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Sustainable Aviation Biofuel Feedstock Potential in sub-Saharan Africa

A systems analysis investigation into the current and future potential for sustainable biofuel feedstock production in the sub-Saharan Africa region

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Country boundaries follow the delineations of the 2014 Global Administrative Unit Layers (GAUL) distributed by the Food and Agricultural Organization of the United Nations.

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ABBREVIATIONS

CAF	Central Africa
CMIP5	Coupled Model Intercomparison Project Phase 5
dLUC	Direct land use changes
DM	Dry matter
EAF	Eastern Africa
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Databases
GAEZ	Global Agro-ecological Zoning Model
GAUL	Global Administrative Unit Layers
GCM	General circulation model
GHG	Greenhouse gas
GLC SHARE	Global Land Cover SHARE
GLWD	Global Wetland Database
GMIA	Global Map of Irrigated Areas
GMO	Genetically modified organism
GPCC	Global Precipitation Climatology Centre
GUI	Gulf of Guinea
HWSD	Harmonized World Soil Database
KBA	Key Biodiversity Areas
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LUT	Land Utilization Type
ICAO	International Civil Aviation Organization
IIASA	International Institute for Applied Systems Analysis
IPCC	International Panel on Climate Change
PJ	Petajoules
ppm	Parts per million
RCP	Representative Concentration Pathway
REMAIN	Remaining land once environmental and food sustainability criteria have been addressed
RPR	Residue to Produce Ratio
RSB	Roundtable on Sustainable Biomaterials
TJ	Terrajoules
TLU	Tropical Livestock Unit
SAF	Southern Africa
SDG	Sustainable Development Goal
SOC	Soil organic carbon
SSA	sub-Saharan Africa
SSP	Shared Socio-economic Pathway
SUD	Sudano-Sahelian Africa
WDPA	World Database of Protected Areas
WFS	World Food System Model
WWF	World Wildlife Fund

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1. INTRODUCTION

1.1 Background and Motivation

1.1.1 The need to reduce aviation emissions

The Paris Agreement (UN, 2015) signed at COP21 brought the global community together in its commitment to keep global warming within a temperature increase of 2°C, and to pursue efforts towards a maximum 1.5°C increase. To achieve this goal, rapid decarbonisation of all economic sectors is required, including those that are not covered by the Paris Agreement. Aviation is a case in point.

Estimates of the current contribution of global aviation to total anthropogenic CO_2 emissions are between 2% to 2.5% (IPCC, 1999, IPCC, 2007, Lee et al., 2009). International aviation accounts for approximately 65% of total aviation emissions or 1.3% of all anthropogenic CO_2 emissions (ICAO, 2016). In addition to this, the sector further contributes to global warming with its non-CO_2 emissions, which are estimated to have a radiative forcing[1] effect at least equal to that of its CO_2 emissions (Cames et al., 2015). In fact, estimates of climate impacts of all direct and indirect GHG emissions of global aviation expressed as radiative forcing indicate a more substantial current contribution of the sector at almost 5% of anthropogenic warming (Lee et al., 2009). However, aviation non-CO_2 emissions are still subject to significant uncertainty. Hence, to date they have been largely excluded from the sector's emission reduction targets[2].

Compared to the major emitting sectors, these figures of aviation's current contribution to greenhouse gas emissions may not seem very high. Nevertheless, the fast growth in air traffic and the associated increase in jet fuel consumption mean that by 2050 global aviation could account for over 22% of all anthropogenic CO2 emissions (Cames et al., 2015).

While emissions from domestic aviation are covered by the Paris agreement and thus dealt with by countries on an individual basis (or country group basis such as the European Union), emissions from international aviation are the responsibility of the International Civil Aviation Organization (ICAO). In this respect the organisation has adopted two aspirational goals for the sector, namely a 2% annual fuel efficiency improvement through 2050 and carbon neutral growth from 2020 onwards (known as the CNG2020 goal).

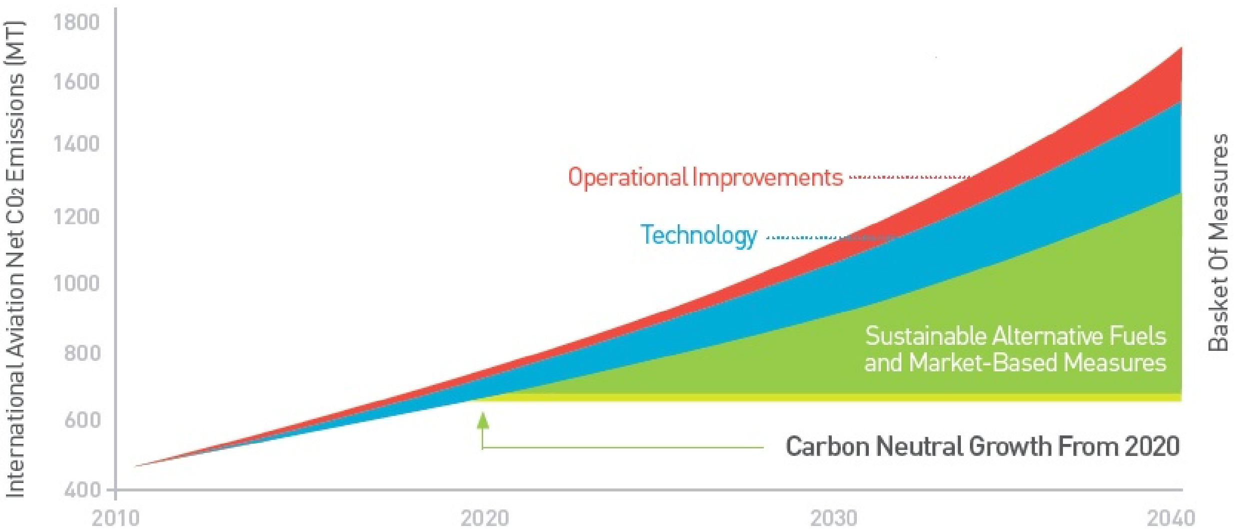
It is already clear that technical and operational advances available today will not suffice to achieve fuel efficiency improvements at a rate of 2% annually; instead, 1.4% has been deemed a more realistic figure (ICAO, 2016). Either way, the projected sector growth of between 4% and 6% annually to 2030 means that even the best achievable improvements in fuel efficiency are going to fall far short of the necessary emission reductions to achieve a carbon neutral growth from 2020. The sector is therefore placing much hope on a combination of alternative fuels and market based measures, mostly in the form of carbon offsets, to mitigate growing emissions and to close the sector's CO2 gap, as shown in Figure 1.1[3].

It is worth noting that the aviation emissions trajectory as proposed by ICAO does not represent an adequate contribution from the sector towards efforts to limit global warming to 2°C. For this, the share of international aviation in global CO2 emissions should remain constant at today's levels, even as global CO2 emissions are reduced following the emission reduction pathway necessary to remain below the 2°C warming target. This translates into a 2050 reduction from international aviation of between 41% and 96% compared to 2005 emissions, largely depending

1 Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in Watts per square meter (Wm-2). Positive values of radiative forcing imply a net warming, while negative values imply cooling.
2 Though it should be noted that they are considerable even at the lower range of the uncertainty intervals.
3 While they were initially seen as separate mitigation options in ICAO's basket of measures, work is currently in progress to integrate alternative fuels into the developing global MBM in the hope it will help incentivize their uptake.

on the point in time at which the sector emissions start declining (Cames et al., 2015). Ambition more in line with such an emission reduction goal has been expressed by members of the Air Transport Action Group that have set the aspirational goal to reduce net carbon emissions of the sector by 50% compared to the 2005 baseline (ATAG, 2016). It is therefore likely that demand for both carbon offsets as well as alternative fuels by the aviation sector will significantly increase in the future, as climate mitigation efforts are stepped up in line with the 2°C target.

Figure 1.1. Contribution of measures for reducing international aviation's net CO2 emissions



Source: International Civil Aviation Organization (ICAO, 2016)

1.1.2 The role of bio jet fuels in reducing aviation emissions

Alternative aviation fuels, mostly based on biomass, are a relatively new entrant into the discussion on mitigation options available to global aviation. When discussing mitigation measures available to the sector, the 1999 IPCC special report on aviation did not consider biofuels as a practical alternative to kerosene-based fuels for commercial jet aircraft (IPCC, 1999). Nevertheless, the first commercial flight fuelled by biofuels took place only 12 years later, demonstrating the fast pace of development in the bio jet arena. Today, sustainable bio jet fuels are considered to be integral to the long-term effort of curbing CO2 emissions from the aviation sector.

There are two basic questions worth asking in relation to the role of biofuels in helping the sector achieve its goal of carbon neutral growth by 2020 and possibly contribute to deeper emission reductions in the longer term. Firstly, how much can bio jet fuels contribute towards fuel supply for the aviation sector? Secondly, and more importantly, what kind of emission reductions could be achieved by replacing kerosene with bio jet fuel? Both questions are subject to significant uncertainty.

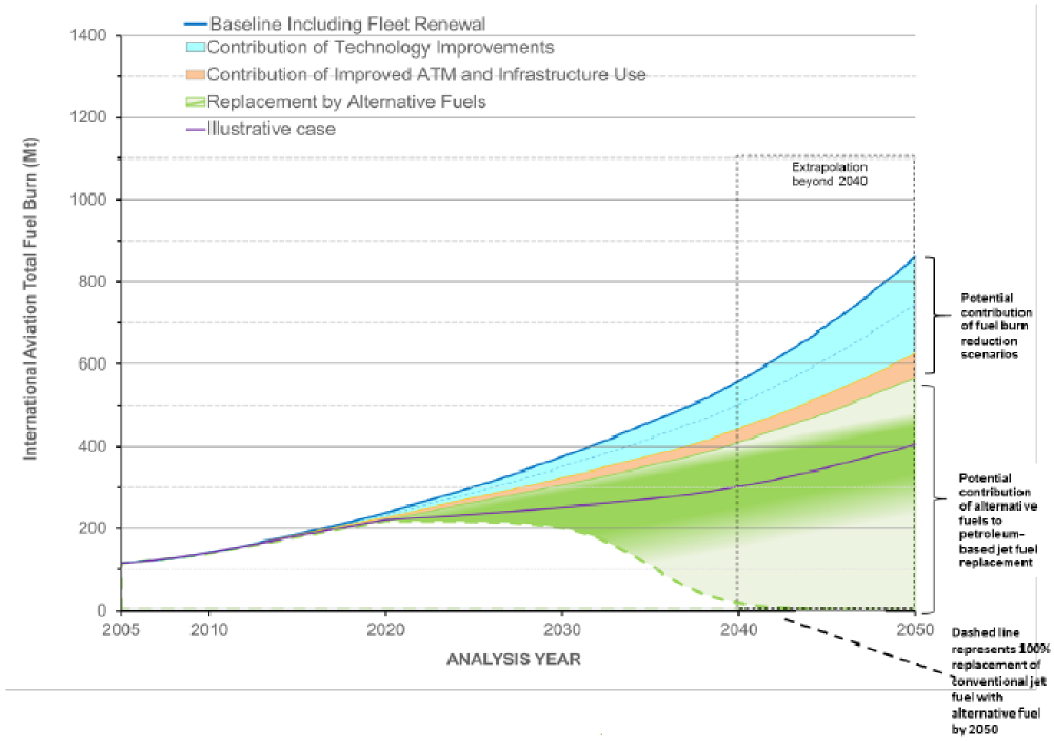
Before looking at potential supply however, let's consider demand. While jet fuel demand estimates exist for both domestic and international aviation, the latter is projected to account for 70% of fuel consumption by 2050 and with the now agreed mandate to reduce emissions, it is likely be the biggest source of demand for biofuels for aircraft. In 2010, international aviation consumed approximately 142 million tons (Mt) of jet fuel, a figure that is projected to increase to between 400 and 550 Mt by 2050, after technological and operational improvements that reduce fuel usage have been taken into account (ICAO, 2016). Presently, all alternative jet fuel production pathways produce a drop-in fuel that must be blended at different levels with kerosene (typically between 10% and 50%). In principle these blending ceilings together with projected fuel demand should constitute the maximum demand for bio jet fuel, at least in the short-to-medium term.

In terms of specific targets, the U.S. Federal Aviation Administration has set the aspirational target of using 1 bln gallons (3.758 bln L) of bio jet by 2018, Australia has aimed for 50% by 2050, the EU 2.5 bln L by 2020 and 40% by 2050, Germany 10% by 2025, Indonesia 2% by 2018, and Israel 20% by 2025 (IRENA, 2017).

ICAO's own Committee on Aviation Environment Protection (CAEP) estimates that up to 2% of the sector's fuel consumption could consist of sustainable alternative fuels in 2020 and up to 100% from 2040 onward (Figure 1.2). These figures are based on a number of very optimistic assumptions – complete fleet renewal with aircraft that can use pure biofuels by 2050, massive capital investments in replacing the fuel storage, blending and distribution infrastructure that can handle pure biofuels and high availability of biomass for the production of bio jet fuel. This is in turn dependent on the realization of the highest assumed increases in agricultural productivity, highest availability of land for feedstock cultivation, highest residue removal rates, highest conversion efficiency improvements, largest reductions in the GHG emissions of utilities, as well as a strong market or policy emphasis on bioenergy in general, and alternative aviation fuel in particular. It also implies that a large share of the globally available bioenergy resource would be devoted to producing aviation fuel, as opposed to other uses (ICAO, 2016).

Estimates that are more reflective of market realities, especially the large price differential between conventional and bio jet fuel, are less optimistic. E4Tech estimates that 3–13 Mt could be produced annually by 2030 (Bauen et al., 2009), which is between 1% and 5% of the projected demand band for 2030, as opposed to ICAO's own projections of 20% to 30%. The International Energy Agency projects even slower growth, expecting biofuels to account for only about 2-3% of aviation fuel demand in 2040 (IEA, 2015). Even in the EU, the European Advanced Biofuels Flightpath Initiative set the objective to achieve 2 Mt of renewable jet fuel by 2020 (or approximately 4% of EU jet fuel consumption); however, the current lack of specific incentives for bio jet fuel are expected to result in only 13 kt produced by 2030, far short of the EU target.

