SIXTH FRAMEWORK PROGRAMME

FP6-2004-INCO-DEV-3

PRIORITY A.2.3.: Managing Arid and Semi-arid Ecosystems

Third Periodic Activity Report
(01.01.2009 – 31.12.2009)
December 2009

ANNEX 2-3-2: Report on potential contribution to sustainable energy supply
Deliverable D2.4 (Lead contractor: Utrecht University, Due date: July 2009)

COMPETE

Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-arid Ecosystems - Africa

Responsible Partner / Work Package Leader:

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Project Co-ordinator:

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COMPETE is co-funded by the European Commission in the 6th Framework Programme – Specific Measures in Support of International Cooperation (INCO-CT-2006-032448).

Project Partners

Partici-pant role	Partici-pant number	Participant name	Participant short name	Country	Date enter project (month)	Date exit project (month)
CO	1	WIP – Renewable Energies, Germany	WIP	DE	1	36
CR	2	Imperial College of Science, Technology and Medicine	Imperial	UK	1	36
CR	3	Utrecht University	RUUTR.STS	NL	1	36
CR	4	Stockholm Environment Institute	SEI	SE	1	36
CR	5	Austrian Biofuels Institute	ABI	AU	1	36
CR	6	Höhere Bundeslehr und Forschungsanstalt für Landwirtschaft, Landtechnik und Lebensmitteltechnologie Francisco Josephinum	FJ BLT	AU	1	36
CR	7	ETA - Energia, Trasporti, Agricoltura s.r.l.	ETA	IT	1	36
CR	8	European Biomass Industry Association	EUBIA	BE	1	36
CR	9	Practical Action	Practical Action	UK	1	36
CR	10	Consiglio Nazionale delle Ricerche	CNR	IT	1	36
CR	11	E+Co, Inc. (not funded)	E+Co	USA	1	36
CR	13	Institute for Sustainable Solutions and Innovation	ISUSI	DE	1	36
CR	14	AGAMA Energy (Pty) Ltd	AGAMA	ZA	1	36
CR	16	Center for Energy, Environment and Engineering Zambia	CEEEZ	ZM	1	36
CR	17	Environnement et Développement du Tiers-Monde	ENDA-TM	SN	1	36
CR	19	Food, Agriculture and Natural Resources Policy Analysis Network of Southern Africa	FANRPAN	ZIM	1	36
CR	20	FELISA Company Limited	FELISA	TZ	1	36
CR	21	Mali-Folkecenter	MFC	Mali	1	36
CR	22	MOI University	MU	Kenya	1	36
CR	24	Tanzania Traditional Energy Development and Environment Organisation	TaTEDO	TZ	1	36
CR	25	UEMOA - Biomass Energy Regional Program (PRBE)	PRBE	BF	1	36
CR	26	University of KwaZulu Natal	UKZN	ZA	1	36
CR	27	University of Cape Town - Energy Research Centre	UCT, ERC	ZA	1	36
CR	28	Chinese Academy of Agricultural Sciences	CAAS	CN	1	36
CR	29	Centro Nacional de Referencia em Biomassa, Brazil	CENBIO	BR	1	36

Project Partners (continued)

Partici-pant role	Partici-pant number	Participant name	Participant short name	Country	Date enter project (month)	Date exit project (month)
CR	30	Indian Institute of Science	IISC	IN	1	36
CR	31	The Energy and Resources Institute	TERI	IN	1	36
CR	32	Universidad Nacional Autonoma de Mexico	UNAM	MX	1	36
CR	33	Universidade Estadual de Campinas	UNICAMP	BR	1	36
CR	34	Winrock International India	WII	IN	1	36
CR	35	Interuniversity Research Centre for Sustainable Development - University of Rome "La Sapienza"	CIRPS	IT	1	36
CR	36	Universitetet i Oslo	UiO	NO	1	36
CR	37	University of Bristol	UNIVBRIS	UK	1	36
CR	38	University of Botswana	UB	Botswana	1	36
CR	39	University of Fort Hare	UFH	ZA	1	36
CR	40	TWIN	TWIN	UK	1	36
CR	41	Joint Graduate School of Energy and Environment	JGSEE	TH	1	36
CR	42	African Development Bank Group (not funded)	AFDB	Int.	1	36
CR	43	Energy for Sustainable Development Ltd.	ESD	UK	1	36
CR	44	Eco Ltd.	Eco	UK	1	36
CR	45	Chinese Association of Rural Energy Industry	CAREI	CN	1	36
CR	46	Food and Agriculture Organisation of the United Nations (not funded)	FAO	Int.	1	36
CR	47	Conservation International Foundation (not funded)	CI	USA	1	36
CR	48	Foederation Evangelischer Kirchen in Mitteldeutschland	EKMD	DE	1	36

Deliverable D2.4: Report and synthesis (scenarios) for possible introduction schemes for sustainable biomass production, integrated in current agricultural practices (including pasture lands) and provide estimates for the potential contributions to sustainable energy supply, income and employment generation as well as ecological impacts (and benefits) for the South African region.

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1 Introduction

1.1 COMPETE Project

This work has been conducted in the framework of the project COMPETE (Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-Arid Ecosystems – Africa), co-funded by the European Commission in the 6th Framework Programme – Specific Measures in Support of International Cooperation (Contract No. INCO-CT-2006-032448).

COMPETE seeks to enhance sustainable use of renewable natural resources and stimulate bioenergy implementation in the semi-arid and arid regions of Sub-Saharan Africa. The principle objective of this work package (WP2) is to provide an overview of experiences and concepts for sustainable production (and use) of biomass for energy.

1.2 Deliverable 2.4: Potential Contribution to Sustainable Energy Supply

Sub-Saharan Africa is characterized by shortcomings in provision and quality of energy, which, in turn, strongly affect the social and economic situation of the region. The low access to electricity is representative of these shortcomings. Electrification rates range from 70% in South Africa to only 7% in Burkina Faso and 6% in Mozambique (UNDP, 2008). Energy access in general is even worse in rural areas than in urban areas. Average access to electricity in urban Sub-Saharan Africa is 53% while this is only 8% in rural areas. Growing populations and economic development are likely to exacerbate this problem even more.

In addition to low access to energy and electricity, also important is the type or quality of energy used. Sub-Saharan Africa energy use is met primarily (80%) by traditional biomass (IEA 2004 cited in Davidson et al., 2007) such as collected fuelwood, charcoal, leaves, agricultural residue, animal waste, etc. The traditional biomass use in combination with often inefficient stoves has many disadvantages, most importantly possible soil and forest degradation, large amounts of time to collect the biomass and indoor air pollution.

Providing modern energy services may improve especially health and education but can also increase added value of African products, which in turn can lead to economic growth and socio-economic improvements of the regions (Davidson et al., 2007). Especially in rural communities, modern bioenergy can provide such benefits by producing the energy source locally and, particularly in remote areas, at a lower price than fossil fuels, generating additional outlets for farmers' products and reducing the time spent on collecting biomass.

In contrast to currently low access and use of energy, Sub-Saharan Africa has been shown to have a large potential for modern bioenergy production. Smeets et al. (2007) determines the technical potential biomass production in Sub-Saharan Africa in 2050 to range from 49 to 347 EJ y^{-1} , a 3 to 23 fold of current energy use in all of Africa. For the same time period, Hoogwijk et al. (2005) estimate the potential biomass production in Sub-Saharan Africa to range between 47 and 129 EJ y^{-1}, depending on the scenario applied. Marrison and Larson (1996), determining biomass production potential based on country level assessment of land availability and woody crop yields, come to a much lower potential of 16 EJ y^{-1} for Sub-Saharan Africa, which is likely due to Marrison and Larson applying only 10% of available land (non forest, non wilderness, non cropland) for bioenergy production. These potential studies lack to look into the details of land availability and suitability for bioenergy production and the potential yields, while especially semi-arid and arid regions have not been distinguished. Another lack of knowledge is also the potential socio-economic and ecological impacts of such potentials.

The objective of this study (Deliverable 2.4) is thus to estimate the potential contribution of (modern) biomass production to sustainable energy supply for Sub-Saharan Africa, income and employment generation as well as its ecological impacts and benefits.

The remainder of this study is organised as follows: The approach applied for assessing the potential biomass production in Sub-Saharan Africa and for determining bioenergy's economic, socio-economic and ecological impacts is presented in Section 2. Section 3 follows with a description and discussion of the extent of land available for bioenergy production. Section 4 then describes bioenergy crops and their yields in semi-arid and arid Sub-Saharan Africa and presents the results for the geographical potential of biomass production. Section 5 addresses the economics of bioenergy production in the region. Section 6 then focuses on the socio-economic impacts of biomass production, including estimates for overall income and employment generation related to the biomass potential. Section 7 studies the potential ecological impacts associated with producing bioenergy in Sub-Saharan Africa, including GHG emissions, soil nutrients, water and biodiversity. Section 8 presents a summary of the results and the study's final conclusions.

2 Approach

2.1 Focus Area

This study focuses on the same Sub-Saharan countries, which were also investigated in WP1: South Africa, Botswana, Zambia, Tanzania, Kenya, Mali, Burkina Faso and Senegal. This countries were chosen as case study in WP1 because in each several different bioenergy initiatives and COMPETE partners are represented. They are investigated here because WP1 determines available and suitable land areas for bioenergy production, which is a direct input into the potential analysis of this study.

Because of the focus of the COMPETE project on arid and semi-arid ecosystems, only arid and semi-arid regions within these countries are investigated (Figure 1).

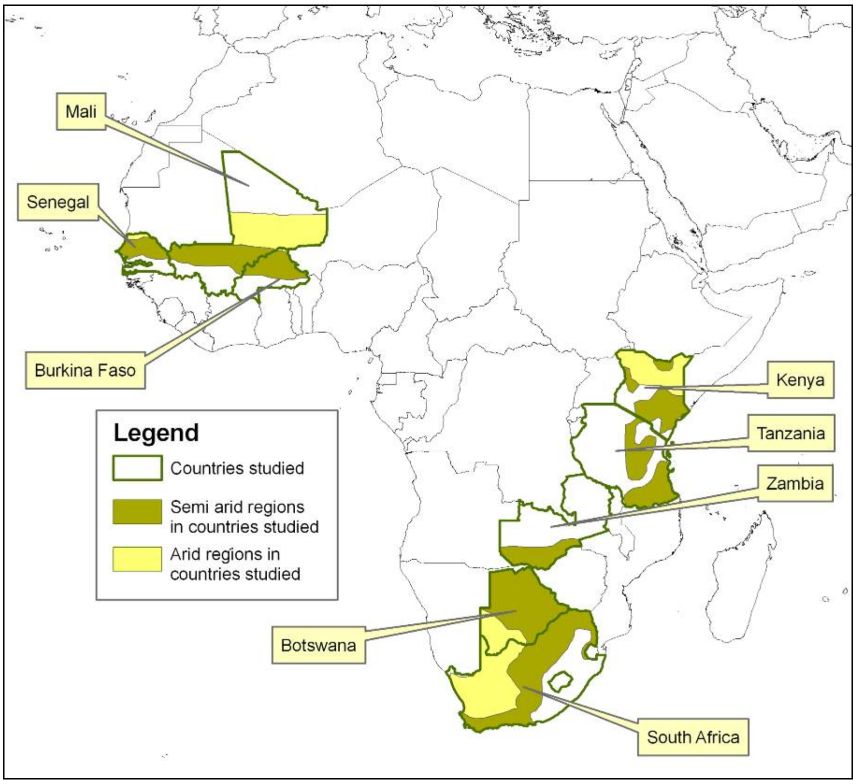

Figure 1: Location of case study countries and their semi-arid and arid regions

Throughout the study, it is attempted to differentiate the input data for these eight countries. However, lack of data does not always allow this differentiation. In those cases, either regional averages, African averages or other proxies are applied. The application of non-country specific data is described in the appropriate sections below.

2.2 Potential Analysis

The geographical potential[1] from biomass production in the eight countries investigated here is determined by multiplying the land area in each country with the yield corresponding to crop and country and dividing by the energy content of the crop. Thus, the *geographical potential* is calculated by

$$GP_i = A_i \times Y_{ij} / EC_j \quad (1)$$

[1] For a definition of the geographical potential see Appendix 10.1.

where GP_i – geographical potential (PJ y^{-1}); A_i – available land for bioenergy production in country *I*; Y_{iJ} – yield of crop *j* in country *I* (t ha^{-1} y^{-1}); EC_j – energy content of crop *j* (GJ t^{-1}); *I* – country; *j* – crop.

The approach taken to determine land availability for bioenergy production and to assess the yields of different crops is described in more detail in the next sections.

2.2.1 Land availability for bioenergy production

Land availability for bioenergy production in the eight countries has been determined by WP1 (Watson, 2009). The methodology applied to estimate the extent of available land is described in Box 1.

BOX 1: Methodological Approach and Data Sources for Defining Available and Suitable Land for Bioenergy Production (Watson, 2008)

The first step in the methodology devised to meet this objective was to decide which data source depicting the spatial extent of arid and semi arid regions in Africa, was the most accurate. The range of sources interrogated gave differences in the area of these regions of up to 16%. It was decided to use the WMO and UNEP (2001) delineation of these regions as they appear to be the most accurate. These regions in all sub Saharan countries were digitized and produced as a map which used all the continent's country boundaries as a template (refer Appendix 9, Figure 2). ESRI (2006) Africa and African country shape files were used.

The second step involved sourcing and acquiring high quality Geographic Information Systems (GIS) data sets that categorize spatial and temporal variations in Africa's physiographic parameters, vegetation cover, land use etc. As a precaution against detrimental impacts on biodiversity, all categories of protected areas, closed canopy forests and wetlands were designated as unavailable for bioenergy crop production and filtered out from the regions depicted in the base map. UNEP et al. (2006) was used to delineate the International Protected Areas, National Protected Areas (Categories I-VI), and National Protected Areas (Uncategorized), (refer Appendix 9, Figure 5).

The ECJRC's (2003) GLC database was used to delineate the following forests:- closed deciduous, evergreen lowland, montane and submontane, and wetlands:- mangroves, swamp bush and grassland. The evergreen lowland category included both closed and degraded forest. It could be argued that the latter should not have been filtered out, as there is little prospect of it being rehabilitated and the rural poor would benefit more from it being converted into bioenergy crop production. The GLC database was also used to delineate areas where (i) crops cover more than half the surface, (ii) croplands occur within a matrix of open woody vegetation, (iii) irrigated crops predominate, and (iv) tree crops predominate. In order to avoid food security concerns these areas were also designated as unavailable for bioenergy crop production and filtered out from the arid and semi arid regions. Lastly, this database was used to delineate the following areas considered unsuitable for bioenergy crop production: cities, bare rock, sandy desert and dunes, stoney desert, and water bodies.

The surfaces remaining as available and/or suitable for bioenergy crop production are: closed or sparse grassland, open grassland with sparse shrubs, open deciduous shrubland, deciduous shrubland with sparse trees, deciduous woodland, mosaic forest/cropland and mosaic forest/savanna.

For a better understanding of the extent of available and suitable land as determined in WP1 and for a discussion of possible limitations to its availability, this study will make an overview of current land use and of changes in land use over time. This is done by collecting land use data from FAO statistics (FAOSTAT, 2009) and the global land cover data base from Joint Research Centre of the European Commission (GLC2000) (Global Land Cover 2000 database, 2003; Land cover map of Africa, see Mayaux et al., 2003), which is also used in the analysis of WP1.

The delineation of land cover classes that are considered available for bioenergy in WP1 excludes, among others, cropland. Despite the GLC2000 definition of cropland including pastures (Table 17 in Appendix), pasture lands are likely not included in the category “agriculture/cropland” because natural grasslands and shrublands are used for livestock production and would more likely be classified as grasslands and shrublands and not as pasture. However, including such pasture lands as available for bioenergy production could result in land use change and land use conflicts that are not intended or desired. Thus, in order to exclude potential pasture land from available land for bioenergy production, this study first compares the extent of agricultural land in GLC2000 (agriculture) and FAOSTAT (cropland, permanent cropland and permanent pastures and meadows) for each of the eight countries. In those cases in which the GLC2000 agricultural land is smaller than the agricultural land area determined by FAO, it is possible that additional land may be used for agricultural production than is accounted for in the GLC2000 database. In order to avoid any possible land use conflicts with food/fodder production, in this study the difference between GLC2000 and FAO agricultural land is assumed to be spread equally over the climate zones (the share of the additional land allocated to arid areas is the same that arid areas make up in the total land use) and the pasture land allocated to arid and semi-arid regions is subtracted from the available arid and semi-arid land area determined in WP1. While this is a simplification of actual livestock/pastureland distribution (i.e. livestock unit maps indicate that more/less in arid zones than in semi-arid zones depending on the country), this allows for an approximation of the reduction caused by livestock raising.

In addition to a reduction in the available land area for grazing, there are likely to be also other factors which further decrease land availability for bioenergy production. Such factors are, for example, high biodiversity, steep slopes, and possible future land demands for agricultural production. While these factors could not be included in this analysis as they exceed the scope of this study, it is important to keep them in mind when interpreting the results.

2.2.2 Crops and Yields

This study will investigate the three crops: cassava, jatropha, and woody crops. These crops are chosen because they are suitable in semi-arid and arid ecosystems.

