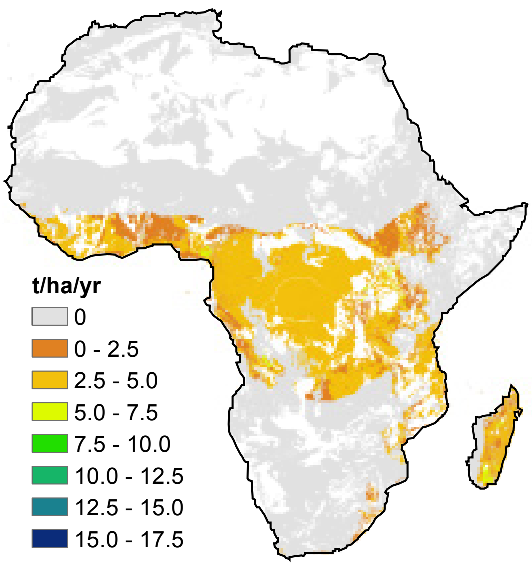
(a) Unconstrained yield potential



(b) Climate-constrained yield potential



(c) Theoretical yield potential



(d) Technical yield potential

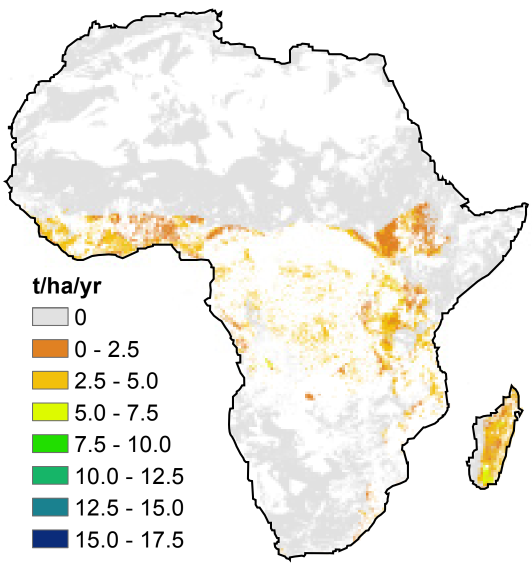


Figure A-7: Yield potentials for *Casuarina cunninghamiana*

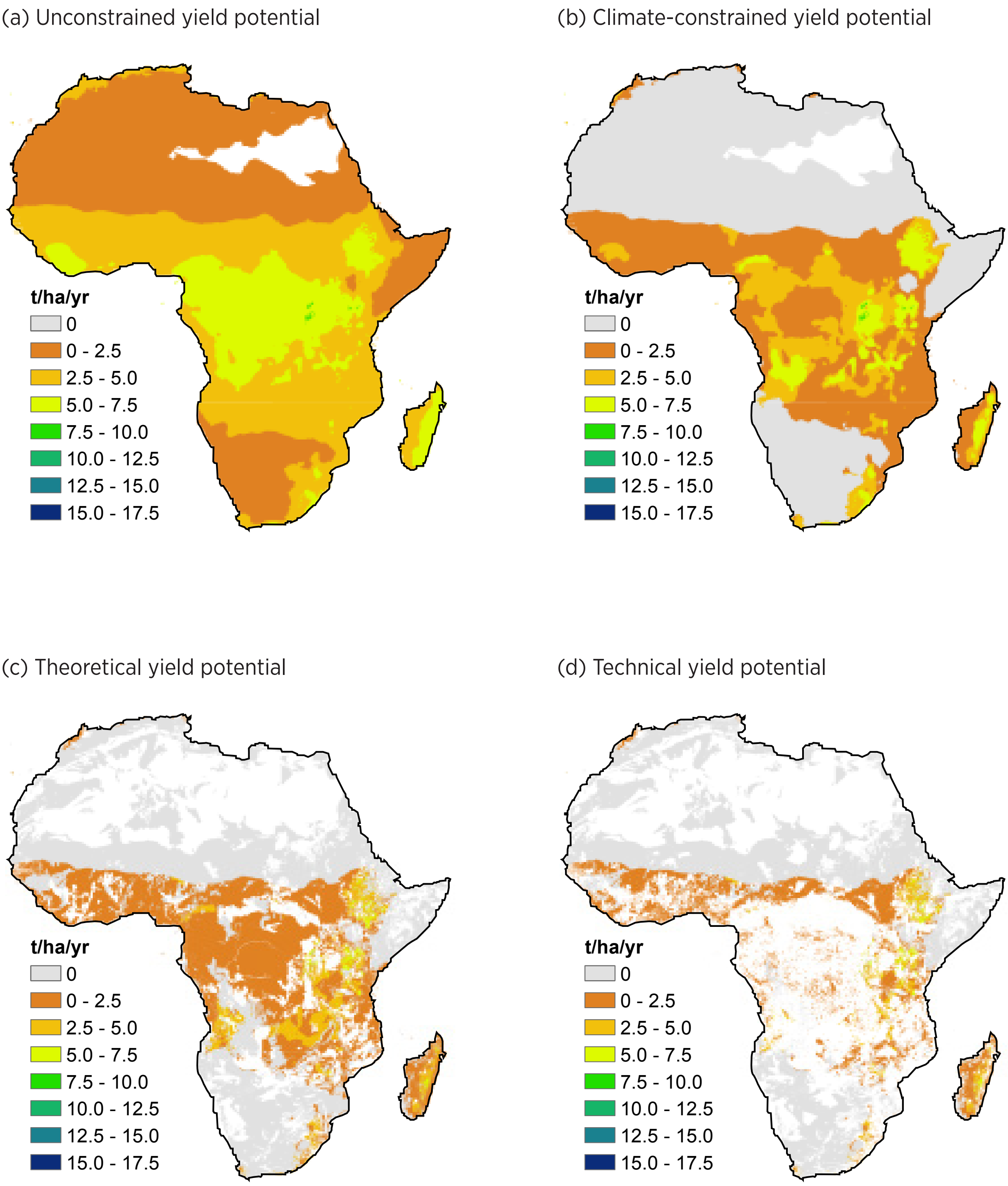