Figure 1.2. Aircraft Fuel Burn from International Aviation, 2005 to 2050 Updated to Include Potential Replacement of Jet Fuel with Alternative Fuels



Source: International Civil Aviation Organization (ICAO, 2016)

If sufficient funds to bridge the price differential between conventional and renewable jet fuel can be mobilised (less the price of unneeded carbon offsets), then the same study predicts only 5% of jet fuel will come from renewable sources by 2030 and about 20% by 2050 (de Jong et al., 2017). A recent report published by WWF-UK estimates that by 2035 the potential contribution from sustainable alternative aviation fuels, with appropriate restrictions on direct and indirect land use change and certification to promote sustainable development, will be between 0.1 and 0.3 Gt CO2e, only 2 to 9% of the CNG2020 goal (WWF-UK, 2016).

The attractiveness of biofuels to help meet the aviation sector's goal of climate neutral growth – at least in the short term - is indeed significantly reduced when compared to the alternative on offer – carbon offsets - on a purely cost basis. Existing biofuel conversion pathways yield production costs of roughly two to four times the average fossil jet fuel price, leading to an average emission mitigation cost of some 270 USD/t CO2 avoided, averaged over 2020-2030 (de Jong et al., 2017).

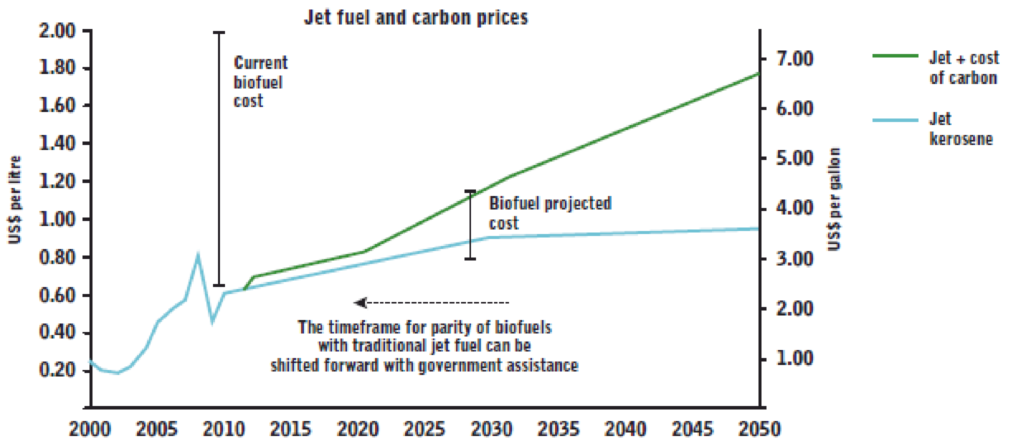
While the rules that will determine what kind of carbon offsets will be allowed under ICAO's market-based mechanism (the so-called Carbon Offset and Reduction Scheme for International Aviation or CORSIA) are still under development, it is plain to see that unless a significant price drop for alternative fuels is achieved, carbon offsets - already available in significant quantity and at relatively low cost - will likely represent the majority of the mechanism used to close the sector's emissions gap, at least in the short-to-medium term[4].

Importantly, estimates also vary widely on the likely carbon savings that would result from increased adoption of bio jet fuel. The Aviation Transport Action Group for instance claims that "If commercial aviation were to get 6% of its fuel supply from biofuel by 2020, this would reduce its overall carbon footprint by 5%" (ATAG, 2016). Based on a set of optimistic assumptions, ICAO CAEP's estimates that complete fuel replacement would reduce net CO2 emissions from international aviation by 63% (ICAO, 2016). Again, many other studies offer a less favourable view of the mitigation potential of biofuels and a number of them have shown the wide ranges of life cycle emissions of biofuels following even the same conversion pathway.

The bottom line is that the carbon life cycle assessment (LCA) outcome of biofuels depends on a large number of factors, including land use prior to feedstock cultivation, farming practices, yields, logistics, processing efficiencies, collection and distribution distances and many more. It is therefore neither possible nor advisable to generalise the mitigation potential of biofuels, including those used in aviation. Rather, every single supply chain should be subject to a rigorous LCA process with adequate system boundaries to determine its value in delivering real, significant and measurable emission reductions.

4 With total cumulative global supply of carbon offsets projected to be up to 26.4 Gt CO2eq over the period 2020-2035, compared to ICAO's expected demand of 3.3-4.5 Gt CO2eq under CNG2020, even restricting the use of credits to those for which there is both relatively high confidence in environmental integrity and strong sustainable development potential provides for a potential supply of 3.0 Gt CO2eq in the form of offsets, or 67-91% of the CNG2020 goal (WWF-UK, 2016). This, at an average price below 5 US$/tCO2eq for certified Gold Standard projects (Hamrick and Gallant, 2016).

Figure 1.3. Indicative projections of jet fuel and carbon prices



Source: Jet kerosene price based on 25% markup over IEA's crude oil forecast in Energy Technology perspectives 2010. Carbon price taken from UK DECC 2010 central case forecast for traded carbon price. All are in constant (inflation adjusted) US dollars. IATA Economics. Schematic, indicative diagram.

Source: International Energy Agency (IEA, 2017)

1.2 Study rationale, aims and objectives

While carbon offsets may represent a more attractive option to meet the CNG2020 goal in the short term, in the longer term their availability might become more constrained and a more structural solution will be needed for reducing emissions in the aviation sector. In view of this, 59 ICAO Member States representing almost 80% of international air traffic[5] have already indicated that they will pursue investments in sustainable alternative fuels for aviation in their Action Plans on Emissions Reduction (ICAO, 2016). Individual airlines through industry groupings such as Sustainable Aviation Fuel Users Group (SAFUG) and the Air Transport Action Group (ATAG) have made similar indications. Their plans are reflected in a number of initiatives and projects around the world aiming to promote the development of alternative aviation fuels[6]. These projects will further increase demand for biomass over and above what will be required for land transportation and by the stationery sector. Current unfavourable market realities notwithstanding, if the international aviation sector provides sufficient market pull, demand for biojet from international aviation alone could reach up to 285 Mt/year by 2050 (50% of projected total fuel use, limited by current blending ceilings). To put this figure in context, global current biofuel production is some 133 Mt/year, and even these volumes have been associated with significant environmental and social externalities. It is therefore easy to see why a doubling of this volume while striving for price parity with fossil-based jet fuel, raises a number of sustainability concerns.

Biomass is a limited resource and the aviation sector will add to demand from other end user applications, especially in regions where the bio-economy is playing an important part of the transition towards a greener economy. The sustainability of large-scale biofuel supply depends on available resources for biomass feedstock production in the context of future demand for food, water resources (for industry and domestic consumption), competing biomass demand for road transport fuels, and land and water requirements for safeguarding natural environments and protected areas.

In addition, Africa, and particularly sub-Saharan Africa (SSA), is seen as one of the major expansion areas for the production of biofuel feedstock, both for land transportation as well as aviation. To ground such aspirations in reality, we need to embed and discuss development of biomass for energy in a wider perspective of agricultural and socio-economic development in sub-Saharan Africa.

5 Expressed as Revenue Tonne Kilometres (RTK)
6 https://www.icao.int/environmental-protection/GFAAF/Lists/Initiatives%20and%20Projects/Projects.aspx

A recent initiative to come to a Marshall Plan with Africa[7] (BMZ, 2017) calls for investments in the private sector to foster GDP growth, boost employment opportunities and income and reduce malnutrition and hunger, which is currently on the rise in SSA. A widely discussed option is to channel investments to the agricultural sector, employing currently about 70 percent of the SSA labour force, in particular into the sustainable production of biofuels through tapping SSA's underutilized agricultural land potential.

This study aims to provide a realistic assessment of the biofuel production potential of countries in sub-Saharan Africa, based on latest available information, and conforming to strict sustainability criteria considering the region's food and environmental safeguard requirements, as well as GHG LCA results of biofuels from alternative feedstocks that could potentially be produced here. The sustainability constraints have been operationalised following the criteria of the Roundtable for Sustainable Biomaterials, which is considered best-in-class in terms of sustainability standards for bioenergy developments (WWF, 2013).

The goal is therefore to estimate current and future sustainable biofuel potentials for sub-Saharan Africa (SSA) in accordance with the principles of the Roundtable on Sustainable Biomaterials (RSB), in light of demand from land-based transportation and aviation. The study objectives include:

- Examine the RSB principles and criteria for implementation in the analysis
- Use future scenarios up to 2050 for the assessment of future food demand and associated land and water requirements
- Compile geospatial land and water resources databases for sub-Saharan Africa

7 See https://www.bmz.de/en/countries_regions/marshall_plan_with_africa/index.html

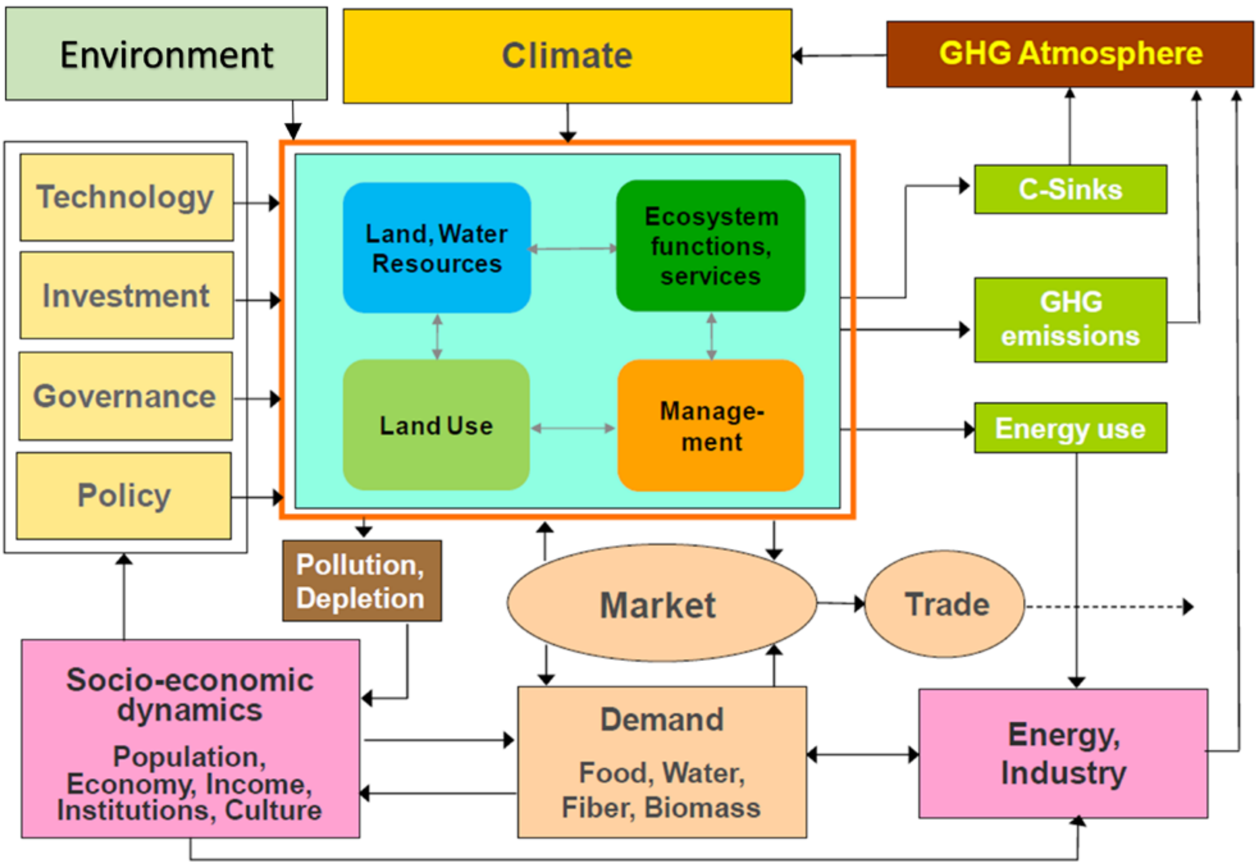
2. STUDY APPROACH

2.1 Systems analysis for studying the food – energy – environment nexus

The transition to a low-carbon economy with biomass as one of its energy sources will intensify the energy-agriculture linkage and add a new dimension to agricultural systems, heighten resource competition in the food system, and may provide new opportunities for rural communities (Prieler et al., 2013). As food, feed and energy feedstock markets integrate more closely, both challenges and opportunities arise. Moreover, the agricultural production system is embedded in a dynamic socio-economic, environmental and cultural setting. Understanding the key linkages within this setting is important for evaluating the possible consequences and indirect effects of alternative policy options for adapting agriculture to changing economic and environmental conditions.

Increasing biofuel feedstock production in sub-Saharan Africa, while at the same time meeting food demand targets and strictly following sustainability principles, faces a high degree of complexity. Approaches of systems analysis, nexus research and integrated solutions are best suited to address complex development pathways. A core principle of systems analysis is awareness of the full system in the analysis of its individual (sub-) components. Complex systems, such as the agriculture-energy-environment nexus require a systems perspective to attain the sustainability goals and avoid unintended consequences. Figure 2.1 sketches essential features and characteristics of agricultural systems embedded in a dynamic socio-economic, environmental and cultural setting with key elements discussed below.

Figure 2.1. Key components of agricultural systems embedded in a socio-economic and environmental setting



Source: adapted from Fischer, 2011

Agricultural production (centre and top Figure 2.1) results from a complex land use system. Human demand for ecosystem services and the opportunities and constraints of the specific agro-ecological setting determine the characteristics and alternative options of the land use system. Its resource endowment includes current and future climate conditions (temperature range and seasonality, precipitation amount, within year distribution and variability; frequency of occurrence of extreme temperature and precipitation events), topographic features (altitude, terrain slope, and geographical exposition), soil quality and characteristics, and prevailing land cover/vegetation.