Yields are estimated based on different approaches for the different crops because of varying data availability. Country average yields for cassava are available through FAO Statistical Database (FAOSTAT, 2009) and are used here because more detailed country data distinguishing semi-arid and arid regions is lacking. Point data for yields in semi-arid and arid regions in Africa in general is collected from literature and used to validate/discuss the average country data from FAO.

Jatropha yields are more difficult to estimate because collection of yield data has not been conducted on large-scale or different countries. Point data from different countries, climate zones, ages of shrubs and management are collected from literature and average value of these is applied in this study. Due to lack of data with respect to climate data links with yields, yields for semi-arid and arid regions cannot be distinguished.

Woody crop yields are defined based on results of the Integrated Model to Assess the Global Environment (IMAGE) for woody energy crops. A brief description of the IMAGE model and its methodology for estimating yields can be found in Box 2, while for a detailed description is given in Leemans and van den Born (1994) and Bouwman et al. (2006).

From the IMAGE model woody crop yield map, yields for woody crops in semi-arid and arid regions in the eight countries are extracted as follows. The delineation of semi-arid and arid regions in the eight countries as applied by WP1 is overlaid with the yield map from IMAGE in ESRI’s ArcGIS 9.3 software and the average yields in these regions is calculated by the Zonal Statistics tool (determining the yield in each grid cell within the delineated semi-arid or arid region and an average yield is determined). Average yields are determined distinguishing semi-arid and arid ecosystems. In order to validate and discuss the resulting yields, a literature review of woody crop yields in semi-arid and arid Sub-Saharan Africa is also made.

2.3 Production costs

Production costs of bioenergy in semi-arid and arid ecosystems in Sub-Saharan Africa are assessed based on existing literature. Production costs are then compared to market prices of products that this bioenergy production could substitute such as fuelwood, fossil diesel or gasoline. This comparison serves to determine the economic feasibility of bioenergy production.

BOX 2: The Integrated Model to Assess the Global Environment (IMAGE)
“IMAGE is an ecological-environmental framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues like climate change, biodiversity and human well-being” (PBL, 2009).

The biomass yields are modeled according to the Crop and Grass Production Model in IMAGE (Leemans and Born, 1994), which is based on the FAO Agro-Ecological Zones approach and determines the potential distribution of different crops and their potential productivity based on climatic conditions and crop requirements (see figure below). The yields are spatially explicit on a 0.5 by 0.5 degree grid cell resolution. Here the yields for woody energy crops are modeled under rain-fed conditions. The rain-fed yields are adjusted to account for grid-specific soil conditions by multiplying the rain-fed yields with a soil reduction factor that accounts for the three soil-quality indicators, nutrient retention and availability, level of salinity, alkalinity and toxicity and rooting conditions for plants (Leemans and Born, 1994). The IMAGE model then applies a management factor to account for differences in theoretically feasible and actual yields (Hoogwijk et al., 2005). For woody bioenergy crops the IMAGE model uses a global average management factor of 0.7 (Hoogwijk, 2005).

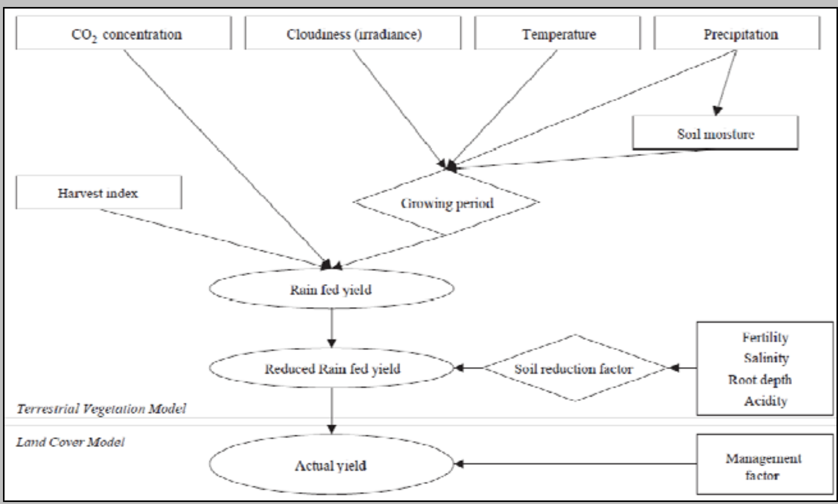

Figure: Schematic representation of the simulation of land productivity within the IMAGE 2.2 model (Hoogwijk et al. 2005 based on Leemans and van den Born, 1994)

2.4 Income and employment generation

Income and employment generation from bioenergy production in semi-arid and arid ecosystems in Sub-Saharan Africa is assessed based on existing knowledge in the scientific literature. Income generation is measured by the Net Present Value (NPV), which indicates the overall economic feasibility of a system by comparing production costs and benefits over time. The NPV determines the income of a farmer over the period that he manages the plantations. The NPV is calculated as follows

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i} \qquad (1)$$

where B_i – benefits in year *i*; C_i – costs in year i (including initial investments in the first year; r – discount rate; n – lifetime of project

In this study, the net present value of the three crops is determined from existing literature.

Employment generation is analyzed in terms of labor intensity - the number of labor hours required per hectare for each of the production system. This is done by assessing the time required for each activity of the production process and averaging it over the lifetime of the plantation (cassava – 1 year; jatropha - 20 years; woody crops – 20 years). Labor intensities are then extrapolated for the total potentially available land area to be able to estimate overall employment generation from bioenergy production and, when comparing it to the total labor force of the country, to determine whether labor represents a limiting factor.

2.5 Ecological impacts and benefits

Ecological impacts and benefits of bioenergy production in semi-arid and arid ecosystems in Sub-Saharan Africa are investigated in terms of greenhouse gas (GHG) emissions, water use, soil nutrient balance and biodiversity. The latter three aspects are analyzed qualitatively based on existing knowledge in scientific literature. An overview of GHG emissions from the different crops included in this study is made for typical production systems in Africa based on existing literature (see, for example, Nguyen et al., 2007; Gibbs et al., 2008; JRC et al., 2008; Hoefnagels et al., forthcoming). The GHG balance includes carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) emissions from all steps of the production process including land use change, establishment and operation of the plantation, transport and processing. Emission credits are awarded if by-products are generated and not used within the production system.

2.6 Integration of bioenergy production in current agricultural practices

This report focuses on dedicated production of bioenergy. The main argumentation behind this is that integration of bioenergy and food/fodder production may reduce food/fodder production. But since food security is already a significant problem in many Sub-Saharan countries, it was here chosen to study bioenergy production only on land, which is not in agricultural use. However, it is possible, and in many cases also desirable, that bioenergy will be produced in combination with food and fodder crops whether on land not currently used for agricultural production or on existing agricultural land. An important benefit of an integration of bioenergy and agricultural production on land not currently used for agriculture is that additional food/fodder would be produced and food security issues could be reduced.

While the integration of bioenergy and agricultural production is not included in this analysis, a brief, qualitative discussion is held of how the bioenergy production systems that are studied here can be combined with food and fodder production and of its benefits. This discussion is solely based on literature findings.

3 Land Availability for Bioenergy Production in Semi-Arid and Arid Sub-Saharan Africa

Table 1 shows the land area available and suitable for bioenergy production as determined in WP1 (Watson, 2009). The corresponding maps, depicting the location of these available areas, are presented on the COMPETE website.[2] From Table 1 it can be seen that large areas of land may be available for bioenergy production in the eight countries. The largest area is available in South Africa, which is nearly twice as much as the country with the next largest available land area Kenya. Botswana follows next, then with a significant lower area available Mali, Tanzania, Zambia, Burkina Faso and Senegal. The share of the available and suitable land in the total land area of each country is the largest in Kenya (65%) followed by South Africa (59%), Botswana (50%), Tanzania (16%), Mali (15%), Zambia (9%), Burkina Faso (8%) and Senegal (8%).

Table 1: Overview of available and suitable land for bioenergy in relationship to total land area

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
Total area (1000 ha)	**58734**	**27234**	**58187**	**125228**	**19601**	**122136**	**94138**	**75192**
Arid region	12829	512	23089	38973	1409	37842	0	0
Semi-arid region	45332	14486	22702	24823	9705	52293	31674	16028
Other regions	573	12237	12396	61432	8487	32002	62464	59164
Total available (1000 ha)	**29186**	**2276**	**37970**	**19244**	**1578**	**72288**	**14725**	**6738**
Arid area	10219	0	20976	12140	1020	35394	n/a	n/a
Semi-arid area	18967	2276	16994	7104	558	36894	14725	6738
Share available / suitable of total area (%)	**50**	**8**	**65**	**15**	**8**	**59**	**16**	**9**
Share available / suitable of total arid and semi-arid area (%)	**50**	**15**	**83**	**30**	**14**	**80**	**46**	**42**

Source: Watson, 2009

It is important to place this area into context with other land uses in order to determine whether these areas may actually be available for bioenergy production. This is done by comparing the available and suitable area calculated in WP1 to other land use/land cover data. Two data sets are applied here: JRC GLC2000 (Mayaux et al., 2003) on which the results from WP1 are based (see Section 2.2.1) and FAOSTAT data on land resources (FAOSTAT, 2009).

Figure 2 shows the comparison of the available land areas determined in WP1 to land use data from GLC2000 for each of the eight countries. Based on the definition of which land cover categories may be applied for bioenergy production of WP1, the available land area appears in nearly all countries to be comparable to the extent of grassland (see also Table 16 in the Appendix). However, it is important to note that WP1 also includes the categories “shrub cover, closed-open (evergreen and deciduous)” and “woodland” as potentially available for bioenergy (combined as one category in Figure 2) (for definitions for the various categories see Table 17 in the Appendix). Therefore, also some woodlands / shrublands are included in the available land area while some grassland may also be excluded if it falls, for example, under a protected area.

[2] http://compete-bioafrica.net/current_land/current_land.html

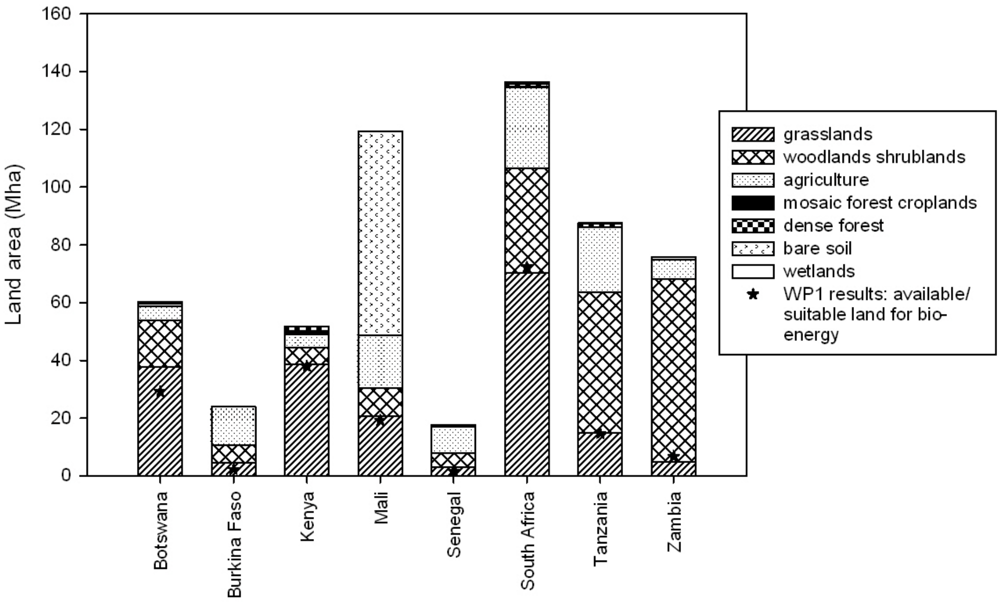

Figure 2: Composition of land area of Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia in 2000 according to GLC2000 and amount of land available and suitable for bioenergy as determined in COMPETE WP1
Source: Mayaux et al., 2003; Watson, 2009

More insight into the context, which the available land determined in WP1 is situated in, comes from comparing the extent of available land to the statistical data on land resources by FAOSTAT (2009) (Figure 3; see also Table 18 in the Appendix). Figure 3 shows how the available and suitable land area for bioenergy as determined in WP1 compares to the extent of the land use categories applied by FAO ("other land", "permanent pastures", "permanent crops", "arable land" and "forest area" – for a definition of these land categories see Table 19 in the Appendix). In Burkina Faso, Mail, Senegal and Tanzania the available and suitable land area is smaller than the "other land" area, so that agricultural land and forests are not likely to be affected. In Botswana, Kenya, South Africa and Zambia, however, the available and suitable land area determined in WP1 is larger than the "other land" and could threaten the extent of agricultural land and/or forest land. While the definition of land cover classes available for bioenergy in WP1 excludes forest and cropland, pasture lands may not always be included in the category "cropland" in the GLC2000 analysis. This is because natural grasslands and shrublands are used for livestock production and would be classified as grasslands and shrublands and not as pasture. This issue can be identified when comparing the extent of agricultural land in GLC2000 (Table 16) and FAOSTAT (Table 18). In six out of the eight countries, FAOSTAT agricultural land is between 1.5 and 6 times higher than agricultural land identified by GLC2000. FAOSTAT agricultural land is primarily composed of permanent pasture land, which may suggest that, despite the GLC2000 definition of cropland including pastures (Table 17 in Appendix), not all grazing land is classified as agricultural land in GLC2000 but rather as grasslands.

Displacing livestock production by bioenergy production could lead to indirect land use change,[3] land tenure and social conflicts because of the still needed feed/fodder demands for raising livestock. An option for avoiding such displacement is integrated bioenergy/food/feed production (Section 4.4). This issue is even more important considering that past trends of land use change suggest increasing agricultural area coming at the cost of a reduction in forests (as well as in the "other land" area). In all eight countries except South Africa, forest areas have decreased - in some cases strongly (Tanzania, Zambia) while in others only slightly (Burkina Faso, Kenya) (see Figure 20 in the Appendix).

[3] Indirect land use change is the idea that the use of land with previous other purposes such as agricultural crop production will lead through market forces to the conversion of undisturbed land elsewhere in the world and to additional GHG emissions (Kim et al., 2009).

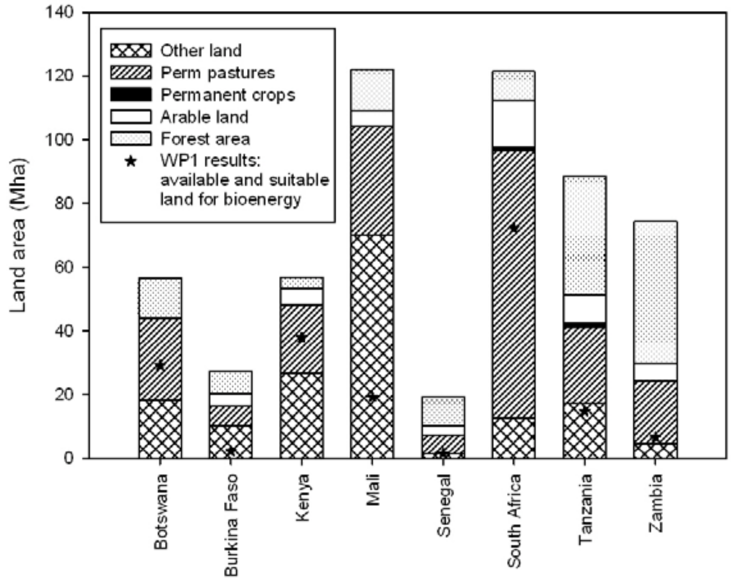

Figure 3: Composition of land area of Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia in 2000 according to FAOSTAT and amount of land available and suitable for bioenergy as determined in COMPETE WP1
Source: FAOSTAT, 2009; Watson, 2009

This study excludes possible pasture land from the available land determined in WP1 (see section 2.2.1 for a description of the approach). Table 2 presents the percentage reduction of available land as a result of accounting for pastureland and the reduced, potentially available land area for bioenergy production. It is interesting to notice that in Burkina Faso and Senegal no reduction is required while in South Africa 63% and 83% of the available land is accounted for as pastureland in arid and semi-arid regions, respectively.

Table 2: Percentage reduction of available land based on pastureland requirements and the resulting available land

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
Percentage reduction – accounting for pastureland requirements								
Arid (%)	45	0	41	53	0	63	n/a	n/a
Semi-arid (%)	86	0	50	57	0	83	26	58
Available land – accounting for pastureland requirements								
Arid (1000 ha)	5616	0	12381	5765	1020	13125	0	0
Semi-arid (1000 ha)	2699	2276	8542	3044	558	6122	10848	2815
Total (1000 ha)	**8315**	**2276**	**20923**	**8809**	**1578**	**19248**	**10848**	**2815**

The overview of the available land area as determined in WP1 and other land cover/use categories presented here indicates the difficulties of defining when and what land areas may be available for bioenergy production. The (reduced) available land area presented in Table 2 is used in the potential analysis and also in extrapolating the employment and ecological impacts.

4 Bioenergy Production in Semi-Arid and Arid Sub-Saharan Africa

In this study three crops are analyzed for their biomass/bioenergy production potential, their economics, socio-economics and ecological impacts. These crops are cassava, jatropha and woody crops. They are chosen because of their presumed tolerance to semi-arid and arid climates. Each crop is explained in more detail below.