Figure A-8: Yield potentials for *Casuarina equistefolia*

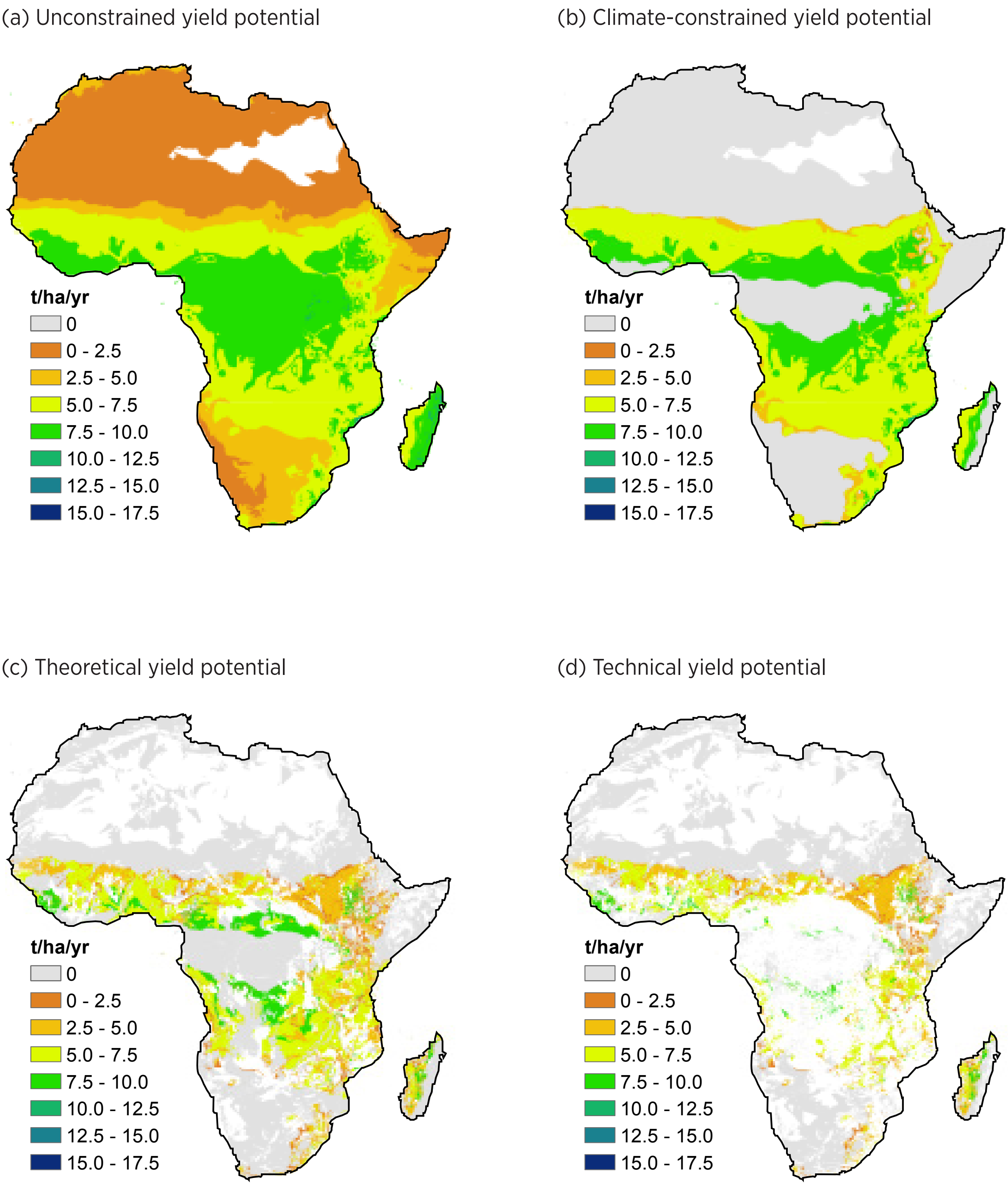


Figure A-9: Yield potentials for *Conocarpus lancifolius*

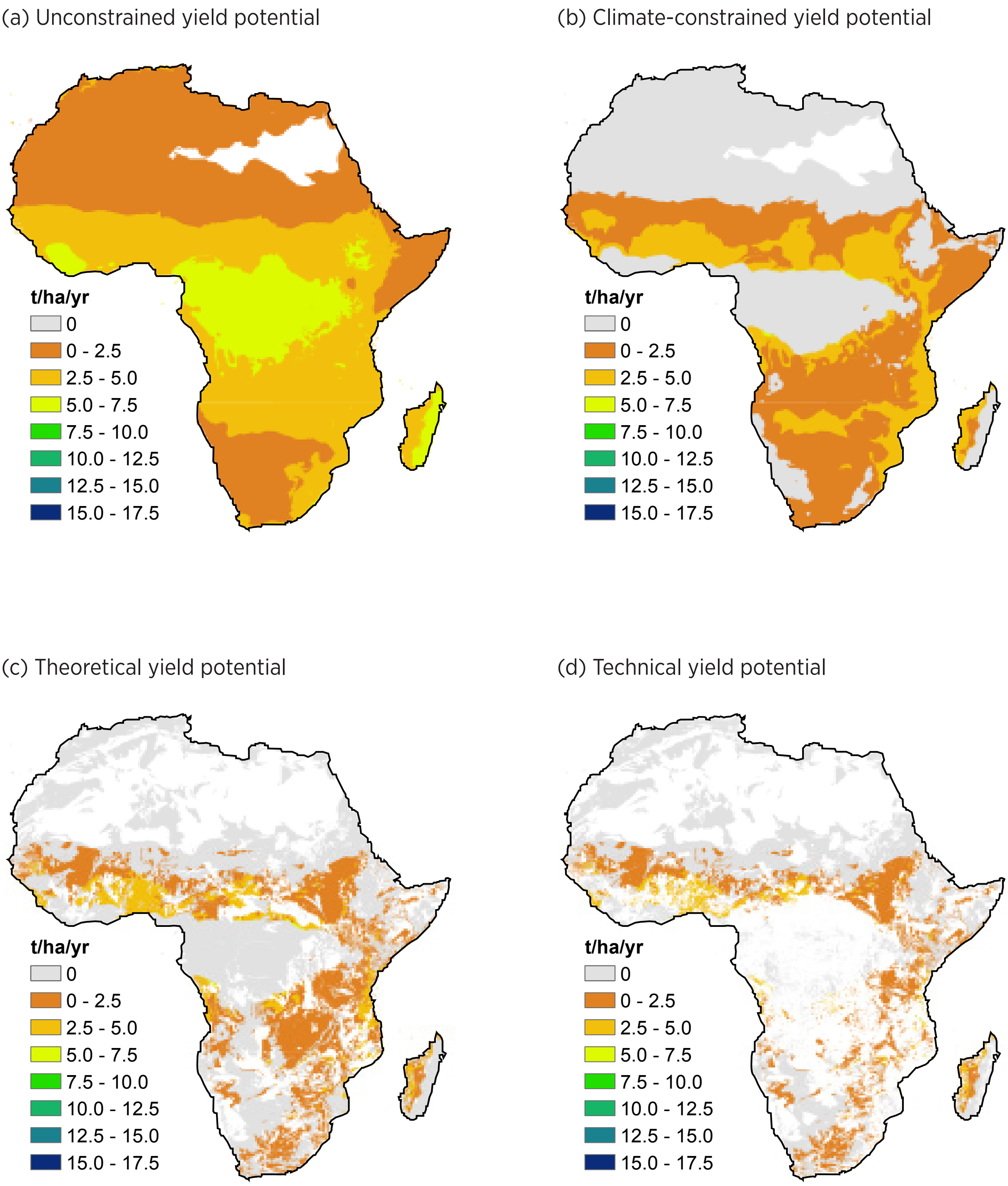