The purpose of agricultural land use can range from subsistence production, meeting basic food needs of a rural household, to commercial farming supplying commodities to the national and international markets. The geographical conditions together with socio-economic and legislative conditions determine access to resources and land management characteristics, i.e. intensity of input-output relationships.

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The agricultural system is to a large degree demand driven (lower Figure 2.1) with major commodity markets integrated in the global economy. Judging the adequacy of future agricultural production is therefore dependent on future levels and kind of demand for agricultural products. sub-Saharan Africa is among the regions with a projected trajectory of strong increases in population combined with significant economic development resulting in increasing demand for food and feed. At the same time, the continent is home to the world's most precious ecosystems including hot-spots of biodiversity (upper left Figure 2.1). Sustainability must thus be addressed in a forward-looking perspective towards solutions applicable for both short- and long-time horizons.

Agriculture production does not exist in isolation but relates to, complements and competes with other economic sectors in a country. Agricultural land includes cultivated land for the production of annual crops and permanent cultivations ('cropland') and grassland for browsing ruminant livestock. Globally cropland amounts to 1550 million hectares, is concentrated on the world's most fertile lands and used for a variety of products including food, feed, fibre, and biomaterials for industrial purposes.

On average, globally humans use half of cropland extents for food consumption of crop products, almost one-third for food consumption of livestock products, some 12% for non-food industrial uses, and a remainder of 8% is required for seed production or lost as on-farm waste generated during harvest. In contrast, in sub-Saharan Africa, more than two thirds of cropland is cultivated for direct human food consumption, 12% for feed crop production, and 6% for non-food industrial use[8] (Fischer et al., 2017).

The rapid increase in the production of biofuels between 2000 and 2008 has triggered extensive debates, centred on food security impacts and the magnitude of achieved net greenhouse gas (GHG) emissions savings. Direct and indirect land use changes for increased biofuel feedstock production may limit the amount of cropland available for food production and reduce the amount of GHG emission savings achieved by the replacement of fossil fuels with biofuels (Fischer et al., 2009a, Prieler et al., 2013, Searchinger et al., 2008).

8 Results refer to the year 2010 calculated as average for the period 2009-2011. Non-food industrial use includes fibers (mainly cotton) for textiles, tobacco, and vegetable oils for the oleo-chemical industry.

The geographic configuration as well as the main objectives of agricultural production have been changing dynamically in response to the socio-cultural changes and economic development of each country. Four broad factors (left Figure 2.1) determine the dynamics of an agricultural land use and production system:

(i) technology development and availability, as in other economic sectors, is a key determinant of land use effectiveness, both in terms of input-output relationships as well as environmental impacts;

(ii) level and portfolio of investments in agriculture are critical for achieving growth and expansion of agricultural production;

(iii) governance systems and institutions play an important role in determining social aspects of agricultural production, equitable access to resources, resilience and robustness of the system in case of shocks and extreme events; and

(iv) policies create incentives or disincentives for producers and consumers, may cause economic distortions and protection, and set the regulatory context both for overall economic development and agricultural development in particular.

Finally, it is important to note that agricultural production is not only affected by climate change but is also a major contributor to global warming through CO_2 and non-CO_2 greenhouse gas emissions from land use change, in particular deforestation, application of nitrogen fertilizers, ruminant livestock production, methane from rice paddies, and fossil fuel use in cultivation, processing and transportation of agricultural products.

Systems analysis approaches are well suited to address the complex interlinkages of the spatial and temporal dimensions of the agriculture-energy-environment system. Clearly, the pilot study presented here must define system boundaries for its assessment, combining a high-resolution spatial dimension (grid-cell analysis) with a temporal dimension of scenario analysis until the 2050s.

The study uses ensemble projections of climate change to reflect future growing conditions. It is beyond the scope of this study to evaluate the feasibility of climate goals portrayed by the IPCC AR5 radiative forcing pathways as well as land, water, nutrients and other resource implications resulting from measures required for achieving these pathways. For example, the majority of low emission scenarios assume negative emissions (i.e. carbon dioxide removal from the atmosphere) such as carbon capture and storage (CCS), bioenergy with carbon capture and storage (BECCS), and afforestation (Gasser et al., 2015, Smith et al., 2016). Huge efforts would be needed to achieve the scale of CCS and BECCs foreseen in current stabilization scenarios, while publicly supported demonstration projects are still struggling to deliver large-scale installations (Fuss et al., 2014, Scott et al., 2013).

2.2 Incorporation of sustainability principles

The guiding principles for the sustainability assessment in this study are those developed by the Roundtable on Sustainable Biomaterials (RSB[9]). The RSB is an independent and global multi-stakeholder coalition, which works to promote the sustainability of biomaterials, including biomass and biofuels. The RSB has been developing principles and criteria for the sustainable production of biomass, biofuels and biomaterial (RSB, 2016). RSB principles are general tenets of sustainable production and processing, while RSB criteria describe the conditions to be met to achieve these tenets, either immediately (minimum requirements) or over time (i.e. three years - progress requirements).
The RSB principles follow a hierarchic structure with 12 main elements:

1. Legality
2. Planning, monitoring and continuous improvement
3. Greenhouse gas emissions

9 See www.rsb.org

4. Human and labour rights
5. Rural and social development
6. Local food security
7. Conservation
8. Soil
9. Water
10. Air quality
11. Use of technology, inputs, and management of waste
12. Land rights

Specific biofuel production projects may apply and qualify for RSB certification. For this study, we have considered all 12 principles and associated criteria for implementation in the assessment of potential sustainable biofuel production in sub-Saharan Africa. Clearly some principles are applicable and can be assessed only at the project level of a specific biofuel production supply chain. For example, legality, human and labour rights, or land rights must follow country-specific requirements and can only be assessed at the project level.

In contrast, several principles such as greenhouse gas emissions savings (RSB principle 3), food security (RSB principle 6), the conservation of biodiversity and ecosystems (RSB principle 7) and the principle regarding irrigation water use (RSB principle 9) can be applied at broad geographic scales and can be used to constrain potential biofuel feedstock production to stay within those sustainability domains. These have been integrated in the biofuel assessment conducted in this study by defining the following constraints:

Principle 3: Greenhouse gas emission saving

- Potential biofuels must deliver minimum 60% GHG emission savings compared to fossil fuels
- Exclude soils of high organic matter content from biofuel feedstock production

Principle 6: Local food security

- Reserve cropland needed for projected future food, feed and industrial crops (other than biofuel feedstock) production
- Safeguard biomass from grassland/savannah required for feeding ruminant livestock

Principle 7: Conservation

- No deforestation for biofuel feedstock production
- Safeguard protected areas and ecosystems of high value for biodiversity

Principle 8: Soils

- All steep terrain excluded from biofuel feedstock production
- Biofuel feedstock production follows principles of conservation agriculture

Principle 9: Water regime

- No irrigated biofuel feedstock production in water scarce[10] areas

10 Because of uncertain data available for the delineation water scarce areas, the study considered only rain-fed biofuel feedstock production potentials across SSA.

2.3 Approach to the estimation of sustainable biofuel feedstock potentials

The estimation of sustainable biofuel feedstock potentials in this study employs several analysis steps, as summarized in Table 2.1.

Table 2.1. Overview of assessment steps for the estimation of sustainable biofuel potentials

Step	Perspective / Theme	RSB principle
	Land use	
1	Exclude cropland[1] for food production	6 Food security
2	Exclude all forest land	7 Conservation 3 GHG emissions
3	Exclude areas providing critical ecosystem services and high biodiversity value	7 Conservation 8 Soil 9 Water
4	Exclude built-up, water, bare and sparsely vegetated areas	Not applicable
	Land Management	
5	Exclude areas with soils of high organic matter content	3 GHG emissions 8 Soil
6	Set aside land for feed requirements of ruminant livestock	6 Food security
7	Exclude grid-cells with low remaining land share[2]	Not applicable
▸	Estimate "REMAIN(ing) land[3]" potentially available for biofuel feedstock production	
	GHG savings	
8	Exclude grid-cells where none of the suitable feedstock crops can comply with required GHG savings criteria	3 GHG emissions
▸	Sustainable biofuel potentials from REMAIN land	
	Crop residues from food production	
9	Estimate a sustainable potential from crop residues	8 Soil
▸	Additional biofuel potential from crop residues	
	Supply chain considerations	
10	Highlight economic production densities[4]	

1 Cropland includes arable land and land under permanent crops cultivated for food and feed crop production. Currently cultivated non-food crops are also included (e.g. cotton, tobacco). 2 To achieve a viable scale of operation required for economic farm management and commercial feedstock production, we excluded grid-cells where remaining land (after steps 1-6) is less than 10% of the 5x5 arc-minute grid-cell. 3 Land remaining once food and environmental sustainability criteria have been addressed; henceforth termed 'REMAIN land'. 4 Maps show the amount of biofuel production potentials in a circle of 100 km for the identification of clusters that can provide sufficient feedstocks to a biofuel plant with a defined minimum production capacity.

First, adherence to the RSB criteria was implemented by defining several land-use related exclusion layers, where biofuel feedstock production is not considered to take place ("No-Go areas"):

- Respect food security › Exclusion layer FOOD
- No deforestation › Exclusion layer FOR
- Safeguard environment & biodiversity › Exclusion layer ENV

The principle of respecting food security is implemented by setting aside the land cover category "cropland" for food production ("Exclusion Layer FOOD"). This applies to both current cropland and future cropland required for food according to defined socio-economic development scenarios (i.e. future food demand estimated based on population growth combined with dietary changes driven by economic growth).

Food security considerations may also apply to land in use for grazing ruminant livestock (cattle, sheep, goats). Livestock can feed on multiple sources, including:

i) browsing on grassland, shrub land, forests or other tree-covered areas;
ii) feeding on crops cultivated on cropland (e.g. corn)
iii) crop residues from food crop production (e.g. straw)
iv) by-products from food processing (e.g. cake from crushing oil crops)
v) other food residues and waste

Depending on available feed sources, livestock management characteristics (e.g. stocking densities), and biomass potential of grassland and shrub land, the RSB criteria on food security may limit the extents of grassland that can be considered for biofuel feedstock production. Where demand for livestock grazing is affected by large-scale biofuel feedstock production, these areas may not qualify for RSB certified biofuel feedstock production due to threatening local food security. This study estimates livestock land requirements by calculating a simple livestock feed balance at grid-cell level. In this way, extents of grassland and shrub land required for feeding ruminants is excluded from consideration for biofuel feedstock production.

To adhere to the principle of "Safeguard land for environment and biodiversity", this study has compiled a spatial database, which delineates legally protected areas as well as various other areas providing key ecosystem services and high biodiversity value in sub-Saharan Africa that currently do not have a legal protection status, including wetlands, strategic water sources areas and buffer zones around protected areas ("Exclusion layer ENV").

All areas classified as forestland in 2010 are excluded from biofuel feedstock production ("Exclusion Layer FOR"). The land use/cover map used in this study (see 3.1.2.4) indicates area shares of 'forestland' in each 30 arc-second (about 1x1 km) grid cell. Forestland as used here includes 'tree-covered areas and mangroves', which were originally derived from satellite data interpretation and assembled in the GLC-SHARE land cover database published by FAO (Latham et al., 2014). GLC-SHARE applies the FAO land cover classification system LCCS, where a tree is defined as "a woody perennial plant with a single, well-defined stem carrying a more-or-less-defined crown and being at least 3 meter tall (Ford-Robertson, 1971). Where forests enjoy protection status or otherwise carry key biodiversity value, there is overlap between the "Exclusion layer FOR" and "Exclusion layer ENV".

Using soil attribute information of the Harmonized World Soil Database (see 3.1.2.3) we excluded from conversion all soils with high organic matter content. Conversion of these carbon-rich soils is not considered in the analysis, as the carbon debt of land conversion of such soils would not allow biofuels to meet the minimum 60% GHG savings criteria. Detailed GHG accounting and the exclusion of soils with a high content of organic matter was thus implemented to facilitate compliance with defined GHG saving requirements.

Furthermore, the land use categories 'bare land' and 'sparsely vegetated land' have severe biophysical limitations for economic feedstock production and were excluded, as was 'built-up land' and 'water'.

Finally, to achieve a viable scale of operation required from economic farm management and commercial feedstock production, we excluded grid-cells where remaining shrub- and grassland (i.e. after consideration of environment, biodiversity and livestock feed requirements) is less than 10% of the grid-cell extent.

As listed in Table 2.1, the first seven steps in the analysis result in the quantification of remaining land (almost entirely grassland and shrub land) that could be considered for biofuel feedstock production, once food and environmental sustainability criteria have been taken into account, henceforth termed 'REMAIN' land. A layer of REMAIN land has been compiled for base year 2010 and has been dynamically updated to year 2050 along with selected scenarios of socio-economic development and climate change, taking into account projected increases of food demand and related cropland expansion.

The following sections discuss the models, data and scenarios used for implementing the outlined methodology to estimate the volumes of sustainable biofuel feedstock production potentials in sub-Saharan Africa.

3. MODELLING TOOLS, DATA AND SCENARIOS

3.1 The Global Agro-Ecological Zones (GAEZ) modelling framework

Cultivation potential describes the agronomically possible upper limit for the production of individual crops/feedstocks under given agro-climatic, soil and terrain conditions for specific levels of agricultural inputs and management conditions.

The Agro-Ecological Zones (AEZ) approach is based on principles of land evaluation (FAO, 1976, FAO, 1984, FAO, 2007). The AEZ concept was originally developed by the Food and Agriculture organization of the United Nations (FAO) and over time, IIASA and FAO have further developed and applied the AEZ methodology and supporting databases and software packages. This study uses data and calculation procedures of GAEZ version 4. For a detailed description of GAEZ methodologies, we refer to the documentation of GAEZ version 3[11] (Fischer et al., 2012). This most recent update uses 2010 baseline data including land cover, soil and terrain conditions, protected areas, renewable water resources, population distribution and livestock numbers. It applies climatic conditions for the historical period 1981-2010 and for a selection of future climate simulations using recent IPCC AR5 climate model outputs from five general circulation models (GCMs) and for four different representative concentration pathways (RCPs).