4.1 Crop Production Systems

4.1.1 Cassava

Cassava (*Manihot esculenta* Crantz) is a starch crop, which is grown almost entirely in the lowlands of the equatorial belt between 30° N and 30° S of latitude with an annual rainfall between 200 and 2000 mm (Figure 4). Cassava is grown on approximately 80 million hectares in 34 African countries (Infonet Biovision, 2009). It is an important crop in subsistence farming because of the low production skills or inputs requirements. It is drought tolerant, produces reasonable yields under adverse conditions and can be kept in the soil as a famine reserve (Infonet Biovision, 2009).

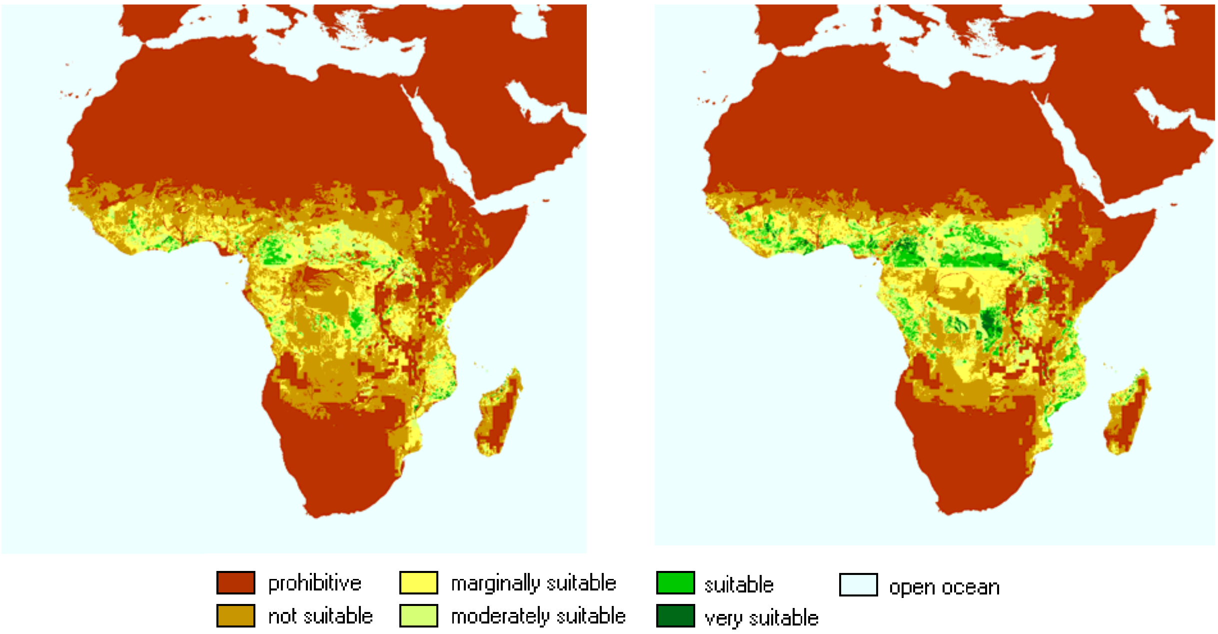

Figure 4: Crop suitability for rainfed cassava, low input level (left) and high input level (right)
Source: FAO/AGL, 2003

According to FAO, suitability for rainfed cassava production is prohibitive in Botswana and South Africa and not suitable in many other regions of the other countries (Figure 4). Despite its unsuitability in many regions of the countries studied here, literature shows that cassava is still produced there and in some countries even with high yields (see section 4.2.1 for a description of cassava yields).

Nguyen et al. (2008) describe cassava cultivation as follows for Thailand, which is indicative also for cassava production in Africa:

> "Well known for its tolerance/resistance to drought and insects/pests, cassava does not require irrigation and insecticide/pesticide application in general. Weeding is required during the first few months until the cassava plants develop shade large enough to compete for sunlight. The

direct farm inputs thus include stem cuttings, diesel fuel, labor, fertilizers, and herbicides. The steps involved in this stage are land preparation, planting, crop maintenance (fertilization, weed control), and harvesting including loading. Land preparation for cassava cultivation in Thailand is done by diesel tractors; most farmers apply plowing two to three times with three-disc plow, seven-disc plow, four-disc plow and/or ridging. Land preparation is followed by new crop planting. In general, cassava is propagated vegetatively through stem cuttings prepared from the residual stems left after roots are separated at harvest. Normally, stem cuttings preparation and planting take place at the same site, which is good in terms of saving fuel and labor costs for transportation, loading, and unloading. Manual planting is a common practice in Thailand since it does not consume much labor here, about 1.5 man-days/rai ('rai' is the Thai measurement unit for land area; 1 rai = 0.16 ha). For crop maintenance, commercial fertilizers and locally-prepared manure are the two types of materials farmers use to improve soil fertility/physical conditions. Weeding is carried out by hand, herbicides and/or small tractors. Cassava can be harvested either manually or mechanically; in Thailand manual harvest is more usual, though it is considered more labor-intensive, amounting to 3.2–6.4 man-days/rai (Howeler 2000). In the dry season, mould-board ploughs may be used to make manual digging less arduous."

The cassava starch can be used in producing ethanol. Cassava fresh roots contain around 30% carbohydrates, whereas dried chips can have up to 60%, therefore they represent some of the richest fermentable feedstock for ethanol production. The process to obtain ethanol from cassava includes the following steps (Smeets et al., 2009) (see also illustration of Nguyen et al., 2008, Figure 5):

- *Feedstock pretreatment:* washing and crushing;
- *Pulp cooking:* this step is necessary to remove cyanogenic compounds;
- *Saccharification:* this can be achieved by either mixing the pulp with hydrochloric acid or sulphuric acid in pressure cookers or by partial hydrolysis and enzymatic treatment. With these treatments the starch contained in the pulp is transformed into fermentable sugars.
- *Neutralization:* buffering salts such as sodium dicarbonate (Na_2CO_3) are added to the mixture to remove the free acids and bring the pH value in the range 5.0-7.0, that is compatible with the activity of yeasts that carry on fermentation;
- *Fermentation:* this phase lasts for 3-4 days and produces a solution containing 6-12% ethanol.
- *Distillation:* This is obtained by treating the fermented solution (containing also some solid residues) in a multi-column system where ethanol is evaporated at 78°C and condensed into liquid several times. At this stage the concentration of ethanol in the solution can achieve 95%.
- *Dehydration:* fuel ethanol must have 99.75% concentration. To remove excess water, dehydration can be performed by mixing the solution with organic compounds (i.e. cyclohexhane), which are then recovered and reused or by adopting a "molecular sieve" that separates water from alcohol.

Cassava-based ethanol can be used for cooking in improved stoves or as gasoline substitute in cars.

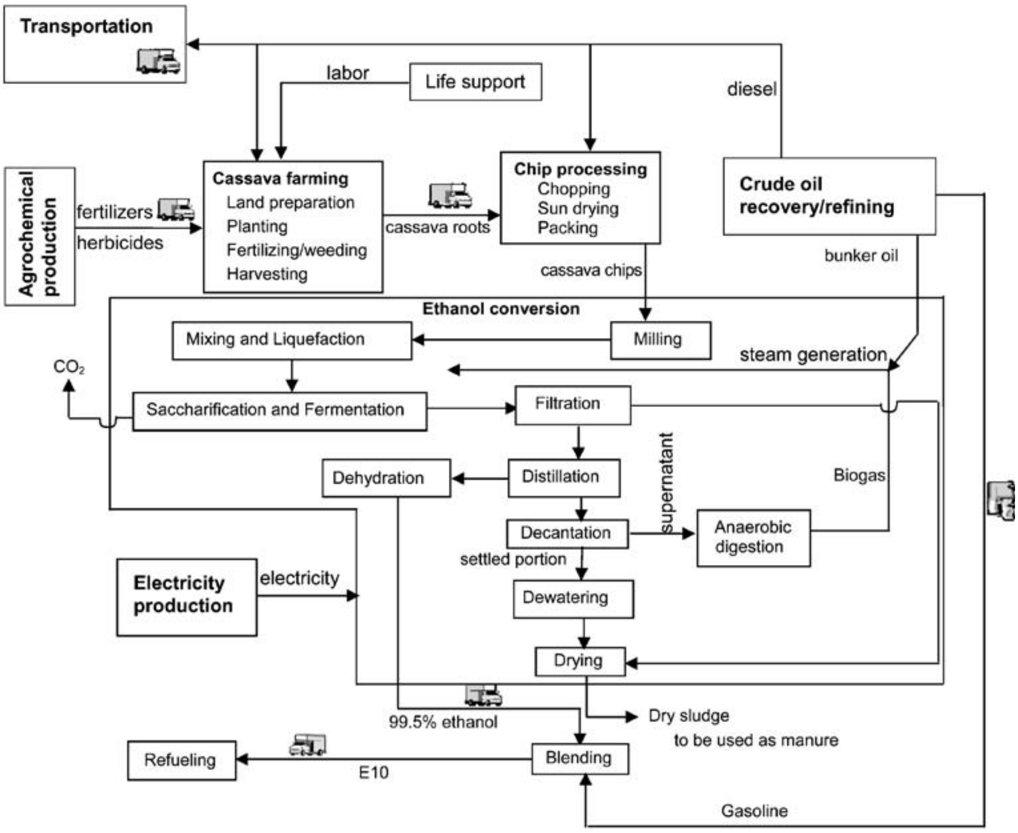

Figure 5: Flow chart of cassava-based E10 production process (Nguyen et al., 2008)

4.1.2 Jatropha

The following description of jatropha and its production system is a summary of the work of van Eijck (2007):

Jatropha curcas L. is a large shrub or small trees (up to 8m) that produces seeds that are rich in oil (30 to 40%) and can live up to 50 years. The root system of Jatropha plants consists of three to four lateral roots and a vertical taproot which can reach five meters into the soil. Jatropha tolerates minimum rainfall of 250 mm and a maximum of 3000mm. Jatropha is found up to an altitude of 1800 m above sea level.

Provided the nutrient level is sufficient, plant growth is a function of water availability, especially in the tropics. When water is available Jatropha growth is rapid and a thick hedge can be formed within nine months after planting.

The shrub produces fruit between 5 months to 3 years after planting and is usually harvested in the dry season, when agricultural labor demands are low. The fruit contains two seeds that are non-edible but rich in oil. The oil contains a toxic substance, curcasin, which is a strong purgative. The press cake is rich in nitrogen and therefore often used as fertilizer. Because Jatropha is not a nitrogen-fixing plant, it requires nitrogen rich soils for good seed production. Still, Jatropha is easy to establish even in soils which are quite infertile and is drought resistant.

Jatropha oil can be used directly for running diesel engines or used to produce methyl ester which can be used in almost every engine that is designed to run on petroleum diesel (Smeets et al., 2009). Vegetable oil methyl esters are produced by reacting 10 parts of vegetable oils with 1 part of methanol. The products of the reaction are 10 parts of vegetable oil methyl ester (biodiesel) and 1 part of glycerin. The resulting methyl esters can be used in practically any diesel engine with minimal - if any - modification. They have a very similar energy content per liter to petroleum diesel and a very similar viscosity. However, unlike petroleum diesel they are no more poisonous than vegetable oils and are quickly biodegradable (Smeets et al., 2009). However, it is important to note that the production of biodiesel from jatropha oil is expensive due primarily to the high costs of methanol imports.

An important by-product of jatropha oil or jatropha biodiesel production is the press cake. It is actually considered a secondary product because of its volume (70% of the seed volume) and its economic value (e.g., in Tanzania it is traded at about 50 to 60 Euro t^{-1}). The press cake can be used for, for example, fertilizer, fuel for industrial boilers or as feedstock for local biogas and power generation. However, in Africa where nutrient balance are already a problem it is important that the nutrients taken out must be replenished, whether this is through direct use of press cake or the biogas substrate as fertilizer or providing alternative sources of fertilizer. While it was found that the GHG balance of jatropha oil is better when the press cake is used for energetic purposes rather than fertilizer (Reinhardt et al., 2007), it could be advantageous option to first use the press cake for biogas production and then use the substrate as fertilizer – providing both energy and fertilizer. However, as jatropha seeds are commonly transported to a central location where they are processed, the logistics of returning the press cake back to fields is likely to be difficult and too costly.

4.1.3 Woody crops

Woody crops are generally fast-growing plants like grasses or trees, which are cultivated for energy production, but can also be forestry or agricultural residues. In this study, the focus is placed on dedicated woody biomass production for energy, which among the different types of woody crops has the largest potential. Short rotation woody crops are fast growing hardwoods, planted at high density and generally harvested two to twelve years after planting. In the case of arid and semi-arid climates, the rotation period is likely to be closer to the higher end of this range in order to allow for more efficient harvesting.

Maintenance of the plantation can include weeding, fertilizer and pesticide application, and clearing of fire breaks. During harvest, the stems are cut down to near ground level. Coppicing species are chosen so that new shoots emerge from the stump and grow until the next harvest.

The harvested wood can be used for various energetic purposes such as direct use as fuel wood for cooking, heating and lighting, (co-)firing for electricity production, ethanol production via fermentation and biodiesel via gasification/Fischer-Tropsch process. In this study, the focus is placed on wood used as fuelwood as this does not require major modification to current energy use in Africa while the other technologies are also not widely available yet in Africa. In order to make full use of the potential, it is important that fuelwood from dedicated bioenergy production is combined with more efficient stoves (see also Smeets et al., 2009).

4.2 Yields

4.2.1 Cassava

Cassava yields are given in FAO statistics (FAOSTAT, 2009) and their developments over time are presented in Figure 6. Large fluctuations can be seen in almost all countries. For all countries except Senegal and Burkina Faso increases in yields, especially in the last 15 years, can be seen.

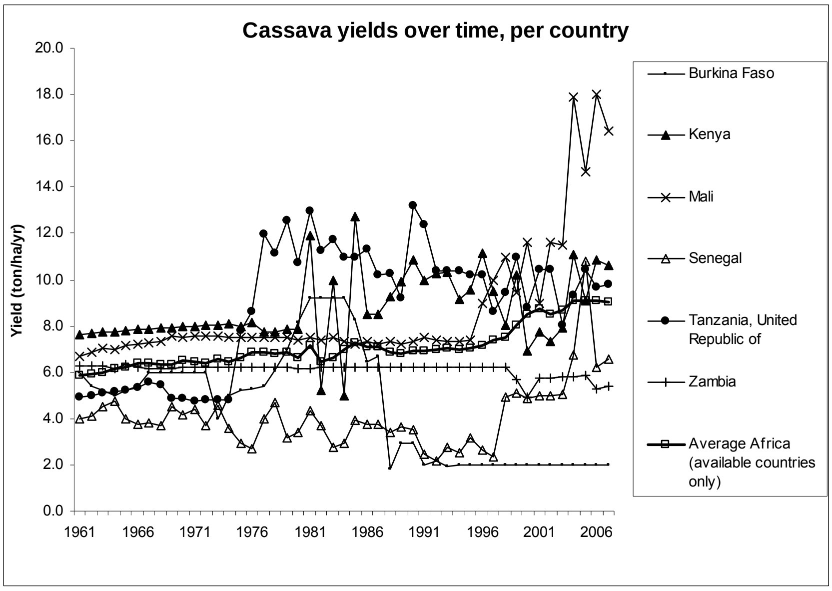

Figure 6: Cassava yield over time
Source: FAOSTAT, 2009

The average yields for 2000 and 2007, as well as the average of annual yields between 1997 and 2007 are presented in Table 3. Large differences in the countries studied are found, where the highest yield is found in Mali and the lowest in Burkina Faso. Cassava yield data for Botswana and South Africa are not available in FAOSTAT.

Table 3: Overview of national average cassava yields in 2000, 2007 and average of 1997 to 2007

	Burkina Faso	Kenya	Mali	Senegal	Tanzania	Zambia	Average
				t ha^{-1} yr^{-1}			
2007	2.0	10.6	16.4	6.6	9.8	5.4	8.5
2000	2.0	6.9	11.6	4.9	8.8	4.9	6.5
1997 – 2007	2.0	9.0	12.8	5.7	9.6	5.7	7.5

Sources: FAOSTAT, 2009
Note: 2007 is the last year for which yield data is available from FAOSTAT. Cassava production data for Botswana and South Africa are not available in FAOSTAT.

Because FAOSTAT data does not distinguish between different climatic zones it is important to review the literature for yield estimates in arid and semi-arid regions. However, not much information is available that refers specifically to cassava production yields in arid and semi-arid regions. Sama and Kunchain Darunee (1991), for example, suggest that the average cassava yield in semi-arid tropics in Sub-Saharan Africa is 4.8 t ha^{-1} yr^{-1}.

For two of the eight countries investigated here (Zambia and Burkina Faso), sub-national yield data could be obtained. Zambia's provinces Southern and Western are the provinces most affected by semi-arid conditions. In these two regions, cassava yields of 0.15 t ha^{-1}y^{-1} and 2.47 t ha^{-1} y^{-1} could be obtained for the cropping season 2007/2008, respectively (Central Statistical Office Zambia, 2009). The national average according to this source amounts to 3 t ha^{-1} y^{-1}, which is significantly lower than FAOSTAT data. While reasons for this discrepancy could not be determined based on the existing information, it is important to note the much lower yield in the Southern province than the national average. A possible reason maybe the climatic differences. But they may also be other factors and erratic rainfall could have been a cause for lower than usual productivity, no other years to compare with.