Figure A-10: Yield potentials for *Croton megalocarpus*

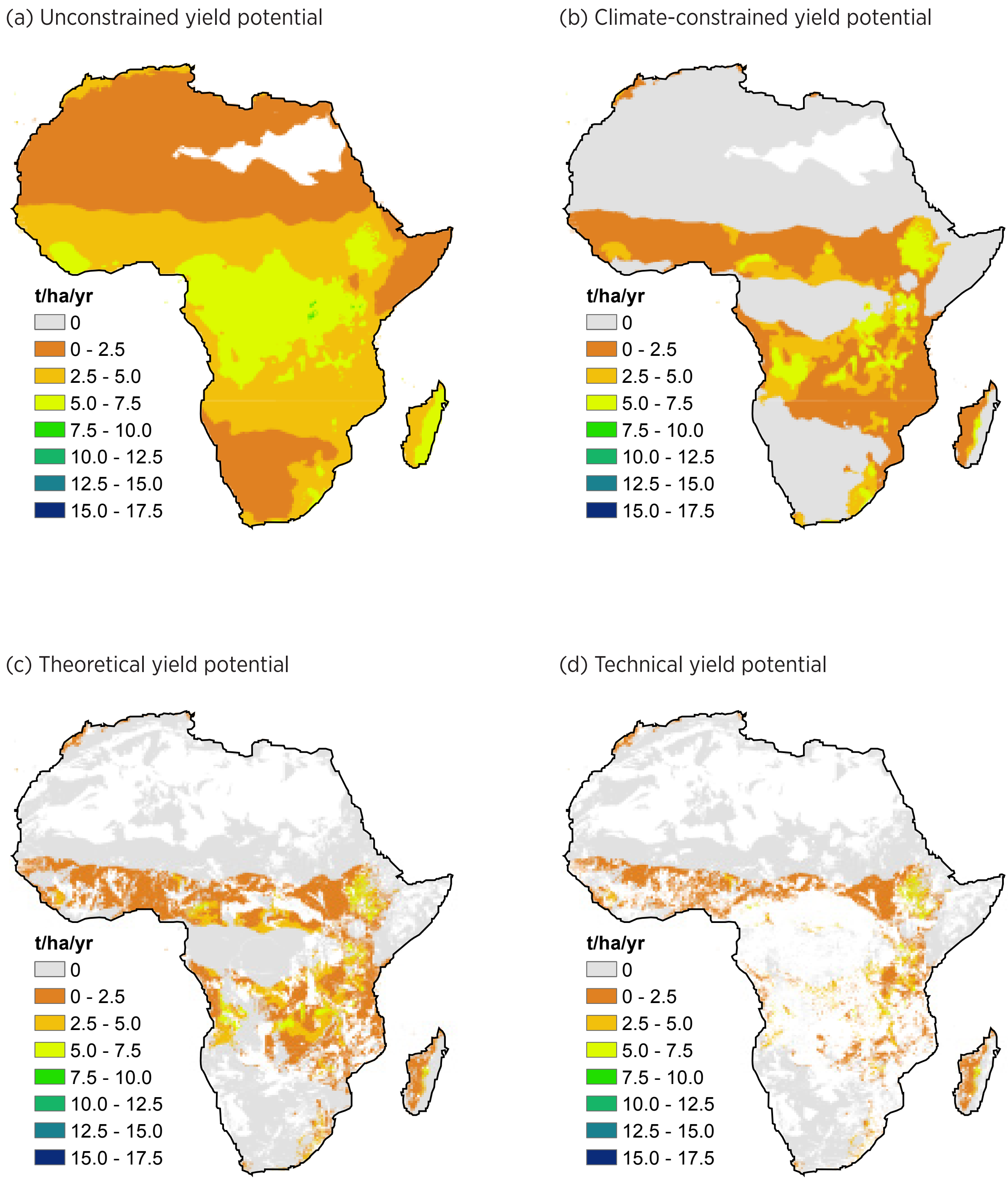
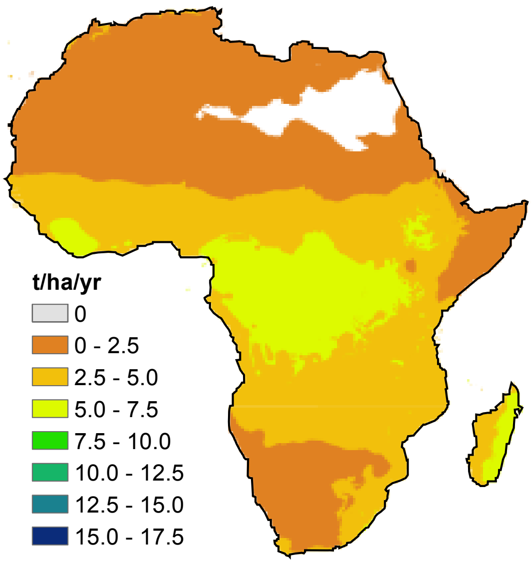
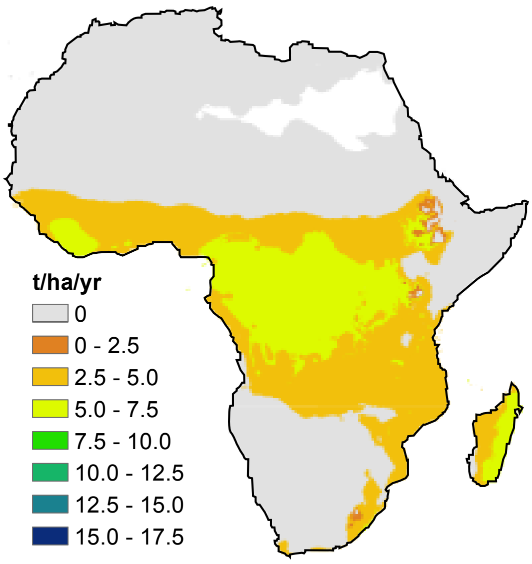