Climatic data comprises precipitation, temperature, wind speed, sunshine hours and relative humidity. These climate parameters are used to compile agronomically meaningful climate resources inventories including quantified thermal and moisture regimes in space and time. Geo-referenced global climate, soil and terrain data are combined into a land resources database, which is assembled based on global grids, with 5 arc-minute and/or 30 arc-second resolutions.

Matching crop requirements and land conditions to identify crop/feedstock specific limitations of prevailing climate, soil and terrain resources and evaluation with simple crop models, under assumed levels of inputs and management conditions, provides estimates of maximum potential and agronomically attainable yields for basic land resources units under different agricultural production systems defined by water supply (rain-fed or different irrigation systems) and levels of inputs and management circumstances. These generic production systems used in the AEZ analysis are referred to as Land Utilization Types (LUT).

Attributes specific to each particular LUT include crop/feedstock information such as eco-physiological parameters (harvest index, maximum leaf area index, maximum rate of photosynthesis, etc.), cultivation practices and input requirements, and utilization of main produce, residues and by-products. The GAEZ procedures are applied separately for rain-fed and irrigated conditions.

Several calculation steps are applied at the grid-cell level to determine potential yields for individual LUTs. Growth requirements are matched against a detailed set of agro-climatic and edaphic land characteristics derived from the land resources database. Agro-climatic characteristics, including estimations of evapotranspiration and crop/feedstock-specific soil moisture balances, are used for assessments of LUT specific intermediate outputs of agro-climatic suitability and productivity.

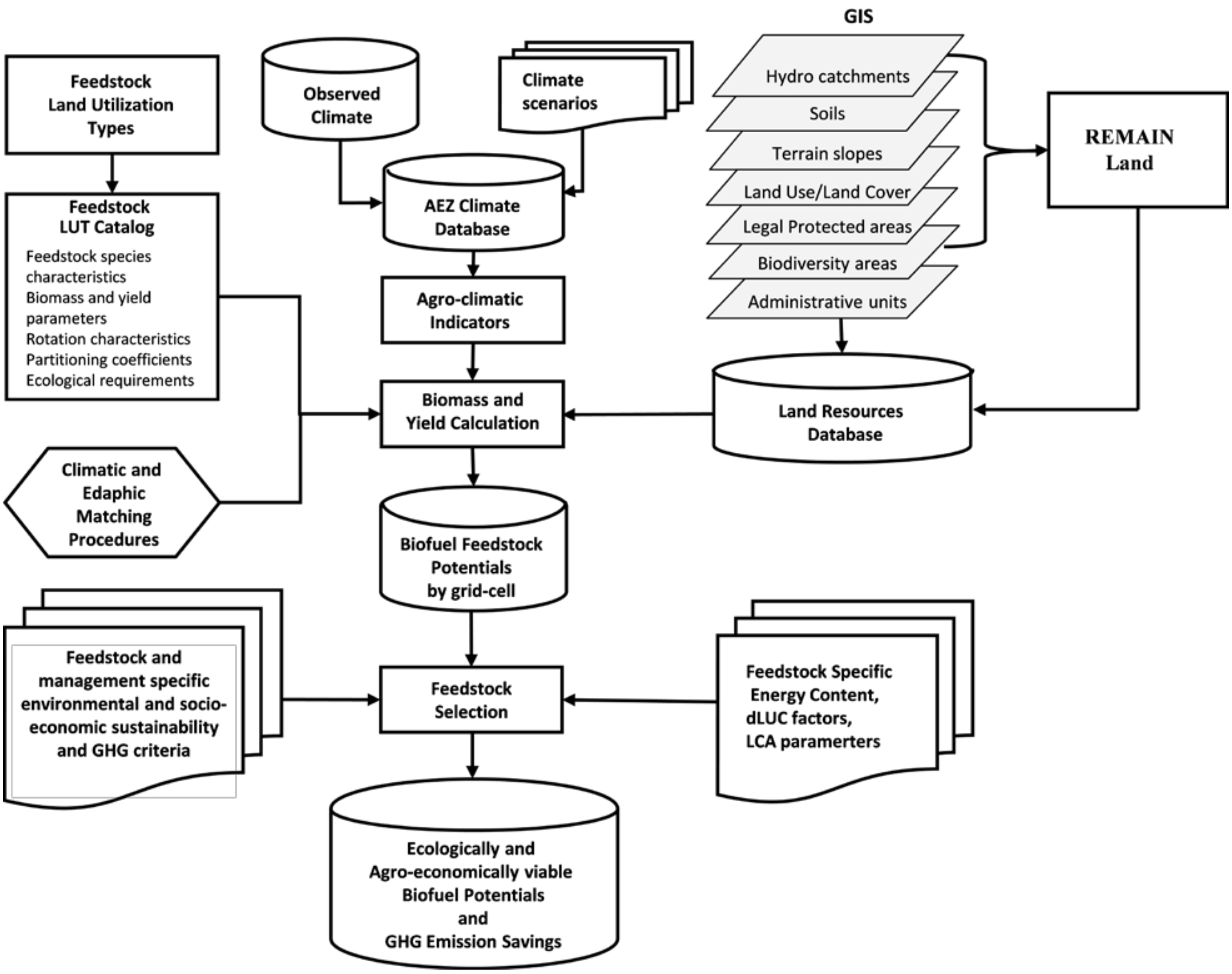
Recent national, regional and global land cover data and land use statistics have been used to produce a global land cover database consisting of a quantification by 30 arc-second grid cell of main land use/land cover shares.

11 See http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/ and http://www.fao.org/nr/gaez/en/

3.1.1 Structure and overview of GAEZ procedures

The suitability of land for the cultivation of a given feedstock/LUT depends on feedstock requirements as compared to the prevailing agro-climatic and agro-edaphic conditions. GAEZ combines these two components by successively modifying grid-cell specific agro-climatic suitability according to edaphic conditions of location specific soil and terrain characteristics. The structure allows stepwise review of results. Figure 3.1 summarizes the GAEZ methodology and information flow as applied for the present assessment of biofuel feedstock potentials.

Figure 3.1. AEZ methodology. Information flow and integration



Calculation procedures for establishing suitability estimates include five main steps of data processing, namely:

- Climate data analysis and compilation of general agro-climatic indicators
- Feedstock-specific agro-climatic assessment and water-limited biomass/yield calculation
- Yield-reduction due to agro-climatic constraints
- Edaphic assessment and yield reduction due to soil and terrain limitations
- Estimation of feedstock specific GHG emission balances
- Integration of results into feedstock-specific grid-cell databases.

GAEZ operates on a 5 by 5 arc-minutes latitude/longitude grid-cell resolution (about 9 by 9 km). For land use, soil and terrain conditions input data are available at a 30 arc-second resolution (about 1 by 1 km) and sub-grid distributions of these variables are retained for each 5 arc-minute grid-cell.

3.1.2 GAEZ input data for biofuel feedstock modelling

3.1.2.1 Biofuel Feedstock Land Utilization Types

Land Utilization Types (LUT): The AEZ procedures have been used to derive potential biomass and yield estimates for rain-fed biofuel feedstock production by grid-cell, under the assumption of high level inputs/advanced management. High input refers to main socio-economic and agronomic/farm-management components, i.e., the farming system is (1) market oriented; (2) commercial production is a management objective, and (3) production is based on currently known and available cultivars, is mechanized with low labor intensity, and assumes adequate applications of nutrients and pest, disease and weed control.

The quantified description of biofuel feedstock LUTs include characteristics such as vegetation period, ratoon practices, photosynthetic pathway, rate of photosynthesis in relation to temperature, maximum leaf area index, biomass partitioning coefficients, and parameters describing ecological requirements of biofuel feedstock produced under rain-fed or irrigated conditions.

For this study of sub-Saharan Africa, 11 different biofuel feedstocks have been assessed. This includes eight feedstocks for which AEZ model parameterizations were available from earlier work, i.e., jatropha, oil palm, soybean, sugarcane, sweet sorghum, maize, cassava and miscanthus (Fischer et al., 2009b, Fischer et al., 2012). For three additional feedstocks (Solaris energy tobacco, camelina and triticale) eco-physiological data has been collected and model parameterizations have been set up for use in AEZ models.

3.1.2.2 Climate data

Observed climate data

For the GAEZ historical assessment time series data were obtained from the Climate Research Unit (CRU) at the University of East Anglia, the Global Precipitation Climatology Centre (GPCC), and the EU WATCH Integrated Project.

GAEZ uses CRU TS v3.21 time-series datasets (Jones and Harris, 2013). These are month-by-month variations in climate over the last century covering the period January 1901 to December 2012. CRU TS v3.21 data were calculated on 0.5x0.5 degree grids, which were based on an archive of monthly average daily data provided by a large number of weather stations distributed around the world. CRU TS v3.21 variables applied in GAEZ are temperature, diurnal temperature range, cloud cover, vapour pressure and wet day frequency.

For representing spatial patterns of monthly precipitation, the GPCC Full Data Reanalysis Product Version 6 was used (Becker et al., 2011). Available data covered the period from 1901 to 2010.

New global sub-daily (3 hours) meteorological forcing data were provided in WATCH[12] for use with land surface- and hydrological-models. The data are derived from the ERA-40 and ERA-Interim reanalysis products via sequential interpolation to half-degree resolution, elevation correction and monthly-scale adjustments based on CRU (mean-temperature, diurnal temperature range, cloud-cover) and GPCC (precipitation) monthly observations combined with new corrections for varying atmospheric aerosol-loading and separate precipitation gauge corrections for rainfall and snowfall. The ERA-40 and ERA-Interim products include all the key near-surface meteorological variables required in GAEZ models.

12 WATCH was a large Integrated Project funded by the European Commission under the Sixth Framework Programme, Global Change and Ecosystems Thematic Priority Area (contract number: 036946). The WATCH project started early 2007 and continued to 2011.

Original monthly data were interpolated to a five arc-minute grid-cell resolution, applying a bilinear interpolation method within ArcGIS. In the case of temperature, the downscaling procedures applied a lapse rate of 0.55 degree Celsius per 100-meter elevation. First, the respective digital elevation model of the source data was used to calculate temperature values adjusted to sea level, where a bilinear interpolation was performed. Second, a five arc-minute DEM, derived from Shuttle Radar topography Mission (SRTM) data, was used to calculate temperature at actual elevations.

Year-by-year climatic data analysis in GAEZ and time series data were used to compile three 30-year baseline data sets (for respectively the periods 1961-1990, 1971-2000 and 1981-2010) and associated CV/SD statistics

Climate Scenarios

IPCC AR5 climate model outputs for four Representative Concentration Pathways (RCPs) are used to characterize a range of possible future climate distortions for agro-climatic resources inventories and crop/feedstock potential assessments for the 2020's, the 2050's and the 2080's.

Acknowledging the importance of the fundamental linkages between climate and socio-economic development, the climate change research community is pursuing development of a new framework for the creation and use of scenarios to improve interdisciplinary analysis and assessments of climate change, its impacts, and response options. To define a range of future scenarios, this process includes a set of forcing pathways, known as the Representative Concentration Pathways (RCPs), which can be combined with alternative Shared Socio-economic Development Pathways (SSPs) (Moss et al., 2010, O'Neill et al., 2017).

RCPs comprise of a set of four greenhouse gas concentration (not emissions) trajectories developed for the climate modelling community as a basis for long-term and near-term modelling experiments adopted by the IPCC for its fifth Assewssment Report (AR5). The four RCPs - RCP2.6, RCP4.5, RCP6, and RCP8.5 – are named after the assumed level of radiative forcing values in the year 2100 and together span the range of values found in the open literature, i.e. from 2.6 Wm-2 under stringent emission mitigation measures to 8.5 Wm-2 associated by-and-large with fossil fuel-based 'business as usual' development assumptions. These concentration pathways are documented in a special issue of Climatic Change (Van Vuuren et al., 2011), and climate model simulations based on them were undertaken as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012).

Multi-model ensembles for each of the climate forcing levels of the RCPs were analysed based on spatial data from the IPCC's AR5 CMIP5 process, with data bias-corrected and downscaled to half-degree resolution for use in the Intersectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013). ISI-MIP data at half-degree resolution of five climate models (GFDL, HadGEM2, IPSL, MIROC, NorESM) and for four RCPs (RCP 2.6, 4.5, 6.0 and 8.5) - totalling 20 combinations of respectively RCPs and climate models - were used for generating climate input data in GAEZ for the 2020s (period 2011-2040), the 2050s (period 2041-2070) and the 2080s (period 2070-2099).

3.1.2.3 Soil and terrain data

GAEZ uses the Harmonized World Soil Database v1.21 (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) as source of soil resources data for spatially detailed evaluation of soil qualities and edaphic suitability. The HWSD is composed of a global level geographical layer containing reference to some 30,000 soil map units. This information is stored as a 30 arc-second map unit raster in GIS, linked to an attribute database containing harmonized soil profile data for each map unit. HWSD includes 17 soil attributes generalized for 0-30cm and 30 -100 cm soil depth.

The use of a standardized structure in HWSD creates a harmonized data product across the various original soil databases. This allows the consistent linkage of the attribute data with the raster map to display or query the composition of soil mapping units and the characterization in terms of selected soil parameters. Soil attributes include organic carbon, pH, soil water holding capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry.

Terrain data from the updated 90 m (3 arc-sec) SRTM data (Rabus et al., 2003), obtained from the CGIAR Consortium of Spatial Information (CGIAR-CSI), was processed in GAEZ to compile a global terrain slope and aspect database at 30 arc-seconds comprising the following elements:

1. Median elevation (m) of 3 arc-second grid-cells within each 30 arc-second grid cell
2. Distributions (%) of calculated 3 arc-second terrain slopes in terms of eight slope gradient classes: 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and > 45%.
3. Slope aspect information (%), compiled at 3 arc-seconds and stored at 30 arc-second in distributions of five classes: slopes below 2% (undefined aspect), slopes facing North (315°–45°), East (45°–135°), South (135°–225°), and West (225°–315°).