While the Central Statistical Office Zambia suggests lower yields than FAO, the Southern Africa Root Crops Research Network (2008) assesses yields for 2007/8 to be much higher than FAO estimates. The overall mean cassava root yield in farmers fields in 10 Zambian districts is 18 t ha^{-1} y^{-1}, while a minimum of 2 t ha^{-1} y^{-1} and a maximum of 56 t ha^{-1} y^{-1} was recorded (Southern Africa Root Crops Research Network, 2008).

For Burkina Faso only few data points for sub-national cassava production could be obtained (Statistique sur l'Agriculture et l'Alimentation du Burkina Faso, 2009) for 1984 to 1986. Data is available for the provinces Namentenga, Bam and Sanmatenga in the region Centre Nord, which is semi-arid. Yields in 1984 to 1986 ranged from 14.5 to 24.5 t ha^{-1} y^{-1} (Namentenga), 15-32 t ha^{-1} y^{-1} (Bam) and 3-15.8 t ha^{-1} y^{-1} (Sanmatenga) (Statistique sur l'Agriculture et l'Alimentation du Burkina Faso, 2009). These yields were generally higher than the national average cassava yield in the same time frame (9.2 to 6.5 t ha^{-1} y^{-1}) provided by FAOSTAT (2009).

Not included in the country analysis is Nigeria but its sub-national data for cassava production is useful to present here. The average yield in semi-arid areas is 4.3 t ha^{-1} y^{-1} in 1998 and 3.6 t ha^{-1} y^{-1} in 2002, while national averages are 10.7 t ha^{-1} y^{-1} and 11.8 t ha^{-1} y^{-1} respectively (Anonymous, undated). The national average in 1998 is identical to the one presented by FAOSTAT, while the FAOSTAT 2002 average is 9.9 t ha^{-1} y^{-1}. This example shows that yields can be significantly lower in semi-arid and arid regions than country averages from FAOSTAT. However, unlike Nigeria, not sufficient and not recent sub-national specific yield data for cassava could not be found for the eight countries studied here to be able to account for variations in yields due to the climatic zones.

While cassava yields in semi-arid regions appear lower than national averages, the available data is sparse. Important to mention is that there are many initiatives that aim at increasing cassava yields. For example, the USAID funded project “Unleashing the Power of Cassava in response to the food price crisis (UpoCA)” aims at yield improvements from current 7 and 12 t ha^{-1} y^{-1} across Nigeria, DR Congo, Ghana, Malawi, Mozambique, Sierra Leone and Tanzania to between 12 and 30 t ha^{-1} y^{-1} (Africa News, 2009). Also high yielding cassava varieties are being developed for drier climates (Mmegi Online, 2007). Thus, while the FAO yields used here are not specific for semi-arid and arid regions more drought-tolerant cassava varieties and improvements in agricultural management may allow reaching such yields or maybe even surpassing them even in drier climates.

Lacking FAOSTAT data on cassava yields in South Africa may be due to the fairly recent development of the production of high quality starch from cassava on an industrial scale (Tewe, 2004). Tewe (2004) suggests that cassava yields of 50 t ha^{-1} yr^{-1} have been observed on a 5000 ha farm in South Africa. However, climatic conditions under which such a yield could be achieved are not specified and it is unlikely that reference is made to rain-fed conditions in semi-arid or even arid regions.

A yield estimate for cassava ethanol production is provided by Gibbs et al. (2008) who suggest the mean yield for dry African tropics to be 1379 liters ha-1 (see also Figure 7). Assuming a conversion efficiency of 180 l t^{-1} (Gibbs et al., 2008), this is equivalent to a cassava root yield of 7.7 t ha^{-1} yr^{-1}.

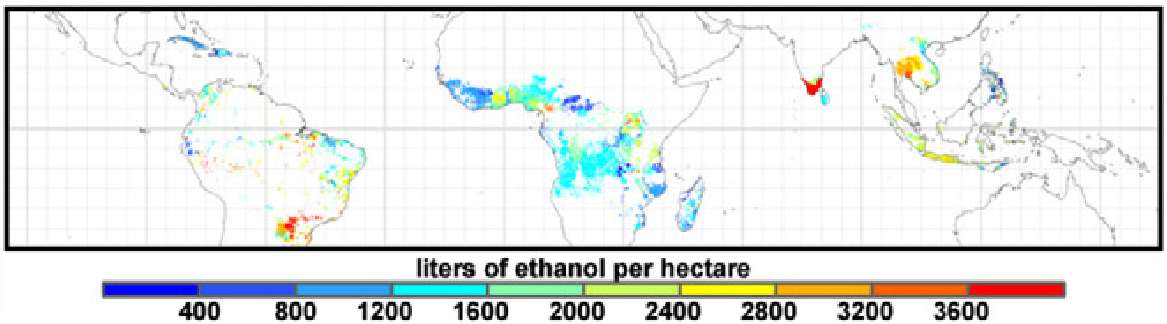

Figure 7: Potential cassava ethanol yields derived from a new global database of crop yields and locations (Gibbs et al., 2008)

Based on the various data sources and their shortcomings presented above, cassava yields from FAOSTAT are applied in the remainder of the analysis. While country specific data is available for six of the eight countries investigated (exceptions are Botswana and South Africa, where no data is available in FAOSTAT), differences in yields in arid and semi-arid regions and national averages are not known. Yields in Botswana and South Africa are assumed to be similar to the average Sub-Saharan yield for semi-arid regions as estimated by Sama and Kunchain Darunee (1991) (4.8 t ha^{-1} y^{-1}).

4.2.2 Jatropha

Large differences in Jatropha yields have been found in literature An overview of some sources has been made by Heller (1996) and Jones and Miller (1993) (In: van Eijck, 2007) and is presented in the appendix (see Section 10.4). Yield estimates from recent studies suggest much lower yields than thought possible earlier. While Openshaw (2000) suggests that yields may range between 0.4 and 12 t ha^{-1} y^{-1}, more recent studies suggest a maximum potential yield of 7.8 t ha^{-1} y^{-1} (e.g. Jongschaap et al., 2007), see also Table 4.

Table 4: Overview of jatropha seeds yields

Reference	Unit	Yield	Notes
Openshaw, 2000	t seeds ha^{-1} y^{-1}	0.4 – 12	
Jongschaap et al., 2007	t seeds ha^{-1} y^{-1}	1.5 – 7.8	potential yield
Reinhardt et al., 2007	t seeds ha^{-1} y^{-1}	2.3/3.8/6.5	today/optimized/best, on poor soils in India
Achten et al., 2008	t seeds ha^{-1} y^{-1}	2 – 3	semi-arid regions and cultural waste lands, citing Heller 1996 and Tewari 2007

Yield estimates for the countries focused on in this study could only be found for Burkina Faso, Mali and Tanzania, where arid and semi-arid regions are not always distinguished (Table 5).

Table 5: Overview of jatropha seed yields

	Burkina Faso	Mali	Tanzania
Yield (kg seeds $shrub^{-1}$)	0.95[b]	1.6 – 5[c]	1.4[a]
Yield (t seeds $ha^{-1}y^{-1}$)	1.5[b]	2.6 – 8.0[c]	2.4[a]
Climatic zone	Not specified	Not specified	Semi-arid

Sources: a – Willem's thesis: average based on the assumption that 0.5 kg per shrub in year 3, 1 kg in year 4 and 5, 1.5 kg in year 6-8 and 2.0 kg in year 9 to 21.

b – van Eijck, 2007 (citing Zan 1985); yield per hectare is extrapolation of yield per shrub assuming 1600 shrubs ha^{-1}.

c – van Eijck, 2007 (citing Henning (personal communication), low value and Larochas (1948), high value); yield per shrub is extrapolation from yield per hectare assuming 1600 shrubs ha^{-1}.

A current study at the Department Earth and Environmental Sciences at Katholieke Universiteit Leuven in Belgium investigates the suitability and potential seed production of jatropha worldwide. The intermediate results for suitability and seed productivity are shown in Figure 8 and Figure 9. Spatially explicit data is not yet available publically.

Yield estimates are also made by Fact Foundation (2009) and illustrated in Figure 10.

Based on the large variation and uncertainties in yield estimates and the lack of sufficient data, this study cannot apply country specific yields. In order to distinguish the productivity of arid and semi-arid regions, this study simply assumes that seed yields of 2.5 t ha^{-1} y^{-1} in semi-arid regions and 1 t ha^{-1} y^{-1} can be obtained. Applying an oil content of jatropha seeds of 34% and an oil extraction rate of 90% (Fact Foundation, 2009), this results in oil yields of 0.8 t oil ha^{-1} y^{-1} semi-arid regions and 0.3 t oil ha^{-1} y^{-1} in arid regions.

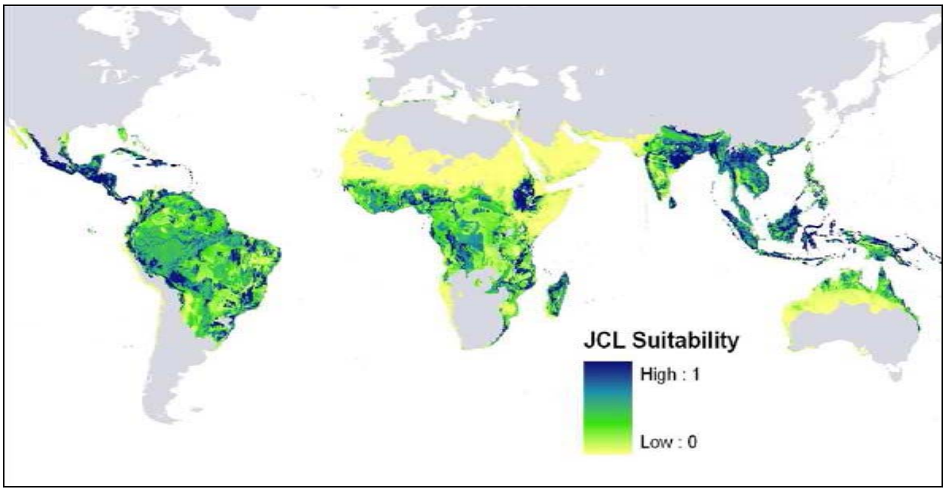

Figure 8: Suitability for jatropha production
Source: Muys et al., 2008

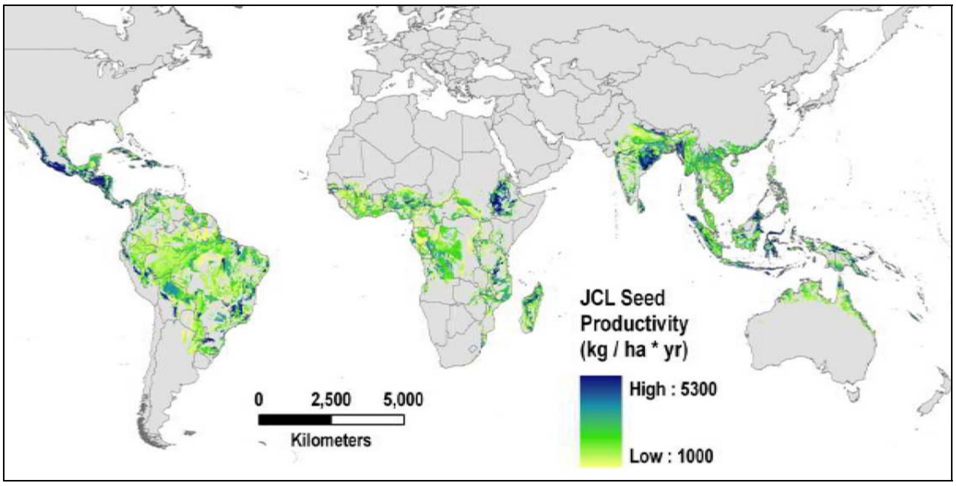

Figure 9: Jatropha seed productivity worldwide
Source: Muys et al., 2008

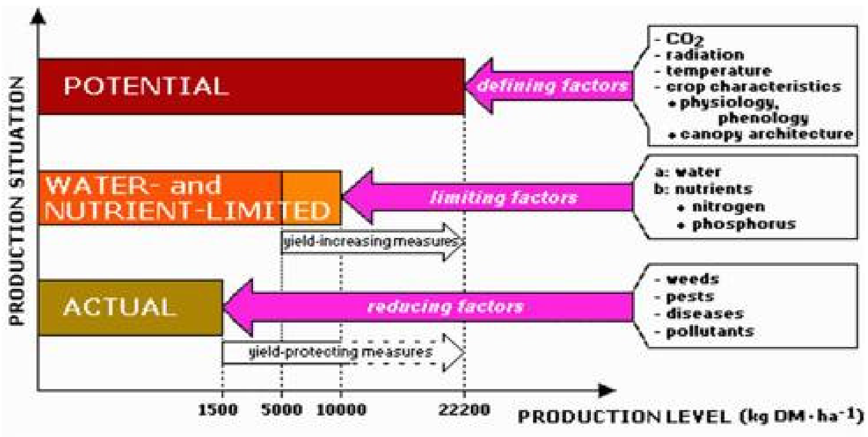

Figure 10: Jatropha seed yield for different production situations
Source: Fact Foundation, 2009

South Africa considers Jatropha an invasive species, which is why it is prohibited from cultivation there. However it is important to mention that there are businesses which are attempting to reverse this government decision so that Jatropha could be used for bioenergy production. Therefore, the analysis includes a calculation of the jatropha oil production potential. However, it should be stressed that this potential is only realizable if the South African government reverses its decision on prohibiting jatropha cultivation.

4.2.3 Woody crops

Woody crop yields are determined in this study based on results from the IMAGE model (Leemans and Born, 1994), see also Box 2. The yields for the eight countries by arid and semi-arid regions are presented in Table 6.

The data presented here are weighted averages and it is important to note that in some areas there maybe higher yields while in others there maybe lower and less economic yields. In order to validate the IMAGE results, here an overview of woody crop yields from literature on Africa is presented (Table 7). A direct comparison among literature findings and with IMAGE results is often difficult because of the lacking or inadequate information on the climatic zone that is referred to in the literature. Still, it is important to note that, for example, Marrison and Larson (1996) determine very comparable yield estimates for semi-arid regions for Botswana and Tanzania, while their estimates are higher than IMAGE results for Burkina Faso, Kenya and Senegal and lower for Mali and South Africa.

Table 6: Overview of average rain-fed yields of woody crops based on IMAGE, by country and climate zone

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
				t dm ha^{-1} y^{-1}				
Arid	0.6	6.8	9.1	2.5	6.1	1.3	n/a	n/a
Semi-arid	5.6	10.0	11.5	8.2	7.4	9.8	13.0	9.7

Note: Yields are based on rain-fed woody crop yields generated by the IMAGE model and calculated by taking the average yields for the area marked as arid or semi-arid in WP1. The average refers to the whole arid or semi-arid region and does not exclude areas that are marked unavailable or unsuitable in WP1.
Source: Bouwman et al., 2006

Table 7: Overview of woody crop yields from literature (no differentiation for climatic zones)

Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia	Africa
				t dm ha^{-1} y^{-1}				
		13.5 – 20.7[b]			8.8[a]	4.6 – 10.2[d]	15.2[c]	3-7[f]
5.3[c]	15.3[c]	16.1[c]	6.6[c]	9.2[c]	6.6[c]	13.3[c]		0.5-6[g]
						10 – 12[e]		

a – Mead, 2001; average productivity of eucalyptus species (mainly *Eucalyptus grandis*) is 21 m^3 ha^{-1} yr^{-1} in South Africa. This is equivalent to 8.8 t ha^{-1} yr^{-1} assuming a wood density of 0.42 t m^{-3} in the case of *Eucalyptus grandis*.

b – Mead, 2001; *Eucalyptus grandis*; 30 m^3 ha^{-1} yr^{-1} in first 6 years, closer to 46 m^3 ha^{-1} yr^{-1} for coppice crop.

c – Marrison and Larson, 1996; yield not specific to semi-arid or arid regions but based on average rainfall of a country.

d – Kimaro et al., 2007; average yield over five years for several acacia species.

e – Nyadzi et al., 2003: yields for *Acacia polyacantha* and *Leuceana leucocephala* over a period of 7 years in Shinyanga (rainfall 700mm on average).

f – IPCC, 2006 (Chapter 4, p. 59); forest plantations in Africa's tropical shrubland (includes both arid and semi-arid ecosystems), aboveground biomass growth for eucalyptus of less than 20 years ranges from 3 to 7 t dm ha^{-1} y^{-1}, average is 5 t dm ha^{-1} y^{-1}.

g - IPCC, 2006 (Chapter 4, p. 59); forest plantations in Africa's tropical shrubland (includes both arid and semi-arid ecosystems), aboveground biomass growth for pinus of less than 20 years ranges from 0.5 to 6 t dm ha^{-1} y^{-1}, average is 3 t dm ha^{-1} y^{-1}.

In addition to yields, also the survival rate of seedlings is very important in determining productivity. Survival rates are often low in very dry conditions, which is why in some cases it may be beneficial to irrigate the seedlings/trees in the initial years of cultivations.