Figure A-11: Yield potentials for *Gliricidia sepium*

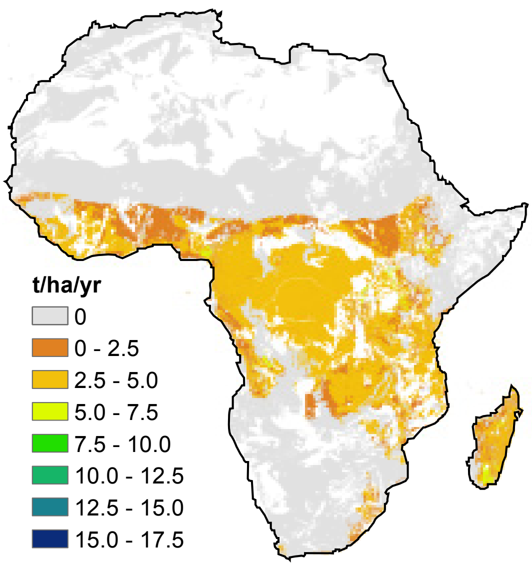
(a) Unconstrained yield potential



(b) Climate-constrained yield potential



(c) Theoretical yield potential



(d) Technical yield potential

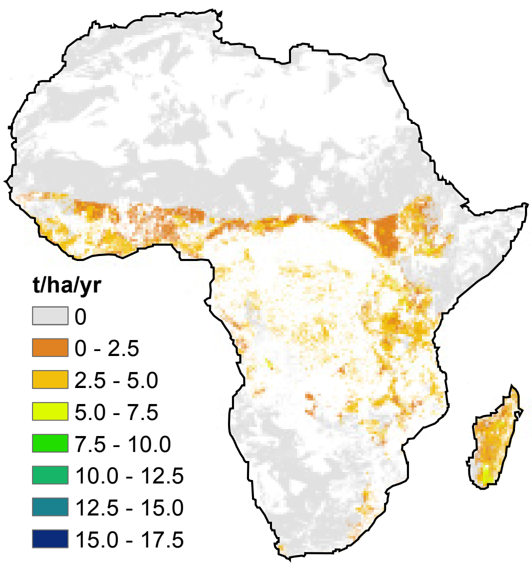
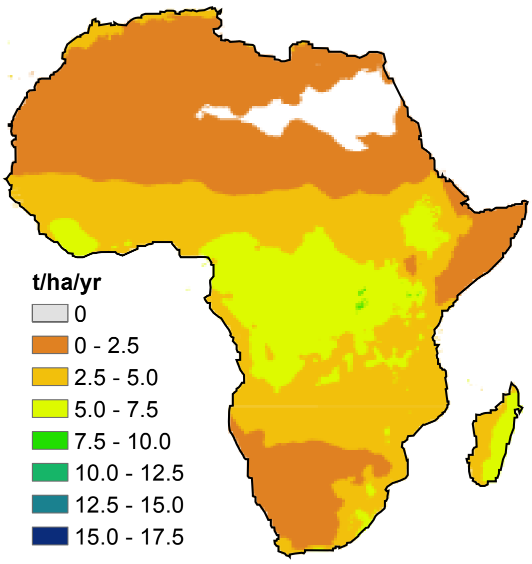
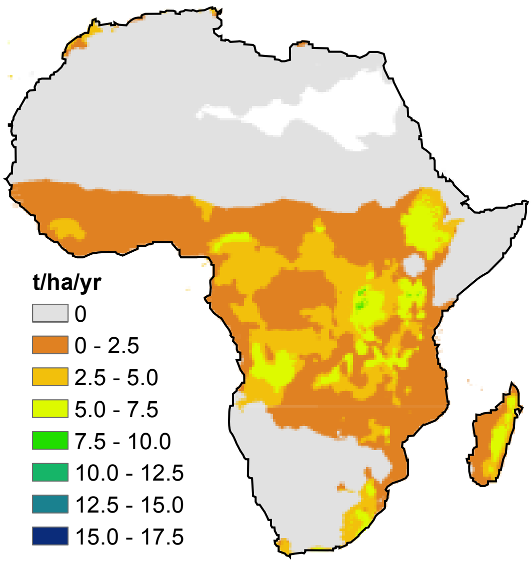