3.1.2.4 Land use/cover data

The GAEZ land use / land cover layer comprises of an area share quantification of the prevalence of seven major land use/land cover classes in individual 5 arc-minute latitude/longitude grid-cells.

Based on recent national, regional and global land cover mapping and land use statistics, FAO's Land and Water Division has published a global land cover database, GLC-SHARE[13] (Latham et al., 2014), consisting of a quantification by 30 arc-second grid cell of area shares occupied by eleven main land use/land cover types.

For use in GAEZ, the shares of arable land and land under permanent crops were calibrated to match with FAOSTAT national and sub-national agricultural statistics of 2009-2011.

Table 3.1. Land use/cover categories applied in this study

No	Land use /cover	Acronym
1	Cropland (i.e. the sum of arable land and land under permanent crops)	Cropland
1a	Cropland, rain-fed	Rain-fed
1b	Cropland, equipped with irrigation	Irrigated
2	Artificial surfaces (i.e. urban, industrial, infrastructure)	Built-up
3	Tree-covered land, Mangroves	Forest
4	Shrub-covered land	Shrub land
5	Grassland, Regularly flooded herbaceous land	Grassland
6	Bare or sparsely vegetated land*	Sparse veg.
7	Water bodies	Water

** includes permanent snow or glacier*

In addition, in order to distinguish rain-fed and irrigated cropland, the GAEZ land cover database includes the information of the Global Map of Irrigated Areas (GMIA v5) (Siebert et al., 2013) calibrated to FAO statistics of 2009-2011, i.e. land equipped for irrigation. GMIA v5 has also been used for its provision of data layers indicating water source of irrigation (surface water, groundwater, other) and spatial estimates of actually irrigated areas.

In summary, the GAEZ land cover database derived from GLC-SHARE provides the following land use/land cover classes: (i) artificial surfaces; (ii) rain-fed cropland; (iii) irrigated cropland; (iv) grassland; (v) tree covered areas; (vi) shrub covered areas; (vii) herbaceous vegetation, aquatic or regularly flooded; (viii) mangroves; (ix) sparse vegetation; (x) bare soil; (xi) snow and glaciers; and (xii) water bodies. Table 3.1 shows the land use/cover classes applied in this study, which distinguish shares of seven aggregate land cover classes for year 2010 including two sub-classes for cropland.

13 Global Land Cover-SHARE of year 2014, see http://www.glcn.org/databases/lc_glcshare_en.jsp

3.2 Selection of biofuel feedstocks

This study includes a number of biofuel feedstocks used for different conversion pathways (Table 3.2). First generation conversion pathways rely on the vegetable oil, sugar and starch components of the respective crops. Conversion processes are well established and extensively employed for industrial scale biofuel production for the road transport sector in Brazil (sugar cane to bioethanol), the United States (cereals, mainly maize for bioethanol), and Europe (vegetable oil to biodiesel).

Table 3.2. Biofuel feedstocks assessed in this study

Bio-material	Feedstock	Produce (DM)	Energy content [GJ / ton]
Vegetable oil	► Solaris	Seed	12.1
Vegetable oil	► Jatropha	Seed	12.7
Vegetable oil	► Oil palm	Oil	34.3
Vegetable oil	► Soybean	Grain	7.24
Vegetable oil	► Camelina	Seed	12.6
Sugar	► Sugar cane	Sugar	15.8
Sugar/Starch	► Sweet Sorghum[1]	Stalk, grain	7.27
Starch	► Maize[2]	Grain / stover	11.1
Starch	► Cassava	Root	10.9
Starch	► Triticale	Grain	9.17
Lignocellulosic[3]	► Miscanthus	Above ground biomass	6.35
Lignocellulosic	► Agric. crop residues[4]	Stalks, leaves, tops, etc.	6.35

1 Sweet sorghum: 1.32 grain + 6.6 sugar in stalk; 2 Maize 13% water; 9.8 grain + 1.3 stover; 3 Second-generation technology, large scale production not yet commercially viable; miscanthus based on 300 l / ton biomass; 4 Crop residues generated from agricultural production including cereals, cotton, sunflower, soybean, groundnut, rapeseed and sugarcane.

The woody and herbaceous plant materials, generally referred to as lignocellulosic biomass, represent a large quantity of potential energy and hold promise as a source of feedstock for second-generation technologies. Cellulose is more difficult to break down and convert to biofuels compared to vegetable oils, starch from grains and roots, and sugar, as used in first-generation plants. This difficulty makes the technology more complex and expensive, and large-scale industrial production is not yet commercially viable. There are extensive research and demonstration projects, yet the speed and scale of future deployment is uncertain.

For three feedstocks, namely Solaris, camelina and triticale, GAEZ crop/LUT specifications were developed specifically for the purpose of this study. Annex I provides short general descriptions of these three feedstocks.

3.3 Land set-aside for environment and of high value for biodiversity

The provisioning ecosystem services employing land and water for food and non-food agricultural production often compete with regulating and habitat ecosystem services. Regulating ecosystem functions include climate regulation, natural hazard regulation, water purification, pollination and pest control. Habitat services highlight the importance of ecosystems to provide habitat for migratory species and to maintain the viability of gene-pools. Both provisioning and regulating ecosystem services are central for sustainable development.

This study has put particular emphasis on developing a state of the art spatial layer representing protected areas and other areas of high biodiversity value in sub-Saharan Africa. For this purpose, we have integrated spatial layers from various data sources (Table 3.3). Using ArcGIS software, we converted the original polygon data to a 30 x 30 arc-second (about 1km) grid and merged them in the order listed in Table 3.3. The high spatial resolution of South Africa's Strategic Water Source Areas (SWSA) database required converting original polygon data to a 3 x 3 arc-second (about 90 m) grid-cell size with aggregation to a 30 x 30 arc-second resolution using a majority rule.

Protected areas and areas of high importance for biodiversity are key for the provision of regulating ecosystem services. Following the RSB requirement that "Operations shall avoid negative impacts on biodiversity, ecosystems, and conservation values", formulated in principle seven on "Conservation", this study sets aside land for the environment and areas of high importance for biodiversity. The map shown in Figure 3.2 was created by sequentially merging the datasets outlined Table 3.3.

Table 3.3. Data sources for delineating areas of importance for the environment and biodiversity

No	Data domain	Acronym	Source and reference
1	World Database of Protected Areas (WDPA)	WDPA	www.protectplanet.net (IUCN and UNEP-WCMC, 2016)
2	Peace Park Foundation (PPF)	PPF	www.peaceparks.org
3	Global Wetland Database (GLWD) Level 3	GLWD	(Lehner and Döll, 2004)
4	Key Biodiversity Areas (KBA) and Alliance for Zero Extinction (AZE) as included in the Integrated Biodiversity Assessment Tool (IBAT)	KBA	www.keybiodiversityareas.org
5*	South Africa Mining Guidelines Category A (Legally protected) and B (Highest biodiversity importance) of original layer included	Highest biodiversity importance	www.sanbi.org (SAMBF, 2012)
6* Category A (Legally protected) and B (Highest biodiversity importance) of original layer included	Strategic Water Source Areas (SWSA) in South Africa	SWSA	www.sanbi.org (Nel et al., 2013)
9 (SAMBF, 2012)	One pixel buffer around WDPA and PPF	Buffer	own calculations in ArcGIS

** apply to South Africa only*

For example, when grid-cells are included in the World Database of Protected areas (WDPA) and in the Global Wetland Database (GLWD), the map in Figure 3.2 marks these areas as WDPA. Note, due to data availability the exclusion classes 5 (land of highest biodiversity importance) and 6 (strategic water resource area) apply only to South Africa.

The fraction of the land set aside to safeguard the environment and biodiversity across SSA adds up to 16% of the total land mass of the sub-continent, but varies across regions, from 14% in Sudano-Sahelian Africa to 46% in Southern Africa. Figure 3.3 highlights extents of the different exclusion categories by region.

It is worth repeating, there is an overlap between the "environment" and "forest" exclusion layers. The former includes those forested areas that are included in any of the databases mentioned in Table 3.3, whereas the latter includes all areas where the current land cover is forest or mangroves. This means that even though not all forests are included in the exclusion layer that sets aside land for the benefit of environmental conservation, all forests are designated as no-go areas for biofuel feedstock production.

Figure 3.2. Land set-aside for environment and biodiversity (Environment exclusion map)

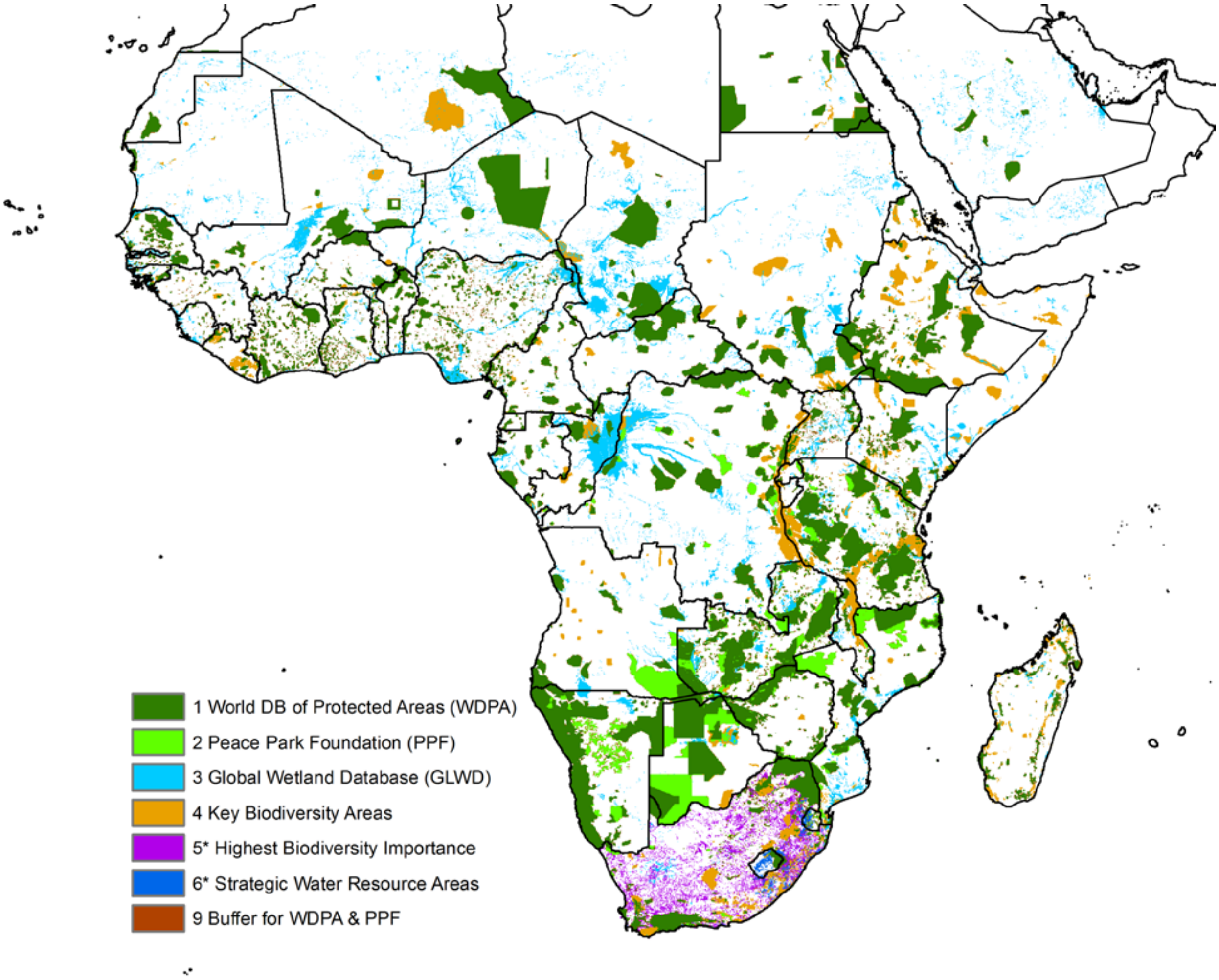


Figure 3.3. Land set-aside for environment and biodiversity, by region

3.4 Land requirements of ruminant livestock

The “Gridded Livestock of the World” database (GLW2) published by FAO represents an estimate of current livestock distribution at a 30x30 arc-sec resolution. The compilation methodology is described in “Mapping the Global Distribution of Livestock“ (Robinson et al., 2014). Livestock data of GLW2 - reported in heads of cattle, sheep, goats and other animals per grid-cell - has been converted for use in this study to ”Tropical Livestock Units” (TLU). Then, a measure of ruminant livestock carrying capacity based on grass/shrub land productivity simulated in GAEZ, augmented with residues available from cropland, was used to determine land requirements for grazing livestock, i.e., the fraction of grass/shrub land in a 5 arc-min grid cell needed to meet estimated ruminant feed requirements. Below some details are described of the calculations applied to determine the share of grassland/shrub land considered to be not available for biofuel feedstock production due to the presence of ruminant livestock.

The share of grassland/shrub land in a grid-cell set aside for ruminants was determined by means of a simple feed balance, calculated according to equation (1):

$$f_{LV} = \min(1, \frac{F_{req}}{F_{sup}}) \tag{1}$$

where

f_{LV} Share of grassland/shrub land to be reserved for livestock feeding

F_{req} Annual forage feed requirement of ruminant livestock [ton DM]

F_{sup} Annual forage feed supply [ton DM]

The forage feed requirements of ruminants in a grid cell were calculated according to equation (2):

$$F_{req} = A * TLU * (250 * 0.02667 * 365) \tag{2}$$

where

A Total area of grid cell [km2]

TLU Ruminant livestock density expressed in tropical livestock units [TLU per km2]

F_{req} Annual forage feed requirement of ruminant livestock [ton DM]

In the calculation of forage requirements the live weight of a TLU is defined as 250 kg and the daily feed requirement per kg of live weight is set as 0.02667 kg DM (Dida, 2017). The ruminant livestock distribution in 2010 is derived from FAO (Robinson et al., 2014) by aggregation of cattle, sheep and goat using weights of respectively 0.7, 0.1 and 0.1 (see Figure 3.4).