4.3 Biomass Potential

4.3.1 Cassava

The cassava ethanol production potential of the eight countries is presented in Table 8. The total in the eight countries amounts to 1251 PJ y^{-1}. Important for interpreting the results is the use of FAO country average yields. This data is not specific for arid and semi-arid regions (Section 4.2.1), where yields and consequently the potential are likely to be lower. However, no better data is available to provide climate specific potentials.

Table 8: Cassava ethanol potential from available land in semi-arid and arid regions in eight countries

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}
Potential total	**84**	**16**	**351**	**175**	**18**	**192**	**360**	**55**
arid	39	0	86	40	7	91	n/a	n/a
semi-arid	45	16	266	135	11	102	360	55

4.3.2 Jatropha

The jatropha oil production potential of the eight countries is presented in Table 9. Total jatropha oil potential in the eight countries amounts to 1621 PJ y^{-1}. Assuming a similar conversion efficiency as palm oil to palm oil biodiesel (0.96 t biodiesel t^{-1} crude palm oil; Wicke et al., 2008), then the biodiesel production potential is equivalent to 1556 PJ y^{-1}.

Table 9: Jatropha oil production potential from available land in semi-arid and arid regions in eight countries

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}
Potential total	**154**	**71**	**420**	**167**	**30**	**(354)**	**338**	**88**
arid	70	0	154	72	13	(163)	n/a	n/a
semi-arid	84	71	266	95	17	(191)	338	88

Note: While the South African government prohibits the cultivation of Jatropha (see also Section 4.2.2), the results are presented here to indicate the potential jatropha production in South Africa.

4.3.3 Woody crops

Woody biomass production potential for the eight countries is presented in Table 10. Total woody biomass production potential in the eight countries amounts to 10929 PJ y^{-1} and is significantly larger than jatropha and cassava production potentials. While a direct comparison of the different crops is not fair due to the different end products (woody biomass vs. liquid biomass), accounting for conversion losses for converting woody biomass to liquid fuels (approximately 50%; Hamelinck et al., 2003) would still result in a larger potential for woody crops than for cassava or jatropha (see also Figure 11 for a comparison between the crops).

While the bioenergy production potential of woody crops is significantly larger than that of cassava or jatropha (Figure 11), with all three crops significant contributions to current energy consumption, which amounted to approximately 6000 PJ yr^{-1} in the eight countries combined in 2006 (see Appendix, Section 10.5), could be made.

Table 10: Woody crop biomass potential from available land in semi-arid and arid regions in eight countries

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}	PJ y^{-1}
Potential total	370	455	4205	782	207	1544	2819	547
arid	69	0	2243	285	124	339	n/a	n/a
semi-arid	300	455	1962	497	83	1205	2819	547

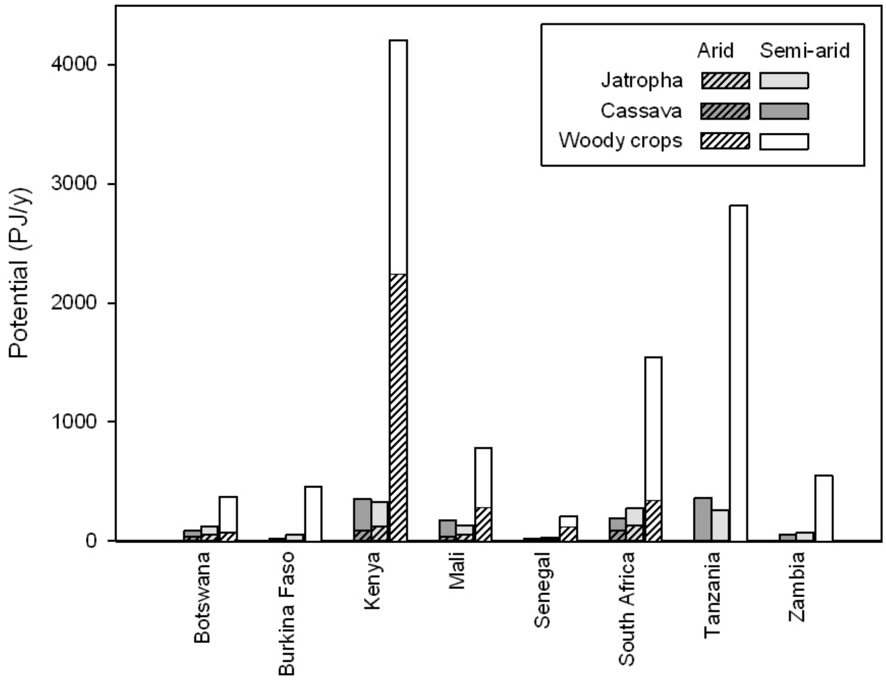

Figure 11: Potential biomass production in arid and semi-arid regions, by country and crop

Note: While the potentials of cassava, jatropha and woody crops are compared to each other here, it is important to note that woody crops are not processed here but assumed to be used as fuelwood. Further processing would allow for a fairer comparison and would reduce the potential of woody crops. This reduction depends on the type of conversion (e.g. ethanol production via fermentation or Fischer-Tropsch fuel) but can be estimated at 50% when not including the co-production of electricity (Hamelinck et al., 2003). Despite such conversion losses, the potential for woody-crops-based liquid biofuels will still be larger than for cassava or jatropha.

Note: While the South African government prohibits the cultivation of Jatropha (see also Section 4.2.2), the results are presented here to indicate the potential jatropha production in South Africa.

4.4 Integration of bioenergy production in current agricultural practices

4.4.1 Cassava

In Africa, cassava is commonly intercropped with vegetables such as yam, sweet potato, melon, maize, rice, groundnut, or other legumes or plantation crops such as coconut, oil palm, and coffee (IITA, 2009). Intercropping is possible due to the wide spacing of cassava and the slow initial development. Due to this slow initial growth and poor initial soil cover, cassava cultivation can cause water erosion and soil degradation (Leihner, 2002). These negative effects can be reduced by planting intercrops (see also the description of ecological impacts of cassava production in Section 7.2).

4.4.2 Jatropha

Jatropha is not frequently cultivated as a mono-crop at this moment because relatively large investments are required and the returns only start coming after a few years. Jatropha is currently planted as fences around fields. It not only serves as a long-term investment and diversification of the farmer's outputs, but also as a fence or barrier for browsing livestock as it is non-edible. Jatropha can also be intercropped with food crops, applying alternating rows of jatropha and the food crop.

4.4.3 Woody crops

As for jatropha, woody crop production requires relatively large initial investments while income is generated only in later years. This is often a problem for small farmers, who may not have the financial means for such investments and slow returns. As a result, woody crops are often integrated with other crop production. Integration of woody biomass and agricultural crop production can take different forms: 1) fences surrounding the field, 2) intercropping alternating rows with trees and food crops and 3) rotational woodlots, where growing of trees and crops are grown in inter-related phases (Wiskerke, 2008). Earlier work within the COMPETE project (Dornburg et al., 2009) describes rotational woodlots as follows: "The idea of rotational woodlots is that trees are planted together with food crops for the first three years and when it is not economical to plant crops under the tree canopy trees are left to grow for other two to three years before they can be harvested for fuel and construction. Farmers, however, have left their trees longer than the predicted rotation age of five years, and some left their trees up to more than ten years. Fast growing Australian acacias have yielded 40 – 90 tons per ha of dry wood in only five years. Rotational woodlots have great potential in rehabilitation of degraded lands in the country. Species used are among others: Australian acacias, Senna siamea, Acacia nilotica, Acacia polyacantha, Brachystegia spiciformis, Teminalia sericea, Pterocarpus angolensis, Afzelia quanzensis, Melia azedrach, Casuarina junghuhniana and Cedrela odorata. Wood can be used to supply both fuelwood and timber."

The integrated production of food and energy crops may result in reduced yields due to competition for light, water and nutrients. For the rotational woodlot system, Nyadzi et al (2003) found that maize yield was similar to sole maize in first two years and that maize yields were higher after the 5-7 tree fallow period than natural fallow or regular cropping. The latter result is likely due to increased fertility induced by woodlots (Nyadzi et al., 2003).

In addition to intercropping with other/food crops, also some tree products, for example leaves or pods of certain tree species, can be used for fodder. These additional products of trees are often an important source of fodder during dry seasons when other fodder crops are not growing.

5 The Economics of Bioenergy Crops in Semi-Arid and Arid Sub-Saharan Africa

5.1 Cassava Production Costs

Cassava production costs are not well described in literature. Tewe (2004) finds that the average costs with traditional agricultural practices in Nigeria amounts to 50 US\$ t^{-1} (40 Euro t^{-1}) but also describes that experience from South Africa indicates that using modern agronomic techniques cassava can be produced at 20 US\$ t^{-1} (16 Euro t^{-1}). The latter compares well with cassava production costs in Thailand, which range between 23 and 28 Euro t^{-1} (Nguyen et al., 2008). The cost structure of cassava root production in Thailand is presented in Figure 12.

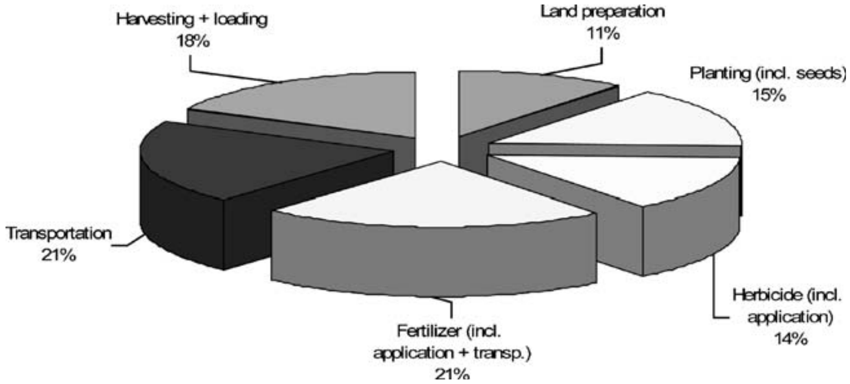

Figure 12: Cassava root production cost structure in Thailand (Nguyen et al., 2008)

Regarding the costs of converting cassava roots to ethanol, the only data found in literature refers to Thailand and is presented here to give an idea of potential ethanol production costs in Africa. In Thailand ethanol production costs 0.4 Euro l^{-1} of which 0.24 Euro l^{-1} are the feedstock costs (Nguyen et al., 2008). Figure 13 shows the cost breakdown of ethanol production in Thailand.

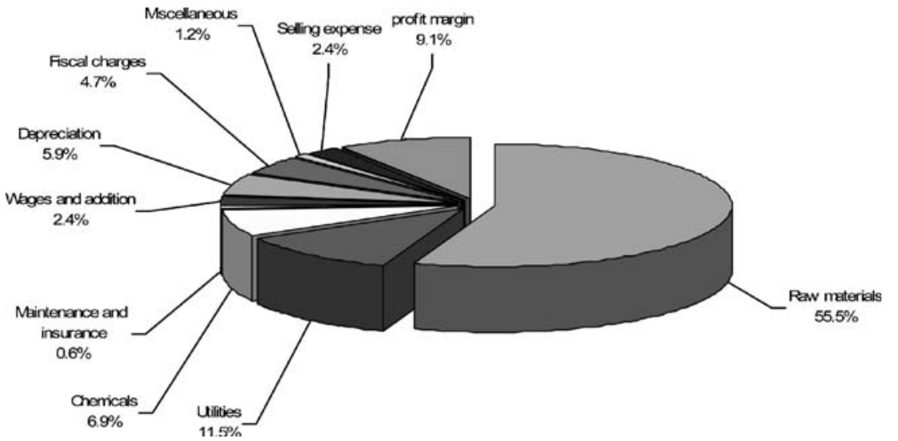

Figure 13: Breakdown of ethanol ex-distillery price in Thailand (Nguyen et al., 2008)

If cassava ethanol production costs in Africa can be made comparable to those presented here for Thailand, then production costs would be lower than the gasoline market prices in the eight countries (**Fehler! Verweisquelle konnte nicht gefunden werden.**) and, when accounting for taxes and distribution costs, cassava ethanol may be competitive with fossil gasoline.

Table 11: 2004 gasoline and diesel prices in Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
				US$ l^{-1}				
Gasoline price	0.66	1.18	0.92	1.16	1.1	0.81	0.93	1.1
Diesel price	0.61	0.94	0.76	0.9	0.9	0.8	0.87	0.98
				Euro l^{-1}				
Gasoline price	0.53	0.94	0.74	0.93	0.88	0.65	0.74	0.88
Diesel price	0.49	0.75	0.61	0.72	0.72	0.64	0.70	0.78

Source: World Bank, 2005

5.2 Jatropha Production Costs

Jatropha seed production costs are estimated by Loos (2009) and Wiskerke (2008). Loos finds that production costs amount to 220 TZS ha^{-1} yr^{-1} on average over 10 years (122 Euro ha^{-1} yr^{-1}). Applying the three levels of yields that Loos uses in his study, then the production costs amount to 81.3 Euro t^{-1} (average yield of 1.5 t ha^{-1} yr^{-1}), 61 Euro t^{-1} (average yield of 2.0 t ha^{-1} yr^{-1}) and 23 Euro t^{-1} (average yield of 5.2 t ha^{-1} yr^{-1}). Wiskerke determines a seed production cost of 98 US$ t^{-1} with an average yield 2.5 t ha^{-1} yr^{-1} over 20 years.

Jatropha oil production costs are determined by Wiskerke (2008) to amount to 0.73 US$ l^{-1} (0.53 Euro l^{-1}). Mulugetta (2009), however, finds that jatropha biodiesel production costs – thus including the additional conversion step from jatropha oil to biodiesel – range between 0.4 and 0.6 US$ l^{-1} (0.27 Euro l^{-1} – 0.41 Euro l^{-1}). A Goldman Sachs study (cited by Société d'Agriculture et de Développement Rural sprl, 2009) estimates production costs of jatropha biofuel to be 43 US$ per barrel, which is equivalent to approximately 300 US$ t^{-1} biodiesel (0.25 Euro l^{-1}) and comparable to Mulugetta's lower estimate.

Considering the diesel market price in the eight countries in 2004 (**Fehler! Verweisquelle konnte nicht gefunden werden.**), the price in Shinyanga, Tanzania in 2007 ranging from 0.83 to 1.00 Euro per liter (Wiskerke, 2008) and the price in Ghana, Kenya and Tanzania in 2008 being 0.88 US$ l^{-1} (0.6 Euro l^{-1}), 0.99 US$ l^{-1} (0.7 Euro l^{-1}) and 0.88 US$ l^{-1} (0.6 Euro l^{-1}), respectively (Mulugetta, 2009), jatropha biodiesel may be competitive with fossil diesel even when accounting for taxes and distribution costs.

5.3 Woody Crops Production Costs

For fuelwood in Tanzania, Wiskerke et al. (Wiskerke et al., 2009) finds a production cost of 0.53 US$ GJ^{-1} (0.39 Euro GJ^{-1}), which is considerably cheaper than the market price of fuelwood at 1.95 US$ GJ^{-1}. Batidzirai et al. (2006) finds wood production costs in Mozambique to amount to 13 to 22.5 Euro t^{-1} dm (0.65 to 1.15 Euro GJ^{-1}). Production costs increase with additional processing. Batidzirai et al. (2006), for example, estimate that pellet production costs amount to between 2.6 and 5.6 Euro GJ^{-1} (local vs. central conversion type), that pyrolysis costs 3.2 – 7.0 Euro GJ^{-1} and Fischer-Tropsch fuel production costs between 6.8 and 10.8 Euro GJ^{-1}.

6 The Socio-Economic Impacts of Bioenergy Crops in Semi-Arid and Arid Sub-Saharan Africa

6.1 Income Generation

6.1.1 Cassava

A large range of NPV of cassava production can be found in literature. Osemeobo (1993) finds a NPV of cassava production Nigeria's savannah of 21.2 US\$ ha^{-1} (18.0 Euro ha^{-1}), while Nair (1993) finds a NPV for Thailand of 673 US\$ ha-1 (572 Euro ha^{-1}). In terms of cassava production, this is equivalent to 1.8 US\$ t^{-1} (1.53 Euro t^{-1}) in Nigeria (applying a yield of 12 t ha^{-1} as suggested by Osemeobo, 1993) and 48.1 US\$ t^{-1} (40.9 Euro t^{-1}) in Thailand (assuming an average national production of 14 t ha^{-1} in Thailand in 1993; FAOSTAT, 2009). The NPV is here also calculated based on the production costs of 50 US\$ t^{-1} (see section 5.1), the cost breakdown found for Thailand (see section 5.1), the average cassava producer price in Sub-Saharan Africa (150 US\$ t^{-1}; see Figure 14) and a discount rate of 12%. The NPV is then 134 US\$ t^{-1}. Assuming more modern production and a production cost of 20 US\$ t^{-1} (see section 5.1), then the NPV is 170 US\$ t^{-1}.