Figure A-12: Yield potentials for *Grevilea robusta*

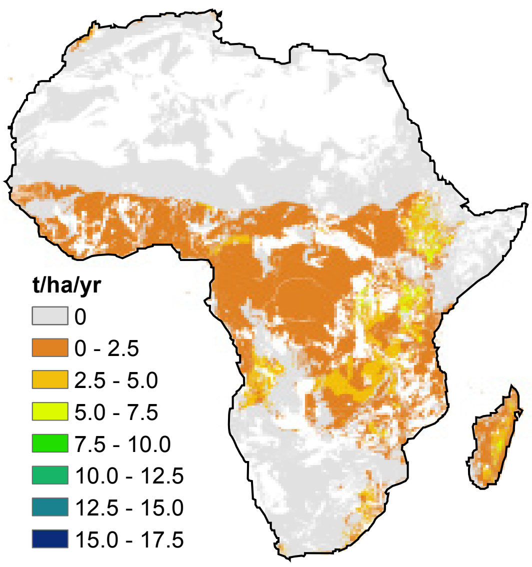
(a) Unconstrained yield potential



(b) Climate-constrained yield potential



(c) Theoretical yield potential



(d) Technical yield potential

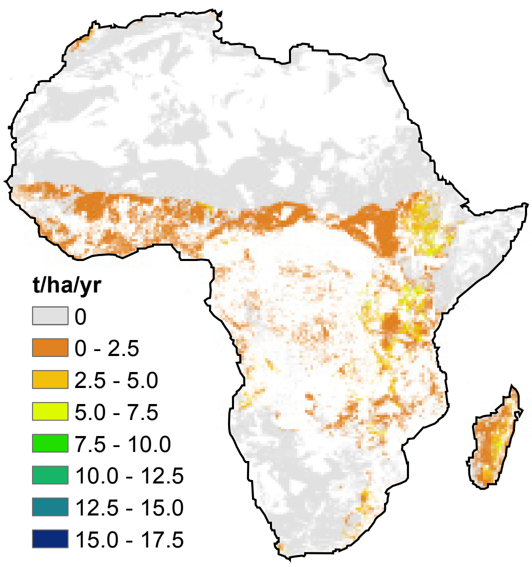


Figure A-13: Yield potentials for *Leuceana leucocephala*

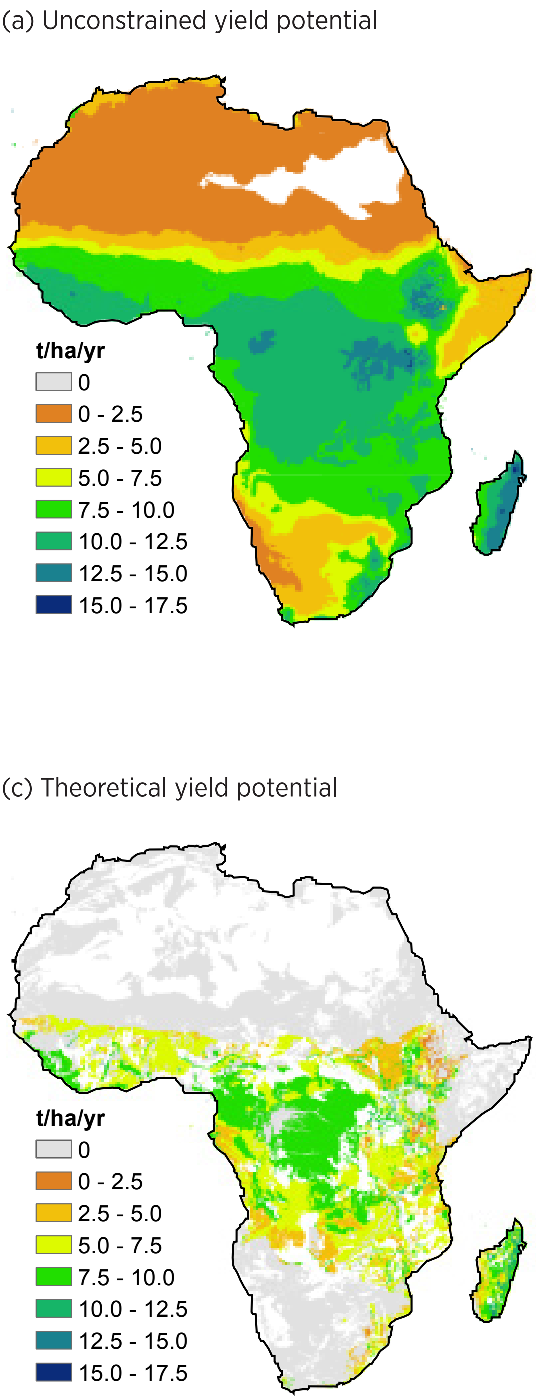


Figure A-14: Yield potentials for *Sesbania sesban*