The calculation of potential forage feed supply uses equation (3):

$$F_{sup} = Y_{grass} * f_{util} * A * (s_{Gr} + \alpha * s_{Sh} + \beta * s_{Cr}) \quad (3)$$

where

F_{sup} Forage feed supply [ton DM]

A total area of grid cell [km2]

Y_{grass} average annual palatable forage/grass yield [kg DM/km2]

f_{util} grass/forage utilization factor [dimensionless]

s_{Gr} share of grassland in grid cell [dimensionless]

s_{Sh} share of shrub land in grid cell [dimensionless]

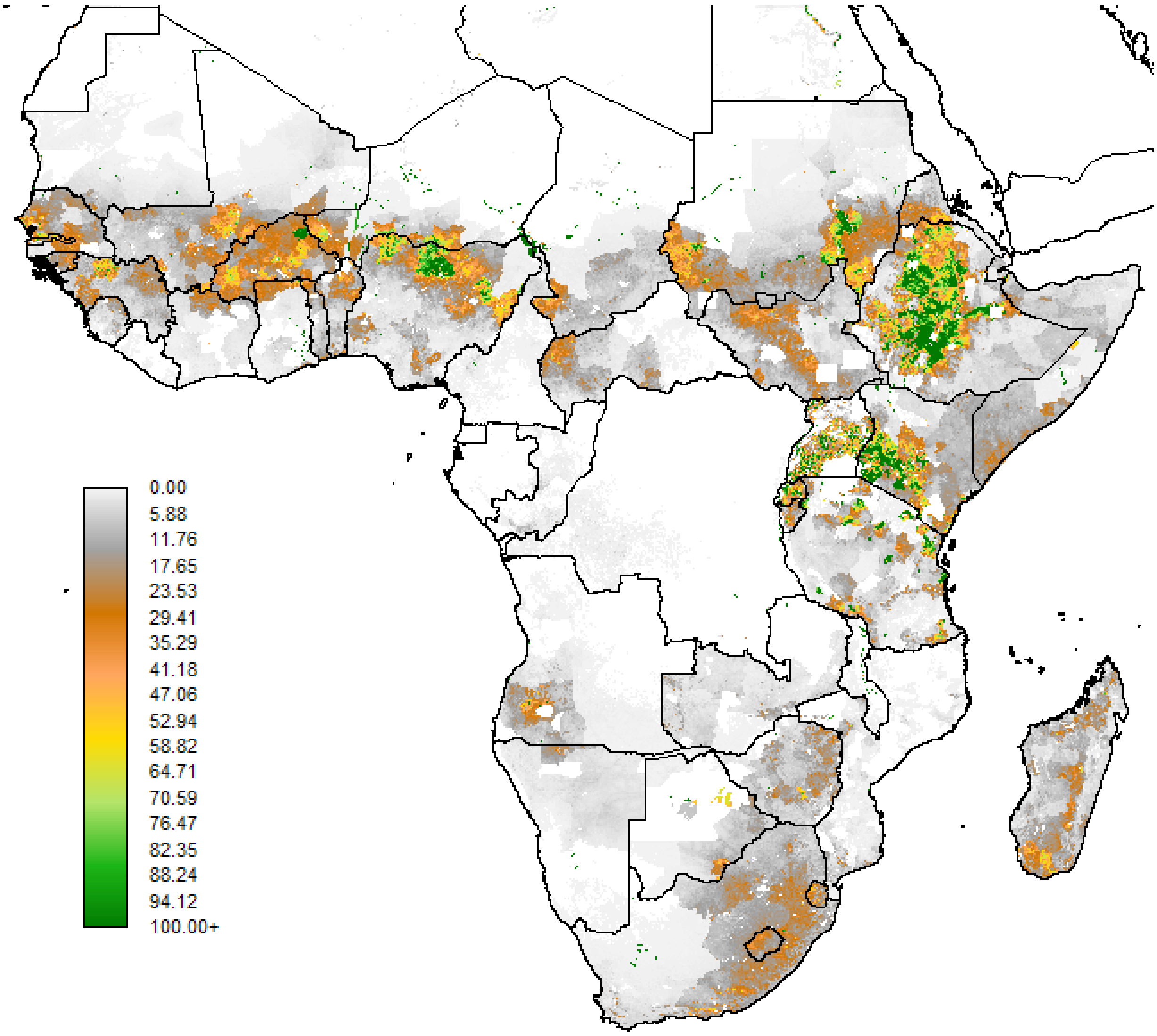
s_{Cr} share of cropland in grid cell [dimensionless]

α forage yield in shrub land relative to potential grass yield [dimensionless]

β forage/feed availability from cropland relative to potential grass yield [dimensionless]

In addition to estimating the forage available from the grassland, equation (3) also accounts for feed from shrub land and/or cropland in a grid cell.

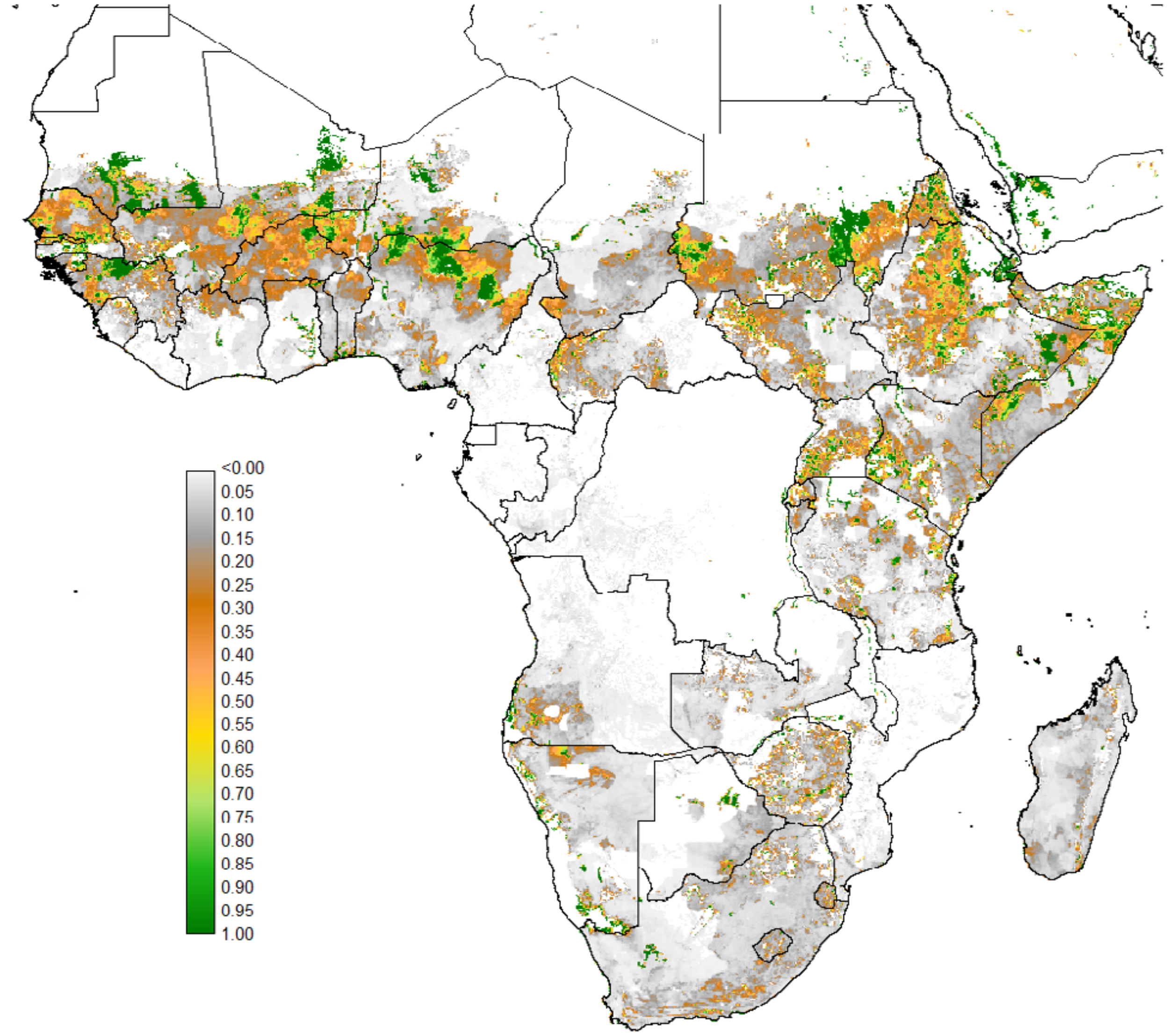
Figure 3.4. Ruminant livestock distribution in 2010 (TLU/km2)



For the calculations in this study we used a potential palatable rain-fed grass yield Y_{grass} as simulated in GAEZ v4 under low input assumptions (i.e., assuming natural grassland) and a feed utilization factor f_{util} = 0.8. The palatable share under low input conditions simulated in GAEZ v4 ranges between 15-50% of total biomass depending on moisture conditions represented by number of growing period days in a location. For shrub land the literature indicates somewhat lower herbaceous yields and we apply a parameter value of α=0.67. For cropland we assume that some crop residues and by-products will be available equivalent to half the amount produced on grassland, hence a parameter value β=0.5 is applied.

Figure 3.5 shows a map of the calculated land shares reserved for livestock. Note, in this figure a value of 1 (i.e., 100%) was assigned to all grid cells where ruminant livestock density exceeds 100 TLU/km^2, regardless of the calculated feed requirement to supply ratio.

Figure 3.5. Estimated share of grassland/shrub land fLV set aside for livestock grazing in 2010



The maximum extent of REMAIN land that can be considered for biofuel feedstock cultivation in a grid cell is consequently limited to

$$A_B = A * (s_{Gr} + s_{Sh}) * (1 - f_{LV}) \quad (4)$$

where

A	Total area of grid cell [km2]
A_B	Maximum extent available for biofuel feedstock cultivation [km2]
f_{LV}	Fraction of grassland/shrub land set aside for livestock feeding [dimensionless]
s_{Gr}	Share of grassland in grid cell [dimensionless]
s_{Sh}	Share of shrub land in grid cell [dimensionless]

3.5 Greenhouse gas (GHG) emissions

A primary objective for the use of biofuels is that they represent a renewable substitute for fossil fuels and can potentially lower GHG emissions from transport. Although in principle CO_2-neutral, the use of biofuel does not lead to a 100% reduction in greenhouse gas (GHG) emissions compared to the use of fossil fuels. Life cycle carbon emissions arise from every step in the fuel chain, from crop cultivation, feedstock conversion, to the distribution and final consumption of the derived transportation fuels in a car. Further, direct or indirect land use changes often result in additional GHG emissions.

Indirect land use changes have been a major focus of discussion in scenarios of accelerated biofuel expansion (Lapola et al., 2010, Plevin et al., 2010, Searchinger et al., 2008, Wicke et al., 2012). The concept of indirect land use change refers to a potential geographical shift in production of crops due to the demand for and production of biofuel feedstocks. Thus, when displacement of crops by biofuel feedstock cultivation triggers changes in land use (e.g. deforestation) and associated GHG emissions, the net GHG balance of biofuels over a given accounting period may be diminished or become even negative. The assumptions applied in this study avoid indirect land use changes because current and future cropland required for food production is reserved up-front ("food first" principle) and not considered for biofuel feedstock production.

Feedstock cultivation, conversion of the biotic raw material to biofuels, and transport and distribution of fuels is not emission-free either. Emissions generated along the supply chain are calculated in life-cycle assessments (LCA) and results vary significantly depending on several factors/assumptions, in particular the type of energy used in the biofuel conversion process.

Additional GHG emissions occur when carbon is lost due to the conversion of land covered in natural vegetation to cropland for biofuel feedstock production. For example, when grassland is ploughed for the cultivation of biofuel feedstocks, the carbon content in the soils will most likely decrease and thereby release carbon to the atmosphere.

The emissions under a biofuel system must be compared to a reference system in which the biofuel would not be produced. Recently, the fossil fuel comparator value used in the GHG calculation method of the EU RED2 proposal has been increased from 83.8 g CO_2eq/MJ to 94 g CO_2eq/MJ (EC, 2017[14]). Requirements for minimum GHG emission savings from biofuels compared to the use of fossil fuels have been set in different legislations around the world (EPA, 2007a, EPA, 2007b, EU, 2009). The RSB requires a minimum threshold of 60% reduction of GHG emissions for a specific biofuel supply chain compared to the emissions of a fossil fuel.

In this study we apply a fossil fuel comparator of 94 g CO_2eq/MJ and a 60% minimum saving requirement for biofuels. Below we summarize lifecycle GHG results of biofuel supply chains (3.5.1) and we describe details of the methodologies applied to estimate GHG emissions from direct land use changes (3.5.2). Section 3.5.3 introduces two different
GHG criteria applied in the analysis of sustainable biofuels, comparing GHG emissions generated by the biofuel production chain and related land use change vis-à-vis the use of fossil fuels.

3.5.1 Life cycle GHG emissions

Life cycle supply chain GHG emissions arise on farm from the cultivation of biofuel feedstocks, from processing of raw material feedstocks into biofuels, and due to transport and distribution of fuels (field to wheel). Emissions related to crop cultivation include N_2O from nitrogen fertilizers and manure, CO_2 from agricultural machinery, emissions related to the production of fertilizers and agro-inputs (e.g. pesticides) applied in cultivation, and the net CO_2 balance of organic material in the soil. Emissions from biofuel processing depend on the energy source used in the process (renewable or powered by fossil fuels) and on the allocation of the GHG burden to different co-products (e.g., vegetable oil versus press cake from oilseeds for livestock feed). As it is challenging to compile estimates of emissions for a large number of individual companies and production circumstances, a variety of defaults, standards and guidelines have been established in the different legislations (EU, 2009, RTFO, 2013).