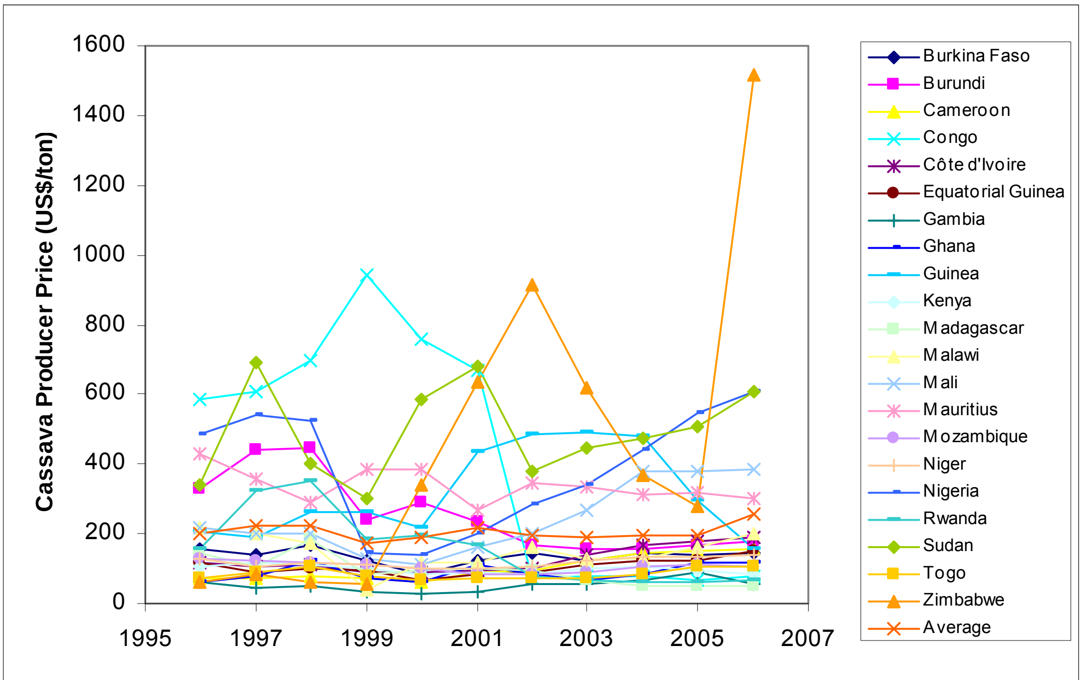

Figure 14: Producer price of cassava in various African countries between 1996 and 2006
Source: FAOSTAT, 2009
Note: All African countries are shown for which producer price data is available in FAOSTAT.

6.1.2 Jatropha

Loos determines the NPV of jatropha seed production for three different yield levels as -210 TZS (-0.12 Euro) (average yield of 1.5 t ha^{-1} yr^{-1}), 83 TZS (0.05 Euro) (average yield of 2.0 t ha^{-1} yr^{-1}) and 2084 TZS (1.15 Euro) (average yield of 5.2 t ha^{-1} yr^{-1}). It is unclear whether the author refers to a NPV on an area basis (in hectare) or a production basis (in ton or kg).

Wiskerke et al. (2009) determines the NPV of jatropha for various end uses: jatropha seed trade, jatropha oil for cooking, jatropha oil for trade, jatropha oil for electrification and jatropha oil for soap production

(Figure 15). The lowest NPV is found for jatropha oil used for cooking, while the highest is found for jatropha soap production.

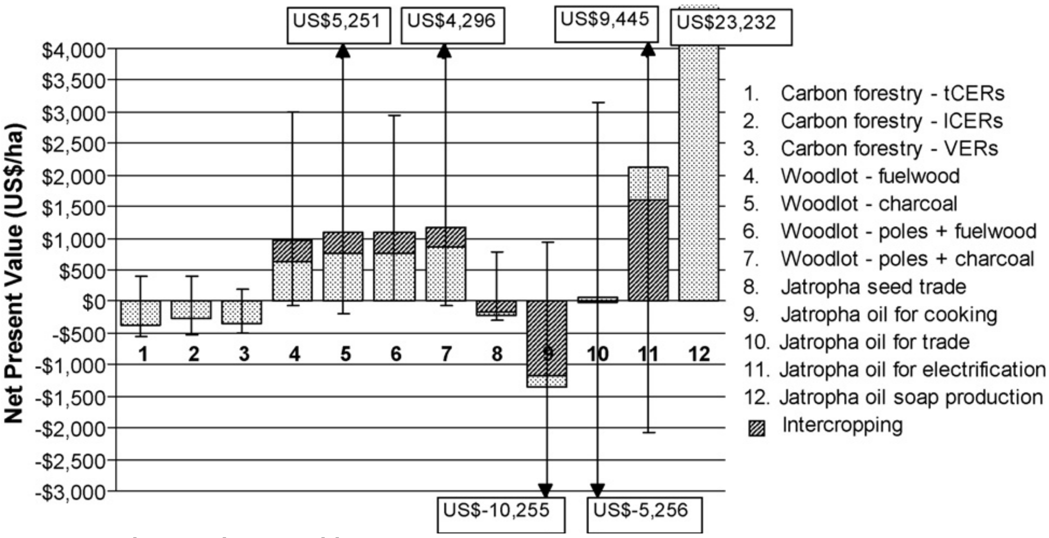

Figure 15: NPV per hectare in East Shinyanga
Source: Wiskerke et al., 2009

6.1.3 Woody crops

The NPV of fuelwood production is determined by Wiskerke et al. (2009) for Tanzania (Figure 15, stack 4) and amounts to approximately 1000 US\$ ha^{-1} (730 Euro ha^{-1}; assuming a yield of 71 t dm ha^{-1} after seven years as is down by Wiskerke et al., 2009, 43.4 Euro t^{-1}) when the trees are intercropped with maize and to 600 US\$ ha^{-1} (438 Euro ha^{-1}; 72.3 Euro t^{-1}) when there is no intercropping. No other sources were found that presented NPV data for fuelwood production.

6.2 Employment Generation

Employment generation is often seen as an important benefit of modern bioenergy production. For some Sub-Saharan African countries, however, there may also be the issue of labor shortages. As a result, high labor requirements may not be possible to meet and strategies for reducing labor requirements would need to be defined. Here, labor requirements and employment generation are assessed for the three crops and the eight countries.

6.2.1 Cassava

While labor requirements of cassava production are generally thought to be low (Infonet Biovision, 2009), labor requirements vary widely in literature. References collected here show a variation between 430 hours ha^{-1} yr^{-1} in Thailand (Nguyen et al., 2007), 600 hours ha^{-1} yr^{-1} in China (Dai et al., 2006) to an average of 1544 hours ha^{-1} yr^{-1} in Congo, Cote d'Ivoire, Ghana, Nigeria, Tanzania and Uganda (FAO and IFAD, 2005); see also Table 12. This variation maybe explained by the different types of production, such as more mechanized production in Thailand or China than in Africa and production as a famine-reserve crop versus intensive cash crop production (FAO and IFAD, 2005). While labor requirements are high in conventional production, mechanical harvesting could reduce these requirements. However, harvesting machines would still need to be developed, which can handle the non-uniform geometry of the roots in the ground (FAO and IFAD, 2005).

Important to mention here is that the data presented in Table 12 does not account for labor requirements for processing. This data could not be found in literature. However, it is clear that processing will generate additional employment. Producing liquid biofuels (especially for woody crops) is generally thought to add relatively little additional employment generation due to the mechanized production (Wicke et al., 2009) but it clearly depends on type of processing.

6.2.2 Jatropha

Literature is divided on the labor intensity of jatropha cultivation. While some studies suggests that it requires low labor inputs (Friends of the Earth, 2009), others suggests that it is actually highly labor intensive (Wiskerke, 2008); see also Table 12. High labor requirements are explained by that individual fruits ripen at different times, which is why separate and manual harvest is required. Low labor requirements are likely based on jatropha being used for combating desertification because maintenance, harvesting and processing is not required (Jongschaap et al., 2007). However, it is important to mention here that the low labor input as suggested by Friends of the Earth (2009) does account for maintenance and harvesting.

6.2.3 Woody crops

Woody crop production is generally seen to have a low labor intensity. While still showing a range of labor requirements, a low intensity is also reflected in the data found in literature (Table 12). Wiskerke (2008) presents data on labor requirements for woodlots (Figure 16). Accounting only for wood production, 25.4 man-days per hectare and year (assuming an eight hour working day this is 203 hrs ha^{-1} yr^{-1}) are required for fuelwood production. Batidzirai et al. (2006) finds that on average 100 hrs/ha/yr are needed for establishing and maintaining a woody crop plantation, while Wicke et al (2009) determine that harvesting, forwarding and loading the wood requires an additional 17 man-days per hectare per harvest. Over the four rotations and 13 years assumed in Batidzirai et al. (2006) this is equivalent to 150 hrs ha^{-1} yr^{-1}.

Table 12: Labor requirements for cassava, jatropha and woody crops – cultivation and harvest

	Labor requirements hrs ha^{-1} yr^{-1}	**Comments and Reference**
Cassava	1544	Average of Congo, Cote d'Ivoire, Ghana, Nigeria, Tanzania and Uganda; Nweke et al 2001 In: FAO and IFAD, 2005
	1456	FAO and IFAD, 2005
	600	China; Dai et al., 2006
	470	Thailand; Nguyen et al., 2008
	433	Thailand; Nguyen et al., 2007
	901	Average
Jatropha	2392	Tanzania; under maximum production; Wiskerke, 2008
	360	Swaziland; average over 20 years; Friends of the Earth, 2009
	1376	Average
Woody crops	203	Wiskerke, 2008 (excluding maize intercropping and charcoal production)
	150	Batidzirai et al., 2006 (establishment, maintenance); Wicke et al., 2009 (harvesting)
	177	Average

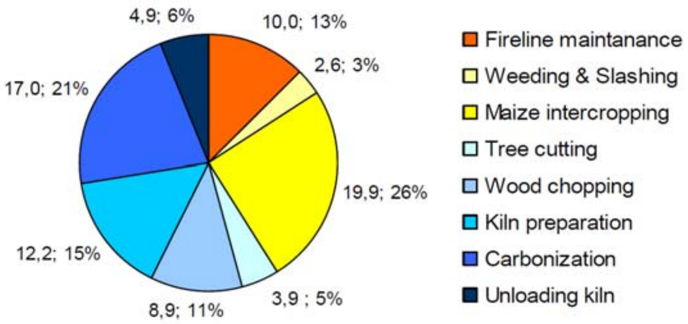

Figure 16: Breakdown of annual labor needed for poles and charcoal production after 7 years, both in absolute values (man-days/ha/yr) and relative values (%) (Wiskerke, 2008)
Note: The total annual labor requirement is 79 man-days/ha/yr. 25.4 man-days per hectare and year are required for fuelwood production (excluding maize intercropping and charcoal production).

6.2.4 Extrapolations

Extrapolating the average labor requirements per hectare (Table 12) to the total available land area results in an estimate of total employment generation of the bioenergy production potential presented in Table 13 for the three crops and the eight countries. Table 13 shows that a significant amount of jobs could be generated in all countries and for all crops. Based on the highest labor requirements for jatropha, jatropha would also lead to the highest employment generation, followed by cassava and woody crops.

When comparing these estimates to the actual labor force, it can be seen that in some countries and for some crops this could result in significant labor shortages (Table 13). This is especially apparent for jatropha where in all countries more than 30% of the current labor force is required. In countries like Kenya and Mali employment generation would even exceed the total labor force. In those cases labor could be a significant limiting factor for the implementation of the production potentials as determined in section 4.3. If those large expansion areas are indeed considered, strategies for reducing labor requirements need to be defined.

Table 13: Employment generation, extrapolation for available arid and semi-arid land

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
Employment generation (1000 jobs)								
Cassava	3546	970	8922	3756	673	8208	4626	1201
Jatropha (average)	5417	1483	13632	5739	1028	12540	7068	1834
Woody crops	695	190	1750	737	132	1609	907	235
Percentage of labor force (%)								
Cassava	**439**	16	**52**	**60**	14	**43**	**24**	**26**
Jatropha (average)	**670**	**24**	**80**	**92**	**22**	**66**	**37**	**40**
Woody crops	**86**	3	10	12	3	9	5	5

Note: In **bold**, all cases where more than 20% of the national labor force is needed to make production possible.

7 The environmental impacts of bioenergy crops in semi-arid and arid Sub-Saharan Africa

7.1 GHG emissions

Table 14 presents an overview of greenhouse gas (GHG) emissions from cassava ethanol, jatropha vegetable oil and woody biomass production. It is important to note that woody biomass is here assumed to be used as fuelwood which is why further processing and resulting GHG emissions are excluded. Including such processing, for example for ethanol production, would result in higher emissions but would allow a better comparison among the different crops. In order to show the order of magnitude here, if ethanol production from lignocellulosic crops was included, total emissions would amount to 11 g CO2 eq MJ^{-1} and would still be much lower than the two other crops. An important reason for only few additional emissions from ethanol production from lignocellulosic materials via fermentation is the generation of surplus electricity for which an emission credit is given.

GHG emissions were not distinguished for different climate zones (arid vs. semi-arid). Climate zones are not distinguished because too little data is available regarding different management in these climate zones. While arid regions are likely to have lower LUC emissions, emissions from production of the biomass may be higher due to additional management for dealing with the harsher climate. Different countries were also not distinguished because management is likely to be comparable in most of these countries while too little information exists to actually define possible differences.

Table 14: GHG emissions of cassava, jatropha and woody crops in arid and semi-arid Sub-Saharan Africa

Crop	LUC	Fossil fuels	Fertilizers	Processing	Credits	Total
			g CO2 eq MJ^{-1}			
Cassava ethanol	6.0	27.9	10.7	30.4	0	75.0
Jatropha oil [a]	3.0	10.6	1.5	12.4	-1.9	25.7 (32.2)
Woody biomass [b]	3.9	0.7	4.3	0	0	8.9 (11.2)

a – Values in parentheses represent the total GHG balance of jatropha biodiesel, i.e. including refining and transesterification of jatropha oil. GHG emissions from refining and transesterification are based on data from palm oil refining and transesterification (Wicke et al., 2008), assuming that it is comparable to the converting of jatropha oil to biodiesel.

b – Values in parentheses represent the total GHG emissions if woody biomass is used for producing ethanol via fermentation rather than fuel wood. This data is presented here to allow a fairer comparison of GHG emissions between the different crops even though this study assumes that there is no processing of woody biomass. Emissions from conversion are based on JRC et al., 2008

The comparison of GHG emissions from conventional fuels indicates the potential GHG emission savings from bioenergy over fossil energy. The GHG emissions of gasoline are 82 g MJ^{-1} (69 g MJ^{-1} for direct emissions from combusting gasoline (IPCC, 2006); 13 g MJ^{-1} for extraction, processing and distribution (JRC/IES et al., 2007) and 88 g MJ^{-1} for fossil diesel (74 g MJ^{-1} for direct emissions from combusting gasoline (IPCC, 2006); 14 g MJ^{-1} for extraction, processing and distribution (JRC/IES et al., 2007). Then the GHG emission savings by cassava ethanol amount to 8% and by jatropha biodiesel to 64%. GHG emission savings from fuelwood production are not determined here due to the complexity of the avoided potential deforestation and degradation of the land.

For each crop there are several aspects to consider when interpreting the GHG balance. These are described below.

7.1.1 Cassava

The calculation of the GHG emissions of cassava ethanol production does not include the aboveground biomass of the cassava plant because insufficient information of the amount of produced biomass was found. As a result, the GHG balance does not account for the carbon sequestration during growth of the plant and carbon dioxide, possible methane and nitrous oxide emissions during decomposition of the residues. At the same time also no credits are given for possible by-products such as using the leaves for fodder. While this use of other parts of the cassava plant is common in some countries, it could result in further degradation of soil due to the greater extraction of nutrients and little or no substitution of these nutrients from other sources.

Cassava production is associated with high soil carbon losses, which are mainly due to tillage and soil erosion. Ringius (2002) suggests the following management options for soil carbon sequestration in Africa, which are relevant for reducing soil carbon losses in cassava production:

- Conservation tillage (no-till/minimum-till) in combination with cover crops, applying green manure and using hedgerows;
- Organic residue management;
- Mulch farming;
- Soil fertility management;
- Avoidance of bare fallow through the introduction of agro-ecologically and physiologically adapted crop/plant species adapting crop rotations and cropping/farming systems; and
- Stabilizing slopes and terraces.

Cassava ethanol production co-produces biogas which is used for generating steam and, in turn, applied in the processing. No emission credit is given because of its internal use. Instead fossil energy requirements for steam production are reduced and thereby indirectly represent the by-product credit.

7.1.2 Jatropha

Important by-products of jatropha oil production are the press cake and the husks. It is assumed here that press cake and husks are sold as fertilizer and the emission credit is based on their nitrogen content and the emissions of the production of synthetic nitrogen fertilizer. Applying press cake as fertilizer is found to have higher emissions than when it is applied for energetic purposes (IFEU, 2008). However, nutrient losses are a significant problem in Africa and it is important for the sustainability of bioenergy production that it does not further deteriorate the soils.

7.1.3 Woody crops

The GHG emissions from land use change towards woody crop plantations assumes that 10% of the soil carbon is released to the atmosphere based on information presented by Gibbs et al. (2008). However, other references (see for example, Unruh et al., 1993; Schroeder, 1994; Kimaro et al., 2007) find that tree plantations can have soil carbon storage benefits and may serve as a soil carbon sink rather than emitters. In this case, the GHG balance would be even lower. Kimaro et al. (2007) finds that soil organic carbon was significantly higher in woodlots (0.8 – 1.3%) than in continuous cropping treatment (0.6%) in Tanzania. Mechanisms for soil fertility replenishment under woodlot are biological N fixation, pumping up or retrieval of nutrients from lower soil horizons, interception of nutrients that would otherwise be lost through leaching and surface runoff, and release of nutrients during litter and root decomposition (Kimaro et al., 2007 citing Rao et al 1998).