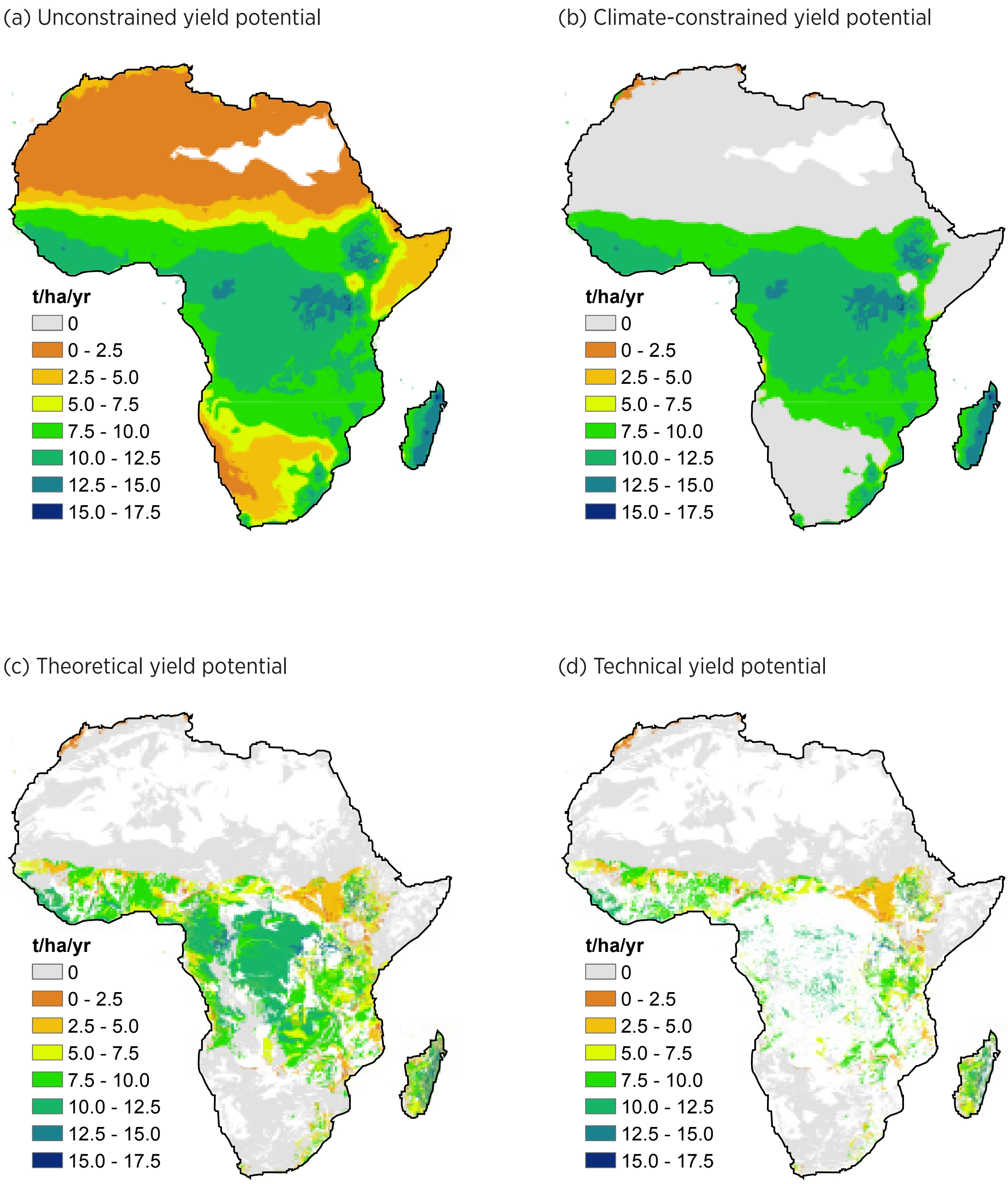
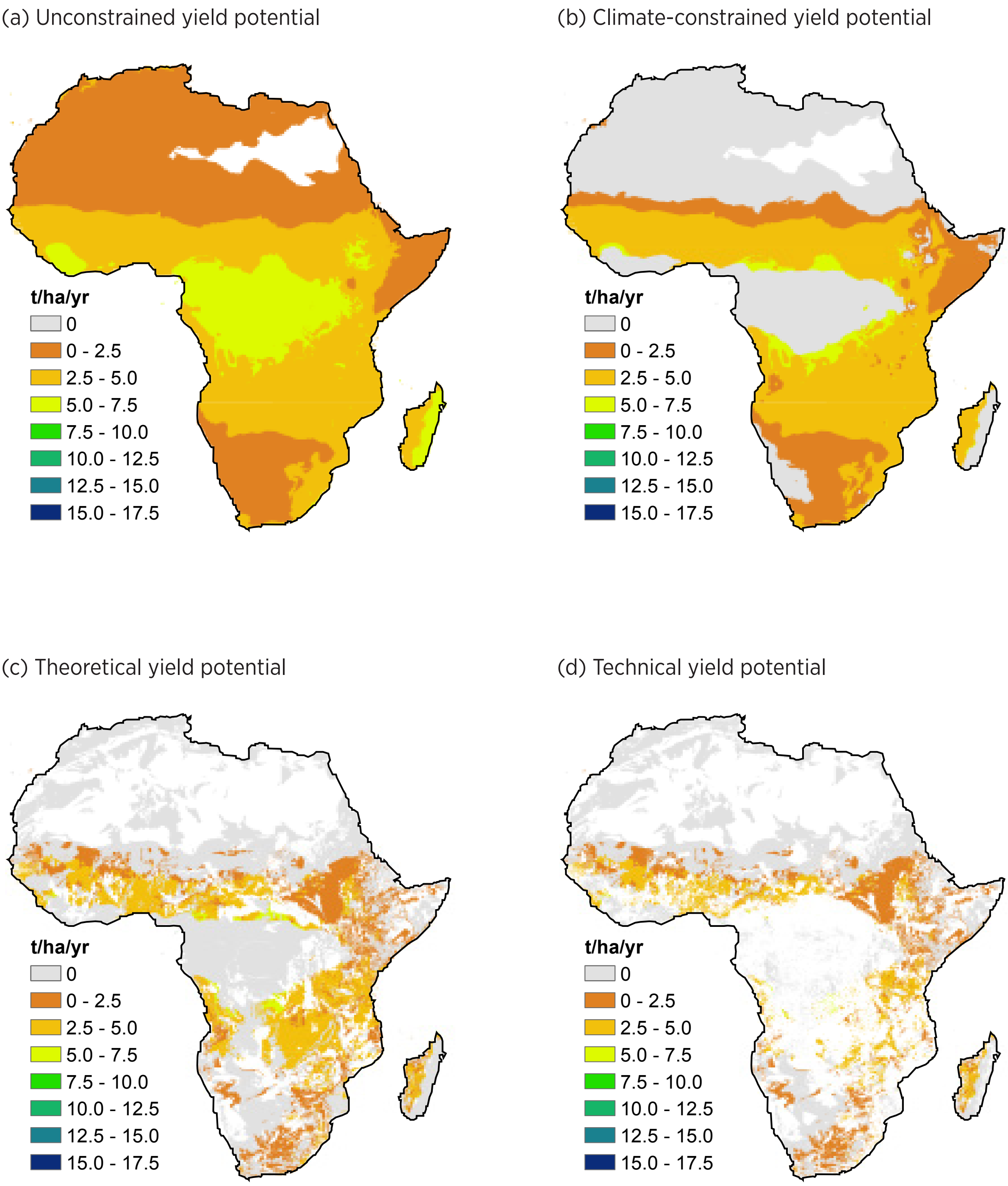


Figure A-15: Yield potentials for *Tamarindus indica*



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