14 http://ec.europa.eu/energy/sites/ener/files/documents/1_en_annexe_proposition_part1_v6_0.pdf

Obviously, supply chain GHG emissions can vary widely. For this study, we have applied a set of life cycle emission estimates found in the literature related to ambitious, yet feasible best-practice management and conversion processes (Table 3.4). Note, the values in Table 3.4 refer to the respective biofuel supply chain but do not include the GHG burden resulting from possible land conversion.

Table 3.4. Supply chain life cycle GHG emissions applied in this study

Feedstock	**Emissions (g CO2 eq / MJ)**		
	Range	**Source**	**Assumed value**
Solaris	22.7	Sunchem, assuming local supply chain	23
Jatropha	22 - 62	EU-RED, SEI	30
Oil palm	32 - 70	EU-RED, EU-RED2, SEI, Stratton, RFTO	32
Soybean	27 – 59	EU-RED, EU-RED2 SEI, Stratton, RFTO	37
Camelina	20 - 44	SEI; Sustainable Oils	20
Sugar cane	10 - 32	EU-RED, SEI, Stratton, RFTO	24
Sweet sorghum	30.6	CARB	31
Maize	30 - 56	EU-RED, EU-RED2, SEI, RFTO	33
Cassava	44 - 62	RTFO	35
Triticale	31 - 60	EU-RED2	35
Miscanthus[1]	14	SEI	14

Source: EU-RED Directive[15] 2009/28/EC (EC, 2009); EU-RED2 (EC, 2017); SEI Stockholm Environment Institute; Stratton (US company); RFTO UK Renewable Transport Fuels Obligations; Sustainable oils; CARB (California's Air Resources Board), for sweet sorghum see here;

***1** Other values for lignocellulosic feedstocks: wheat straw 11 – 14; waste wood 4-17; corn stover 10; switchgrass 17.7*

15 See European Commission Renewable Energy Directive

3.5.2 GHG emissions from direct land use change

Conversion of REMAIN land (i.e. shrub- and grassland) for use in biofuel feedstock production represents a direct land use change and causes additional GHG emissions. The accounting of greenhouse gas emissions from land use change applied in this study is based on the methods described in the documentation of the RSB GHG Calculation Methodology (Version 2.1) and 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

The amount of annual CO2 emissions due to direct land use change (dLUC) expressed in gCO2eq/MJ can be calculated according to equation (5):

$$dCO2_{LUC} = \{[(dC_B + dC_S) * (\frac{44}{12}) * 1e^6] + dL_{fire}\}/Y_{fuel} \quad (5)$$

where

$dCO2_{LUC}$	annualized CO2equ emissions due to direct land use change [gCO_2 equ /MJ]
dC_B	annualized changes in biomass carbon stocks due to land use change [ton C/ha]
dC_2	annualized changes in carbon stocks of mineral soils due to land use change [ton C/ha]
dL_{fire}	annualized changes in GHG emissions from fire due to land use change [gCO2eq/ha]
Y_{fuel}	annual fuel yield of projected land use [MJ/ha]

The change in biomass carbon stocks considers both above-ground and below-ground changes and is calculated according to equation (6):

$$dC_B = dC_{AGB} + dC_{BGB} = (C_{B0} - C_{Bfuel})/T \quad (6)$$

where

dC_B	annualized changes in biomass carbon stocks due to land use change [ton C/ha]
dC_{AGB}	annualized changes in above-ground biomass carbon stocks due to land use change [ton C/ha]
dC_{BGB}	annualized changes in below-ground biomass carbon stocks due to land use change[ton C/ha]
C_{B0}	biomass carbon stock before land use change [ton C/ha]
C_{Bfuel}	biomass carbon stock after conversion to biofuel feedstock cultivation [ton C/ha]
T	accounting period [years]

The calculation of changes in the carbon stocks of mineral soils uses equations (7) and (8):

$$dC_S = (C_{S0} - C_{Sfuel})/T \quad (7)$$

$$C_S = SOC_{ref} * f_{LU} * f_{MG} * f_{IN} \quad (8)$$

where

dC_S	annualized changes in carbon stocks of mineral soils due to land use change [ton C/ha]
CS_0	carbon stocks of mineral soils under land use before conversion [ton C/ha]
CS_{fuel}	carbon stocks of mineral soils of new land use at end of assessment period [ton C/ha]
SOC_{ref}	reference carbon stocks of mineral soil type [ton C/ha]
f_{LU}	carbon stock change factor related to particular land use [dimensionless]
f_{MG}	carbon stock change factor related to management regime [dimensionless]
f_{IN}	carbon stock change factor related to input of organic matter [dimensionless]
T	accounting period [years]

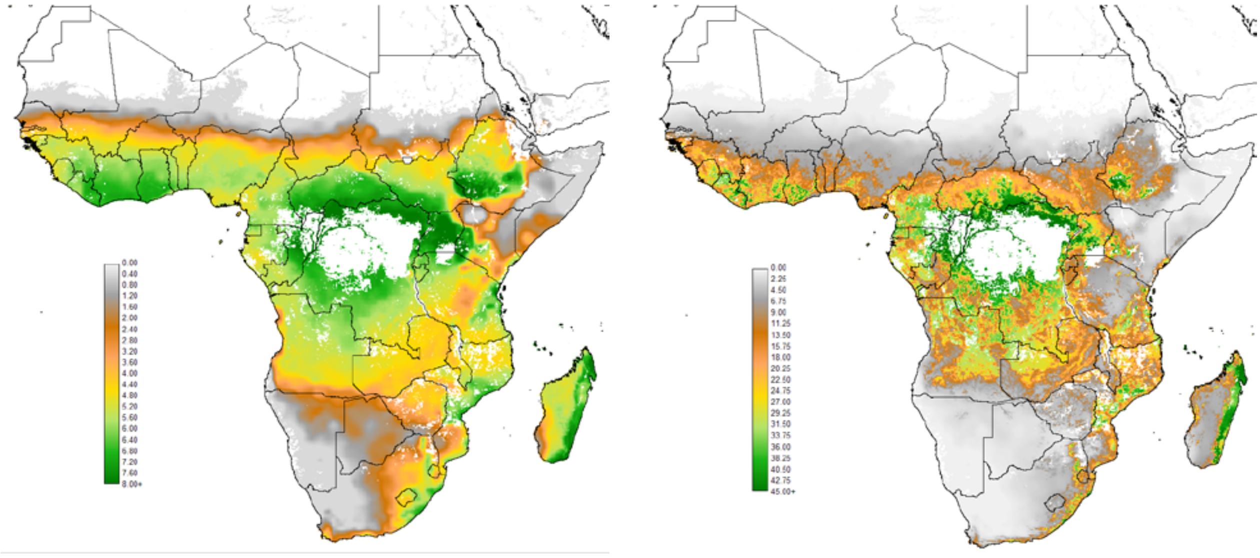
Note: All f-factors related to grassland/shrub land use before conversion are set to 1, i.e. soil carbon stocks before conversion are assumed to equal C_{S0}.

3.5.2.1 Biomass carbon stock changes

For the calculation of changes in biomass carbon stocks, spatial layers with estimates of carbon stocks CB0 prior to conversion were compiled respectively for grassland and shrub land based on IPCC reference values, woody vegetation cover percent according to the MODIS VCF product for 2010, and spatial gradients of land productivity modelled in GAEZ v4, as shown in Figure 3.6.

The applicable biomass carbon stock CBfuel for annual crops is set to zero according to the IPCC and RSB greenhouse gas accounting methodology assuming that all above-ground and below-ground biomass will be harvested. Following IPCC, for perennial crops, which have different harvest practises compared to annual crops, carbon accumulation of half the production cycle of 20 years is taken into account and we use reference values adapted from Table 3-2 to Table 3-5 of the RSB GHG Calculation Methodology (Version 2.1) and summarized in Table 3.5.

Figure 3.6. Biomass carbon stock CBo in grassland and shrub land



a) Carbon stock C_{Bo} in grassland (ton C/ha)

b) Carbon stock C_{Bo} in shrub land (ton C/ha)

Example 1: Assuming land conversion in the tropical dry zone from grassland, with a carbon stock of 4.4 ton C ha^{-1} in above- and below-ground biomass, to cultivation of Solaris tobacco, the procedure indicated in equation (6) results in a total biomass carbon loss of (4.4-0.0) = 4.4 ton C ha^{-1} or an annualized value of 0.22 ton C ha^{-1} per year for the accounting period of 20 years.

Table 3.5. Biomass carbon stocks C_{Bfuel} applicable after conversion to perennial feedstocks

Climate region	**Sugarcane** [ton C/ha]	**Miscanthus** [ton C/ha]	**Oil palm** [ton C/ha]	**Jatropha** [ton C/ha]
Temperate, moist	4.6	16.4	50	25.9
Temperate, dry	4.2	14.9	30	17.5
Tropical, montane	4.6	16.4	50	17.5
Tropical, wet	5.0	17.9	60	34.3
Tropical, moist	4.6	16.4	50	25.9
Tropical, dry	4.2	14.9	30	17.5

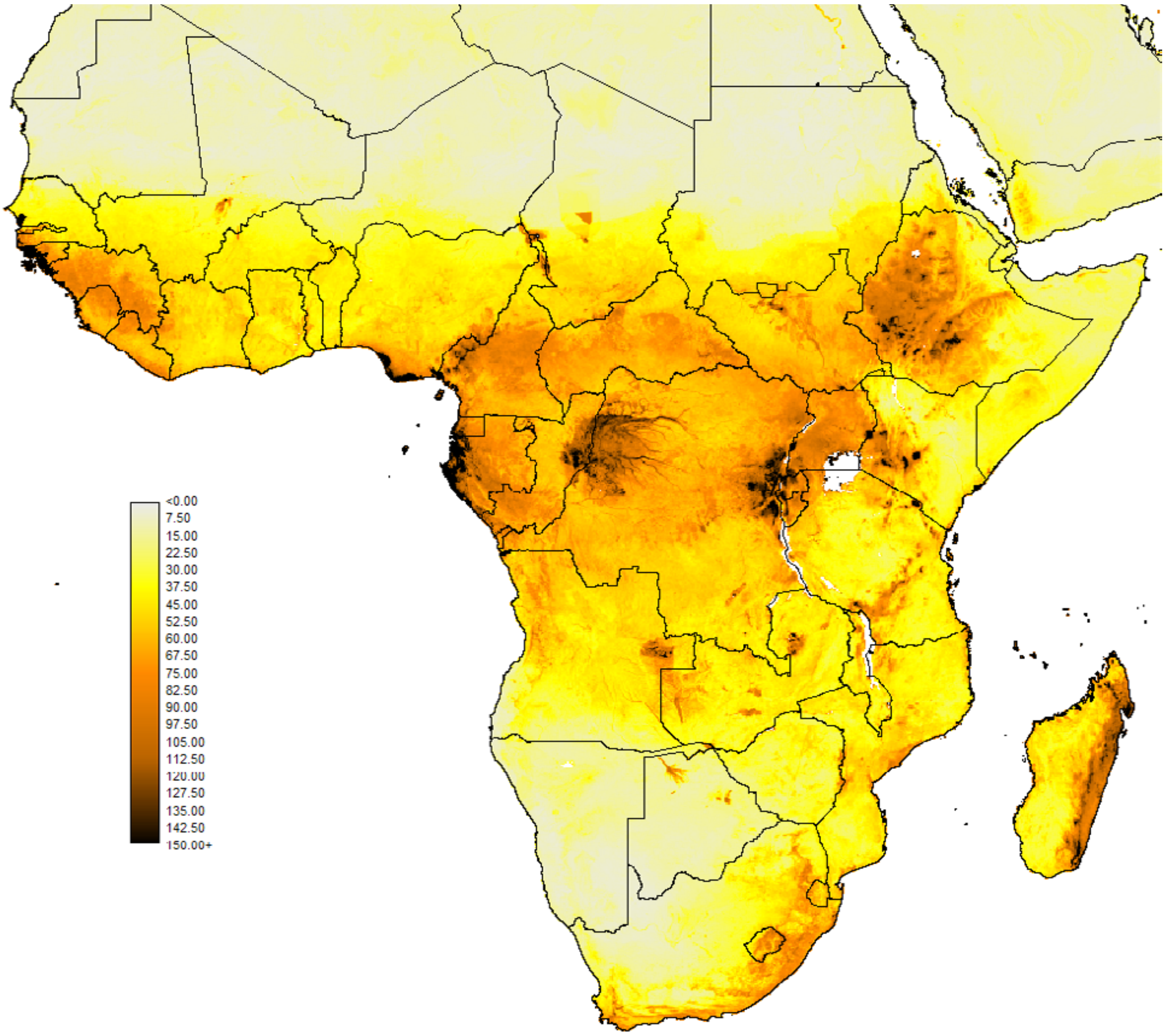
Source: Values adapted from RSB GHG Calculation Methodology (Version 2.1) and IPCC (2006)

Although substantial biomass burning may cause additional emissions and may affect the biomass carbon stocks in grassland and woody savannah areas (before conversion), the annualized changes in GHG emissions from fire dLfire due to land use change in equation (5) were set to zero in the current assessment as a conservative assumption due to large uncertainties and paucity of spatially detailed data. Nevertheless, it is very plausible that emission due to fire from savannah burning would be reduced after conversion of land to biofuel feedstock production.

3.5.2.2 Soil carbon stock changes

A spatial layer of reference carbon stocks SOCref in the top 0-30 cm of the soil profile has been compiled from a recently released global soil database, SoilGrids250m (Hengl et al., 2017), as shown in Figure 3.7. In addition, all soil map units classified as organic soils (i.e. Histosols in FAO classification) in the FAO/IIASA Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) were regarded as unusable for biofuel feedstock production and excluded from conversion.