7.2 Other environmental impacts

7.2.1 Soil nutrient removal

The potential for soil nutrient removal by bioenergy crop production is important to assess because of the possible loss of soil nutrients in addition to already depleted soil nutrients in many areas in Africa (Sanchez, 2002). Soil nutrients are extracted through harvesting the crop but also important are wind and water erosion and can be replenished by applying organic and inorganic fertilizer. However, the application of (especially inorganic) fertilizer remains limited among small-scale farmers in Africa due to the high cost, lack of availability and/or inaccessibility. While nutrient depletion is generally countered by applying mineral fertilizers, these are very expensive in Africa, often between two to six times more than in Europe, North America or Asia (Sanchez, 2002). In addition to high costs, fertilizers are often inaccessible especially in remote areas due to high transportation costs (Agwe et al., 2007).

Soil nutrient removal from cassava production can have two causes: 1) the removal of nutrients by harvesting the roots and 2) soil erosion. The former is less of a problem because cassava can be highly efficient in absorbing nutrients from poor soils while the amounts of nutrients removed in the root harvest are relatively low when compared to other crops, with the possible exception of K (FAO and IFAD, 2001). It is important to note though that, if stems and leaves are also removed from the field, then nutrient removal can be quite high and nutrient depletion of the soil can become a serious problem (FAO and IFAD, 2001), especially when considering the low current use of fertilizer in Africa mentioned above (Sanchez, 2002). A more important cause of nutrient removal is likely the second one mentioned: soil erosion. Due to this slow initial growth and poor initial soil cover, cassava cultivation can cause water erosion and soil degradation (Leihner, 2002; Isabirye et al., 2007). These negative effects can be reduced by planting intercrops mainly because of the additional and faster soil cover. But there are also various management techniques with which soil conservation in cassava cultivation can be achieved (see section 7.1.1, Ringius, 2002 and Leihner, 2002). Steep slopes should be avoided due to an increased erosion potential.

Woody crop plantations reduce water erosion (and thereby nutrient losses) compared to agricultural crop production by improving water infiltration, reducing impacts by water droplets, intercepting rain and snow and physically stabilizing soil by their roots and leaf litter (Kort et al., 1998). Not only can trees reduce the erodibility but they can also increase the supply of nutrients within the rooting zone of crops through the input of nitrogen by biological N2 fixation and retrieval of nutrients from below the rooting zone of crops (Buresh and Tian, 1997). Nyadzi et al. (2003) add that fast growing trees that produce high amounts of biomass, fix greater quantities of biological nitrogen and retrieve nutrients from deep soil horizons are likely to have greater positive effect on soil improvement compared to slow growing trees that produce small amount of biomass and do not fix nitrogen. The use of N2-fixing trees is important when considering soil fertility improvements such as in an improved/tree fallow system.

While woody crop plantations can have positive impacts on soil nutrients during the operation of the plantation, harvesting the biomass can negative affect soil nutrients because harvesting causes a loss of organic matter and increased nutrient leaching, while the decay of organic matter is fastened due to higher soil temperatures (Kort et al., 1998).

7.2.2 Water

Box 3 presents the main conclusions from the review of water demand and availability for bioenergy as drawn in Dornburg et al.'s (2008) assessment of global biomass potential estimates. These conclusions are also relevant for Sub-Saharan Africa and highlight the aspects that require future research in the eight countries studied here.

BOX 3: Main conclusions from the review of water demand and availability in Dornburg et al.'s (2008) assessment of global biomass potential estimates

"Comparing the different analyses shows that problems are analyzed at a higher scale than the solutions formulated. The large variability in regional climate and hydrology asks for a detailed and local analysis of the biophysical possibilities for crop production. The studies analyzed show that conditions show large differences among different regions. In some regions abundant water availability provides ample opportunities for energy crop production, while water scarcity in other regions is seriously restricting any opportunity for energy crops.

To determine water availability for energy crop production a basin scale seems most appropriate in order to assure that the interaction between upstream and downstream water availability and use is taken care of. A suggestion is to execute the following steps: - estimate renewable water resources on the scale of a 'river basin' area - determine how much water is required for food and feed crop production related to local production systems and regional developments and estimate future projections - estimate the environmental water requirements

- verify the available land area for additional (energy) crop production
- assess the regional and crop(type) specific WUE of the energy crops to be cultivated
- assess whether water availability or land area is a limiting factor for bio-energy production for different parts of the river basin.

This procedure favors a multi-scale approach taking into account the influence of local measures on the larger regional scale and vice versa. It does not require just straightforward aggregation but a more detailed analysis of relations to arrive at an optimal water distribution. The local situation should be analyzed to assess the scope for energy production. However, to date, studies at this resolution have only been done incidentally, and global figures give a misleading picture.

A rough estimate of available blue water for energy crops, based on global water flows, is 1,300 – 5,000 km^3, depending on the share required for EWR (50-20%). However, where this water is available and if it can really be used cannot be determined based on available studies. Future change in rainfall patterns will regionally have a large impact, especially in regions that are already water scarce.

Climate change is likely to change rainfall patterns while water transpiration and evaporation will be enhanced by increasing temperatures. The net effect of this is not easy to predict, large variations can be expected among different regions of the world. Especially semi-arid and arid areas and are expected to be confronted with reduced water availability, while problems in many river basins may be expected to increase. On the whole, negative effects of climate change will outweigh the benefits for freshwater systems, adversely influencing water availability in many regions and hence irrigation potentials."

Source: Dornburg et al. 2008

7.2.3 Biodiversity

Land use change towards bioenergy production comes often hand in hand with biodiversity losses, especially when (tropical) forests are converted. While grasslands, shrublands and savannas, which are found in WP1 to be available for conversion to bioenergy production in Sub-Saharan Africa, are generally poorer in biodiversity than forests, they can still be rich in biodiversity and play a significant role in environmental services. Bioenergy will have different effects on biodiversity depending on the current level of biodiversity as found by the curvilinear relationship between species richness and area of original area remaining (Sala et al., 2009). Also important in determining bioenergy's effect on biodiversity is the species density, which differs in different regions across the world: "Because some regions are much more diverse than others, equal proportional losses of area will result in dissimilar total losses of species" (Sala et al., 2009). Another factor that influences the intensity of the effects on biodiversity is the scale of the land use change because broad scale generalizations do not necessarily apply to smaller scales (Sala et al., 2009).

In this study only those areas with high biodiversity could be excluded that are already nationally or international protected even though many other areas are also rich in biodiversity. This is due to the lack of information and maps on where these high biodiversity areas are located. Future research will need to better assess the biodiversity level of the regions targeted in this study and the potential impacts on biodiversity by bioenergy production. Furthermore, areas found to have high biodiversity should be excluded from the potential analysis. A starting point for such research may be the Carbon and Biodiversity Demonstration Atlas of UNEP-WCMC (2008), which already illustrates for several countries, including Tanzania, where such high biodiversity areas are located (also in comparison to protected area) (Figure 17). A comparable map of biodiversity-relevant areas is also presented by Hennenberg et al. (2009) (Figure 18), who further shows the composition of such a map (Figure 19).

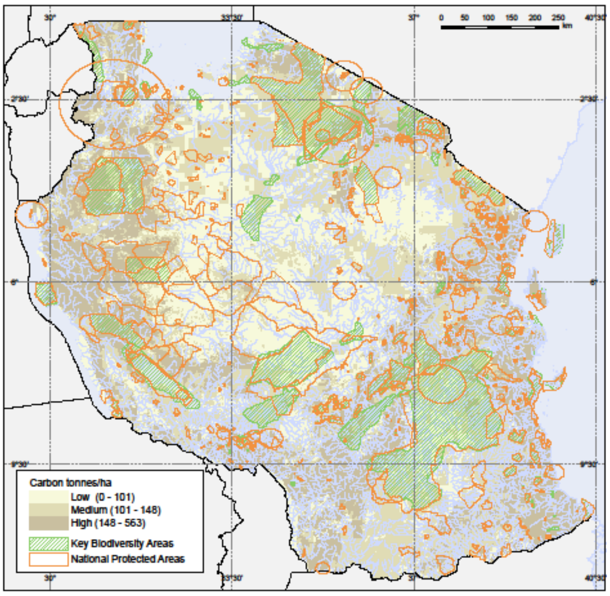

Figure 17: Carbon and biodiversity map of Tanzania (UNEP-WCMC, 2008)

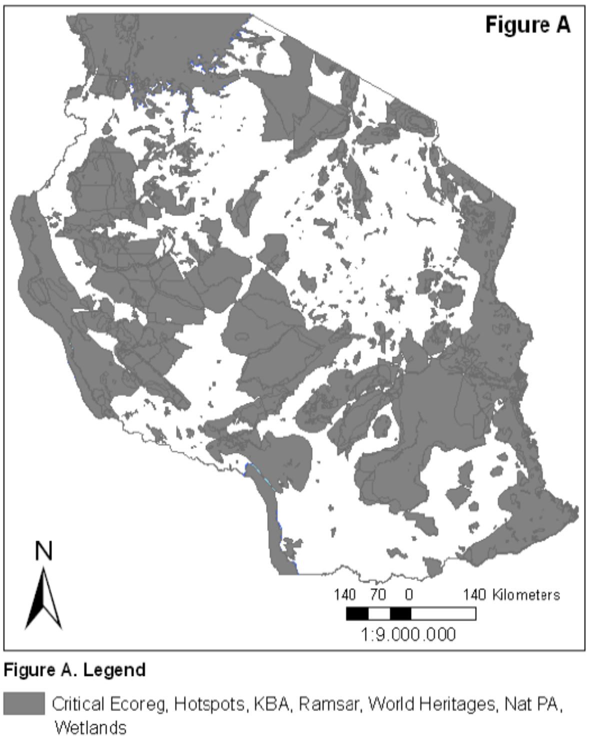

Figure 18: Biodiversity-relevant areas (Hennenberg et al., 2009)

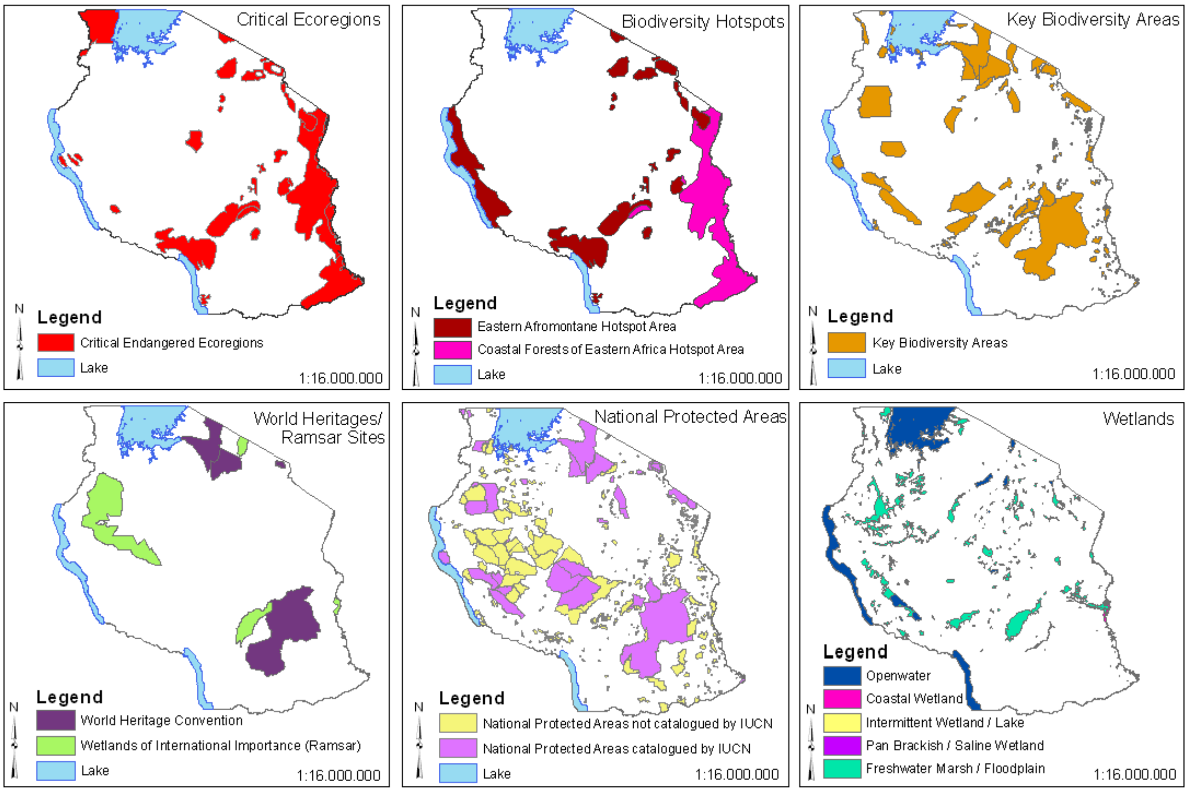

Figure 19: Composition of biodiversity-relevant areas (Hennenberg et al., 2009)

8 Discussions and Conclusions

In this study the potential contribution of biomass production to sustainable energy supply for semi-arid and arid Sub-Saharan Africa, income and employment generation as well as its ecological impacts and benefits are assessed. This study found that, while the bioenergy production potential of woody crops is significantly larger than that of cassava or jatropha, with all three crops significant contributions to current energy consumption could be made as energy consumption in the eight countries in 2006 amounted to approximately 6000 PJ (Table 15). This contribution to energy consumption can increase energy security while positively affecting the trade balance through reduced imports of expensive fossil energy. In addition, local bioenergy production can increase rural development by diversifying (and increasing) agricultural production and increasing availability of (modern) energy carriers even in remote areas. Also positive socio-economic impacts, such as the reduced time needed for gathering fuelwood and the resulting increased time available for other activities as well as increased rural employment, can be registered.

Among the eight countries investigated (Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia), the largest potential is found in Kenya, followed by South Africa and Tanzania (Table 15). These are also the three countries with the largest available land area for bioenergy production. This available land area is a decisive factor in the potential analysis. The land area available for bioenergy production was here based on work from COMPETE WP1, where land is considered available if it is not categorized as forest, wetland, cropland, urban, bare rock, sandy desert and dunes, stony desert or water bodies and is not protected nationally or internationally. While agricultural land is excluded from the analysis, this study found that not all pastureland seems to be excluded as often grassland and shrubland areas are used for livestock browsing. In order to avoid displacement of this activity, a reduction factor accounting for livestock grazing was applied. In addition to livestock production, there are likely other uses of and objectives for the land, such as collecting fuelwood, fruits and medicines, hunting and nature and biodiversity conservation. These factors could not be accounted for with existing datasets even though it would be essential for avoiding direct and indirect land use change and potentially resulting social conflicts. The various uses of land and their effects on land availability for bioenergy production need to be investigated in more detail in the future.

Table 15: Summary of results

Parameter	Units	Cassava	Jatropha	Woody crops
Total technical potential [a]	PJ y^{-1}	1251	1621	10929
Production costs	€ t^{-1} cassava roots / jatropha seeds/ fuelwood	16 – 40	23 – 81	7 – 21
Production costs	€ l^{-1} ethanol / biodiesel	0.4	0.3 – 0.4	n/a
NPV	€ t^{-1} cassava roots / jatropha seeds / fuelwood	2 – 170	-67	43 – 72
Labor generation	hours ha^{-1}	901	1376	177
GHG emissions	g CO2-eq MJ^{-1} ethanol / biodiesel / fuelwood	75	26	9
GHG emission savings	%	8	64	-

a – The total potential refers to the sum of the potentials of the eight countries investigated

Two important aspects of the actual implementation of bioenergy production will be the production costs and the market price of biomass/bioenergy that could be obtained. This study found that production costs of cassava ethanol, jatropha biodiesel and woody crops for fuelwood are all lower than market prices of comparable products (Table 15) and, when accounting for taxes and distribution charges, may be competitive at the market.

Employment generation is often seen as an important benefit of bioenergy production and for all crops additional employment would be created (Table 15). For some Sub-Saharan African countries, however, there may also be the issue of labor shortages. As a result, high labor requirements may not be possible to meet and strategies for reducing labor requirements, such as growing only crops that have low labor requirements or investing in mechanizing production, will be important to investigate.

This study also assessed the ecological impacts of cassava, jatropha and woody crop production. It was found that the GHG emission savings by cassava ethanol are very low and amount to only 8% compared to conventional gasoline, while jatropha biodiesel can save 64% of emissions compared to fossil diesel (Table 15). GHG emission savings from fuelwood production are not determined here due to the complexity in determining emissions from potential deforestation and degradation of the land. Besides avoiding deforestation, woody crop production also has the advantage of improving soil conditions, including better water infiltration, reduced erodibility and increased supply of nutrients within the rooting zone.

The potential analysis and the assessment of the economics, socio-economic effects and environmental impacts of three different pathways for bioenergy production indicate that fuelwood scores well in all categories. While this study has primarily focused on fuelwood production rather than woody biomass used for electricity or liquid biofuel production, for the future economic and social development it will be important to also study the feasibility and impacts of these options in Sub-Saharan Africa.

9 References

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10 Appendix

10.1 Categories of Potentials

Hoogwijk et al. (2005) describe five categories of potentials as follows:

- *The theoretical (available) potential at grid cell level* (T_i): The theoretically upper limit of primary biomass; i.e. the Net Primary Productivity of biomass produced at the total earth surface by the process of photosynthesis (EJ yr^{-1}): $T = A_i \sum_{i=1}^{n} PPP$ where A_i – area of a grid cell, i – grid cell, and PPP – potential primary productivity.
- *The geographical potential G*: The theoretical potential at land area available for the production of biomass for energy (EJ yr^{-1}). We determine a land-claim exclusion factor at grid cell level i (a) to estimate the area available for biomass production: $G = T_i a_i$.
- *The technical potential at grid cell level (Te_r)*: The geographical potential reduced by losses due to the process of converting primary biomass to secondary energy carriers, defined by the conversion efficiency of the conversion technology (η_t) (EJ yr^{-1}): $Te_i = G_i \eta_t$.
- *The economic potential*: The technical potential that can be realized at profitable levels, depicted by a cost-supply curve of secondary biomass energy (EJ yr^{-1}).
- *The implementation potential*: The maximum amount of the economic potential that can be implemented within a certain timeframe, taking (institutional) constraints and incentives into account (EJ yr^{-1}).

10.2 Definitions of Land Types and Their Spatial Extent

Table 16: Land cover and land use in 2000 according to GLC2000

	Botswana	**Burkina Faso**	**Kenya**	**Mali**	**Senegal**	**South Africa**	**Tanzania**	**Zambia**
	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha
dense forest	-	-	1548	1	293	971	1173	153
mosaic forest/croplands	-	-	1189	-	27	531	74	-
woodlands/ shrublands	15976	6034	5903	9835	4901	36458	48715	63361
grasslands	37881	4601	38663	20717	3022	70151	14807	4834
agriculture	4874	13272	4415	18191	9068	27768	22478	6534
bare soil	764	5	41	70631	83	518	24	2
wetlands	812	-	13	66	310	33	253	856
total	**60307**	**23912**	**51772**	**119441**	**17704**	**136430**	**87524**	**75740**

Source: Mayaux et al., 2003

Table 17: Definition of land types according to GLC2000

Category	**Definition**
Dense forest	Closed evergreen lowland forests: Forest classes on land up to 1000 meters above mean sea level with tree canopy cover is greater than 70% and height greater than 5 meters. Closed evergreen montane and sub-montane forests: Forests occurring at greater than 1000m above mean sea level. Degraded evergreen forest: Forest classes on land up to 1000 meters above mean sea level with tree canopy cover is between 40% and 70% and height greater than 5 meters.
Mosaic forest croplands	Mosaic Forest / Croplands: A major feature of the Central African forest biome is the presence of ribbons of secondary forest formations along the road network, either old or recent. These formations correspond to a pattern of land management - the former “paysannats”, which since colonial times follow the road network. The vegetation found here is formed by a complex of secondary regrowth, fallow, home gardens, food crops and village plantations. Mosaic Forest / Savanna: The forest/savannah mosaic class contains vegetation formations including forest elements and savanna elements. Gallery-forests are tree formations developed along the river banks in the middle of shrub or grass vegetation.
Woodlands / shrublands	Closed deciduous woodlands (Dense Miombo): Tree canopy cover more than 40% and canopy height more than 5 meters Deciduous open woodlands: Tree canopy cover is between 15% and 40% and canopy height more than5 meters Deciduous closed / open shrublands with sparse trees: Shrub canopy cover is greater than 15% and canopy height less than 5 meters with a sparse tree layer covering less than 15% Deciduous closed / open shrublands: Shrub canopy cover is greater 15% and canopy height less than 5 meters with no tree layer.
Grasslands	Closed grassland: Herbaceous cover greater than 40% .Tree and shrub canopy cover less than 20%. Open grassland with sparse shrubs: Herbaceous cover between 15% and 40% and shrub canopy cover less than 20%. Open grassland: Herbaceous cover between 5% and 15% without shrub canopy Sparse grassland: Herbaceous cover between 1% and 5%.
Agriculture	Croplands: Areas with over 50% cultures or pastures. Croplands mixed with open vegetation: Mosaic of agriculture and non-forest vegetation Irrigated agriculture: Agriculture depending on artificial water supply Tree crops: The orchards at the proximity of the Nile delta were identified as a specific class.
Bare soil	Bare rock: The main rocky desert are found in Tibesti (Chad), Hoggar (Algeria), Aïr (Niger) et between the Nile and the Red Sea (Egypt). Stony desert (reg): Reg and hamada are vast territories arid and stony. Sandy desert and dunes (erg): Erg is a urge sandy area where dunes, built by the wind can reach a height of 400 m. Salt hardpans: Salt hardpans are dry, saline deserts; water is found only in numerous waterholes surrounding the pan.

Wetlands	Closed evergreen swamp forests: Forests permanently or periodically under the influence of fresh water. Mangroves: Forests permanently under the influence of salt water. Swamp shrubland and grassland: The largest swamp grasslands are found in large inner deltas or depressions where water is often standing due to the flat topography, that preclude the subsistence of trees: Nile in Sudan, Okavango in Botswana, Lake Chad, Niger in Mali. These grasslands are low formations dominated by grasses (Vossia, Echnichloea....) or by Cyperus papyrus.

Source: Mayaux et al., 2003

Table 18: Land use in 2000 according to FAOSTAT

	Botswana	Burkina Faso	Kenya	Mali	Senegal	South Africa	Tanzania	Zambia
	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha	1000 ha
Arable land	350	4040	4891	4589	3050	14753	8800	5260
Permanent crops	1	60	480	85	55	959	1200	27
Permanent meadows and pastures	25600	6000	21300	34000	5650	83928	24000	19650
Forest area	12535	6914	3582	13072	8898	9203	37318	44676
Other land	18187	10346	26661	70274	1600	12604	17262	4726
Total	**56673**	**27360**	**56914**	**122019**	**19253**	**121447**	**88580**	**74339**

Source: FAOSTAT, 2009

Table 19: Definition of land types according to FAOSTAT

Category	Definition
Other land	Other land is the land not classified as Agricultural land and Forest area. It includes built-up and related land, barren land, other wooded land, etc.
Permanent meadows and pastures	Permanent meadows and pastures is the land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land).
Permanent crops	Permanent crops is the land cultivated with long-term crops which do not have to be replanted for several years (such as cocoa and coffee); land under trees and shrubs producing flowers, such as roses and jasmine; and nurseries (except those for forest trees, which should be classified under "forest"). Permanent meadows and pastures are excluded from land under permanent crops.
Arable land	Arable land is the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for “Arable land” are not meant to indicate the amount of land that is potentially cultivable.
Agricultural area	Agricultural area is the sum of areas under a) arable land; (b) permanent crops; and (c) permanent meadows and pastures.
Forest area	Forest area is the land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 meters (m) in situ. Areas under reforestation that have not yet reached but are expected to reach a canopy cover of 10 percent and a tree height of 5 m are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate. Includes: areas with bamboo and palms provided that height and canopy cover criteria are met; forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 ha and width of more than 20 m; plantations primarily used for forestry or protective purposes, such as: rubber-wood plantations and cork, oak stands. Excludes: tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens.

Source: FAOSTAT, 2009

10.3 Land use change over time

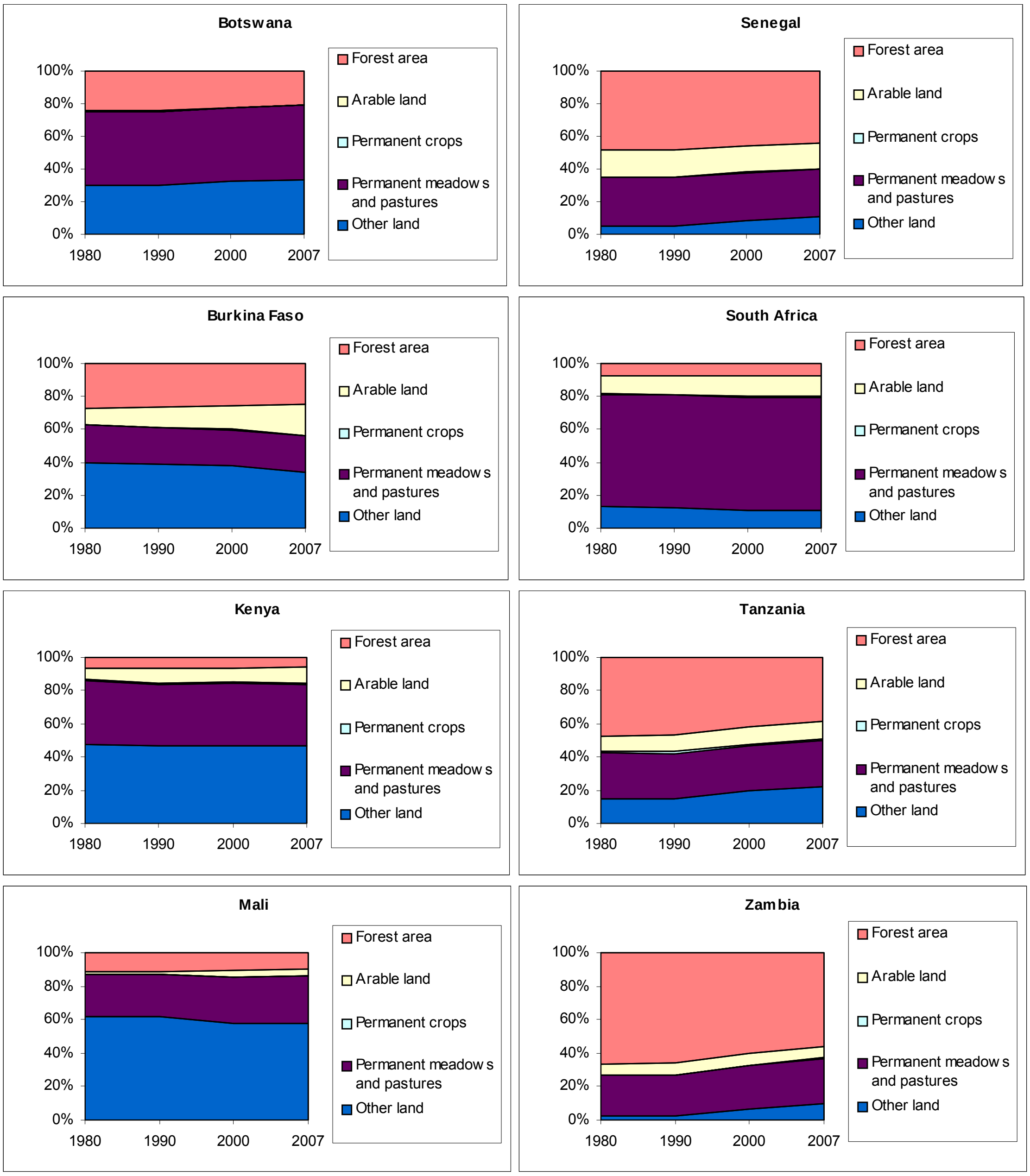

Figure 20: Land use change in Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia 1980 to 2007
Source: FAOSTAT, 2009
Note: For all countries for 1980 there is no data for the categories "forest area" and "other land area"; here it is assumed that it is the same as in 1990.

10.4 Jatropha yield

Table 20: Jatropha yield from several sources (van Eijck 2005 citing Heller 1996)

Reference	Location	Age (years)	Yield Shrub (g)	Yield Hectare (kg)
Avila (1949)	Cape Verde	?	700-900	n.d.
Bhag Mal (pers. Comm.)	India	3	n.d.	1733
Foidle (pers. Comm.)	Nicaragua	?	n.d.	5000
Henning (pers. Comm.)	Mali	?	n.d.	2640[a]
Ishii and Takeuchi	Thailand	?	n.d.	2146
Larochas (1948)	Mali	?	n.d.	8000
Martin and Mayeux	Madagascar	?	3000-3500	n.d.
Matsuno et al (1985)	Paraguay	3	n.d.	100
Matsuno et al (1985)	Paraguay	4	n.d.	700
Matsuno et al (1985)	Paraguay	5	n.d.	1000
Matsuno et al (1985)	Paraguay	6	n.d.	2000
Matsuno et al (1985)	Paraguay	7	n.d.	3000
Matsuno et al (1985)	Paraguay	8	n.d.	4000
Matsuno et al (1985)	Paraguay	9	n.d.	4000
Naigeon (1987)	Cape Verde	?	n.d.	1750
Silveira (1934)	Cape Verde	?	n.d.	200-800
Stienswat et al. (19860	Thailand	1	318	794
Sukarin et al. (1987)	Thailand	1	63.8	n.d.
Zan (1985)	Burkina Faso	Diff.	955	n.d.

Source: van Eijck, 2007
n.d. – not determined
[a] Survey on hedges: 0.8 kg seeds per m hedge. Hectare yield assumes as distance of 3 m between the hedges

Table 21: Jatropha yield from several sources (van Eijck 2005 citing Jones and Miller 1993)

Source	Seed yield	Oil yield	Comments
Raina, 1986	4-6 kg/yr		From average size bush
Basabutra and Sutiponpeibun, 1982	4-6 kg/yr		Mean yield for 5 year old tree in Thailand
Takeda, 1982	2-4 kg/tree		
Banerjee, 1989	4.6 kg/bush		
Martin and Mayeux, 1984	4-5 kg/tree	1.5-2.0 kg/tree	
Sukarin, Yamada and Sakaguchi, 1987	638 kg/ha		1 X 1 m spacing with no fertilizer, NE Thailand
Ishil and Akeuchi, 1987	2146 kg/ha	751 kg/ha	Average annual yield; 35% oil extraction rate, Thailand
Levingston and Zamora, 1983	400-1200 kg/ha		Commercial yield, Cape Verde
Martin and Mayeaux, 1984	650-2000 kg/ha	200-600 kg/ha	Average yield, Cape Verde
Martin and Mayeaux, 1984	5000 kg/ha (kernels)	2.4 t/ha	One location in Cape Verde
Wealth of India	350-1000 lb/ac		
The World Bank, 1991	3 t/ha		Value assumed under rainfed conditions after 5 yr
Srivastava, 1984	4-6 t/yr (assume per ha)		Minas Gerais, Brazil
Calvin, 1985	5 t/a/y		
Srivastava, 1984		1.5-2.3 t/ha	Established plantation in Brazil
Forni-Martins and Diniz da Cruz, 1985		3-4 t/a	3m X 3m spacing, Brazil

Source: van Eijck, 2007

10.5 Energy consumption in Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia

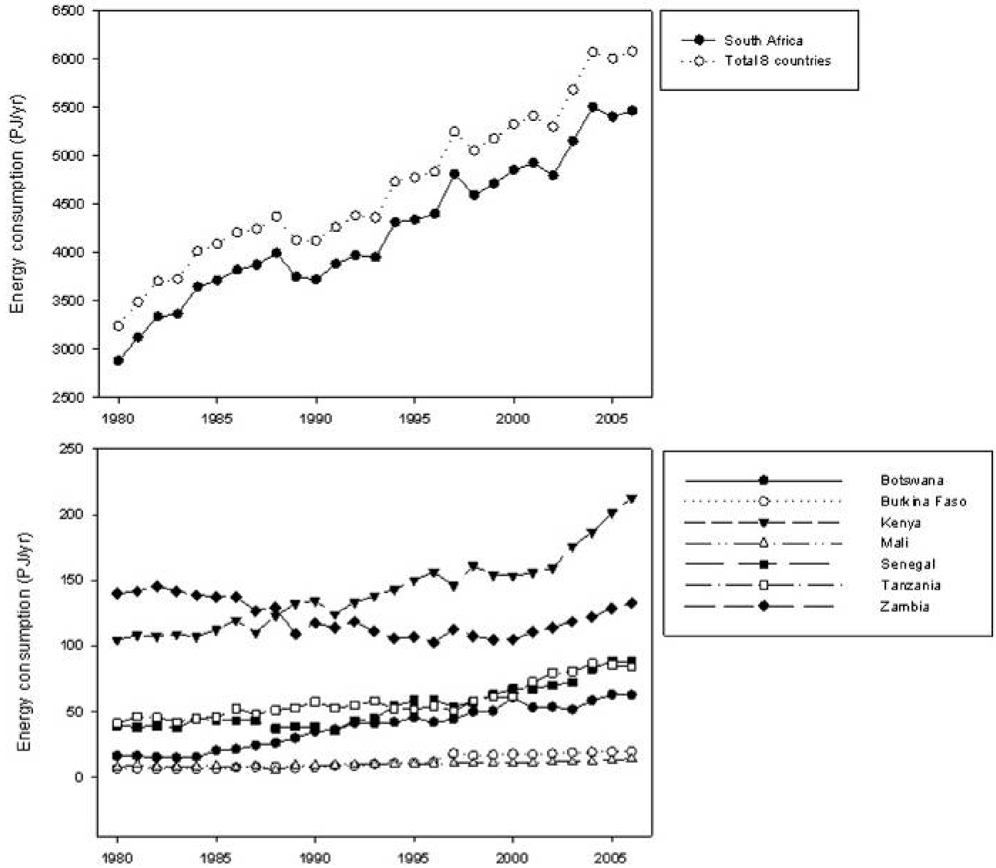

Figure 21: Energy consumption in Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania and Zambia

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