Figure 3.7. Carbon stock of 0-30 cm top soil layer [ton C/ha]



The soil carbon stock change factors applicable under conversion to cropland for biofuel feedstock production were compiled by IPCC broad climatic regions (temperate warm, moist; temperate warm, dry; temperate cool, moist; temperate cool, dry; tropical dry; tropical moist/wet; tropical montane) according to information provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and RSB GHG Calculation Methodology (Version 2.1), as summarized in Table 3.6.

Table 3.6. Range of IPCC soil carbon stock change factors due to conversion for crop cultivation

Climate region	Land use factor (f_{LU})		Tillage factor (f_{MG})			High organic input (f_{IN})	
	Annual crops	Perennial crops	Full tillage	Reduced tillage	No tillage	With manure	Without manure
Temperate, moist	0.69	1.00	1.00	1.08	1.15	1.44	1.11
Temperate, dry	0.80	1.00	1.00	1.02	1.10	1.37	1.04
Tropical, montane	0.64	1.00	1.00	1.09	1.16	1.41	1.08
Tropical, moist/wet	0.48	1.00	1.00	1.15	1.22	1.44	1.11
Tropical, dry	0.58	1.00	1.00	1.09	1.17	1.37	1.04

Source: IPCC (2006)

Selecting an applicable set of management conditions and combining the respective factors listed in Table 3.6 results in an overall soil carbon stock change factor expressing the impact of converting land for the cultivation of biofuel feedstocks relative to the reference carbon content of mineral soils before conversion, SOCref.

Example 2: Assuming land conversion in the tropical dry zone from grassland to cultivation of Solaris tobacco under a land management of reduced tillage and high organic input (without input of manure) of a mineral soil with an average organic carbon content in the topsoil layer (0-30cm depth) of 40 ton C ha-1, the procedure described in equations (7) and (8) estimates a soil carbon loss of 40*(1.0-0.58*1.17*1.04) = 11.6 ton C ha-1, or on average 0.58 ton C ha-1 per year for the accounting period of 20 years. With application of manure the total estimated soil carbon loss would be reduced to 40*(1.0-0.58*1.17*1.37) = 2.8 ton C ha-1, or 0.14 ton C ha-1 per year.

3.5.2.3 Selection of management options for converted grass/shrub land

In this section, we summarize the soil management assumptions and resulting soil carbon stock change factors applied in this study. Accounting of GHG emissions due to land conversion that meets RSB criteria described in the documentation of the RSB GHG Calculation Methodology (Version 2.1) and 2006 IPCC Guidelines for National Greenhouse Gas Inventories entails annualized emissions to be expressed per MJ of biofuel production and requires annualized changes in soil and vegetation carbon stock to achieve minimum GHG saving of 60% compared to the use of fossil fuels. Following the IPCC methodology, the annual CO_2 emissions due to direct land use changes are calculated from:

(i) reference carbon stock of mineral soils[16],
(ii) a soil carbon stock change factor related to land use (f_{LU}),
(iii) a soil carbon stock change factor related to field management (f_{MG}), and
(iv) a soil carbon stock change factor related to input of organic matter (f_{IN}).

Reference carbon stock of mineral soils (SOC_{ref})

Estimates of soil carbon stocks were applied at grid-cell level and have been taken from available global soil databases (see Figure 3.7).

16 All organic soils were excluded from possible conversion due to the large GHG implications.

Carbon stock change factor related to land use (f_{LU})

The guideline values for cropland carbon stock change factors related to land use (f_{LU}) proposed by the IPCC vary depending on climatic conditions between 0.48 and 0.80. For perennials the f_{LU} factors are 1. For sugarcane, f_{LU} is taken as the average of annual and perennial factor values and varies between 0.74 and 0.90.

Soil carbon stock change factor related to field management (f_{MG})

Field management factor (f_{MG}) is related to soil tillage[17]. Broad options which are distinguished comprise of full tillage, reduced tillage or no tillage, where:

Full tillage refers to conventional soil tillage that turn top-soils to either loosen, granulate, crush or compact soil structure. Conventional tillage involves the mechanical soil manipulation of an entire field, by ploughing followed by one or more harrowings. The degree of soil disturbance depends on the type of implement used, the number of passes, soil and intended crop type.

Reduced tillage refers to those practices that minimize degradation of soil properties, including reduced or minimum tillage. This system covers other tillage and cultivation systems not covered above but which meet the 30% residue requirement (Laryea et al. 1991).

No tillage refers to no-till systems consisting of a one pass planting and fertilizer operation in which the soil and surface residues are minimally disturbed. Weed control is generally achieved with herbicides and or crop rotations. It includes as well no-tillage (slot planting), mulch tillage, strip or zonal tillage, ridge till (including no-till on ridges).

IPCC field management factors fMG for full tillage are set to 1.0. Depending on climatic conditions, coefficients are set respectively between 1.02 and 1.15 for reduced tillage, and between 1.10 and 1.22 for no tillage (Table 3.6). Perennials do not require tillage and therefore are treated as no tillage. For annuals (and including cassava), requiring annual field management, we assume as best option no tillage systems and as second option reduced tillage. Analysis shows that with full tillage assumptions the GHG emission criteria set by the RSB cannot be met for annuals when converting grassland or shrub land for feedstock production and therefore the full tillage option has not been further pursued.

Soil carbon stock change factor related to input of organic matter (f_{IN})

IPCC coefficients related to input of organic matter (fIN) are set by input intensity. For annual crops we have assumed a management with high inputs of organic material, but without relying on intense livestock manure applications. Depending on climatic region, the fIN factors for annual crops vary between 1.04 and 1.11 (Table 3.7). For perennial crops, where maintaining soil carbon content after conversion is less difficult than for annual crops, we assume a medium level of inputs with fIN factors set to 1.

17 Tillage is used for seedbed preparation, weed control, evaporation suppression, water infiltration enhancement, and erosion control.

Table 3.7. Soil carbon stock change factors for land use, tillage practices and organic matter input applied in this study (based on IPCC factors in Table 3.6)

Climate region	Land use factor (f_{LU})			Tillage factor (f_{MG})		Organic input	
	Annuals crops*	Sugarcane	Perennial crops	No tillage	Reduced tillage	Annual crops	Perennial crops**
Temperate, moist	0.69	0.85	1.00	1.15	1.08	1.11	1.00
Temperate, dry	0.80	0.90	1.00	1.10	1.02	1.04	1.00
Tropical, montane	0.64	0.82	1.00	1.16	1.09	1.08	1.00
Tropical, wet	0.48	0.74	1.00	1.22	1.15	1.11	1.00
Tropical, moist	0.48	0.74	1.00	1.22	1.15	1.11	1.00
Tropical, dry	0.58	0.79	1.00	1.17	1.09	1.04	1.00

** includes Cassava; ** assumes an intermediate input level of organic matter*

Based on the individual components of soil carbon stock change factors listed in Table 3.7, Table 3.8 summarizes the resulting combined relative soil carbon stock change factors adopted in this study for the calculation of GHG impacts of direct land use changes under the assumed management options of crop types, tillage practices and organic inputs.

Table 3.8. Relative soil carbon stock change factors, by IPCC climate region

	Annuals*	Sugarcane		Perennials	
Climate region	**No tillage**	**Reduced tillage**	**No tillage**	**Reduced tillage**	**No tillage**
Temperate, moist	0.881	0.827	1.079	1.013	1.150
Temperate, dry	0.915	0.849	1.030	0.955	1.100
Tropical, montane	0.802	0.753	1.027	0.965	1.160
Tropical, wet	0.650	0.613	1.002	0.945	1.220
Tropical, moist	0.650	0.613	1.002	0.945	1.220
Tropical, dry	0.706	0.657	0.961	0.896	1.170

**Includes Cassava*

3.5.2.4 Co-product allocation of GHG emissions

Processing of biofuel feedstocks and conversion to biofuels often produces significant amounts of useful co-products, most commonly for use as animal feed. GHG emissions caused by direct land use change should thus be allocated among the jointly produced products derived from the original feedstock, i.e. the biofuel and the various co-products. Note however, tracking of the GHG emissions attributed to the co-products is beyond the scope of this study and only the GHG net balance of biofuels is further pursued.

This study applies economic allocation, a common methodology used to partition GHG emissions in the product chain to the biofuels and the co-products. Other allocation principles sometimes used include GHG attribution by weight (dry or wet), energy content or volume, heating value or food energy content, and carbon content. The rationale for economic allocation is that environmental burdens of a multifunctional process should be allocated in proportion to the respective product market values, because product demand is considered as the main driving force for the production system and product value shares can reveal the relative importance of co-products. Obviously price variations, subsidies and other market interferences may cause distortions and uncertainties in economic valuation.

Crushing and pressing of oilseeds produces vegetable oils and protein-rich meals and cakes, a potentially valuable livestock feed source. Technical coefficients provide oil and meal/cake extraction rates per unit of harvested oilseeds (FAO, 2004). Prices in our calculations were derived from 15-year averages of global export unit values for vegetable oils and protein meals/cakes reported by FAOSTAT[18].

Table 3.9. Co-product specifications used for oil crops

Feedstock	Cake/Meal Extraction rate	Cake/Meal Protein content	Protein to Oil price ratio[1]	Cake/Meal Relative Price[2]	Oil Value Share[3]
Solaris	65 %	32 %	0.614	0.196	0.72
Jatropha	45 %	63 %	0.307	0.193	0.80
Palm kernel	52 %	17 %	0.696	0.118	0.88
Soybean	79 %	48 %	0.850	0.406	0.36
Camelina	62 %	32 %	0.614	0.198	0.75

1 *Calculated as 15-year average (1999-2013) of FAOSTAT export unit values for vegetable oils and cakes/meal. Values for Solaris, jatropha and camelina are based on averages of export unit values calculated for seven oil crops;* **2** *Calculated as (Protein content) * (Protein to Oil price ratio);* **3** *Calculated using extraction rates and relative co-product prices.*

On the other hand, ethanol fermentation of starchy feedstock consumes the grain's starch, while the protein, minerals, vitamins, fats and fibre can be concentrated during the production process to produce wet and dry distillers' grain with solubles (WDGS and DDGS). DDGS has a long shelf life, is relatively easy to transport and its utilization as a feed ingredient is well documented as both an energy and a protein supplement. Current high quality DDGS in the US has a protein content between 26 – 29%.

Table 3.10 summarizes value shares applied in this study for the allocation of the GHG emissions due to direct land use changes. Because every commodity produces some waste and residues, we use a maximum value share of 95 % in the allocation to the biofuel production. For starch-based biofuels (i.e., from cereals and cassava) we assume a GHG allocation of 85 % based on data for maize producing per ton jointly 400 litres ethanol and 0.315 tons DDGS at representative prices of 0.4 US$/l ethanol and 100 US$/ton DDGS.

Table 3.10. Allocation of GHG emissions from direct land use changes

Main produce for biofuel production	Feedstock	GHG emissions allocated to biofuel production	GHG emissions allocated to other co-products
Vegetable oil[1]	Solaris	70 %	30 %
Vegetable oil[1]	Jatropha	80 %	20 %
Vegetable oil[1]	Oil palm	90 %	10 %
Vegetable oil[1]	Soybean	35 %	65 %

18 See http://www.fao.org/faostat/en/#home

Main produce for biofuel production	Feedstock	GHG emissions allocated to biofuel production	GHG emissions allocated to other co-products
Vegetable oil[1]	Camelina	75 %	25 %
Sugar	Sugarcane	90 %	10 %
Sugar and starch	Sweet Sorghum	85 %	15 %
Starch2	Maize	85 %	15 %
Starch	Cassava	85 %	15 %
Starch	Triticale	85 %	15 %
Biomass	Miscanthus	95 %	5 %

1 *see Table 11;* **2** *Based on 1 ton of maize producing jointly 400 l ethanol and 0.315 tons DDGS at a price of 0.4 US$/l ethanol and 100 US$/ton DDGS.*

3.5.3 Application of GHG emission criteria for the estimation of feedstock potentials

Two different GHG criteria were applied in the assessment for testing the greenhouse gas emission efficiency of the selected feedstock types.

The first criterion requires annualized emissions per MJ from biofuel production, including annualized changes in soil and vegetation carbon stock, to achieve at least a minimum GHG saving, set to 60% compared to the use of fossil fuels, as required by the RSB. We apply as fossil comparator in this study a value of 94 gCO2eq/MJ. The first GHG criterion is tested according to equation (9):

$$eCO2_{LCA} + dCO2_{LUC} \leq (1-s_{min}) * eCO2_{fossil} \quad (9)$$

where

$eCO2_{LCA}$ lifecycle emissions of biofuel pathway (excluding land use change) [g CO2eq/MJ]

$dCO2_{LUC}$ annualized CO2equ emissions due to direct land use change [g CO2eq/MJ]

s_{min} minimum GHG saving rate expressed as share of comparator [dimensionless]

$eCO2_{fossil}$ lifecycle emissions of fossil comparator [g CO2eq/MJ]

Considering the soil carbon stock change factors discussed in section 3.5.2.3, meeting GHG criterion 1 puts rather severe restrictions on the possible conversion of grassland/shrub land and on the applicable soil management options for the cultivation of annual crops intended for biofuel feedstock production.

To provide a broader understanding of GHG emission impacts, we also evaluated a second, somewhat less strict, GHG emission criterion demanding two conditions to be met:

(i) The lifecycle emissions of the biofuel production chain, excluding land use changes, must achieve a minimum 60% emissions saving compared to the lifecycle emissions of the fossil comparator.

(ii) The carbon debt accumulated due to land use changes has a payback time of less than half the accounting period, i.e. within 10 years when using an accounting period of 20 years GHG criterion 2 can be described by equations (10) and (11):

$$eCO2_{LCA} \leq (1 - s_{min}) * eCO2_{fossil}$$

and

$$T * dCO2_{LUC} \leq \frac{T}{2} * (eCO2_{fossil} - eCO2_{LCA}) \quad (10)$$

where (11)

$eCO2_{LCA}$	lifecycle emissions of biofuel pathway (excluding land use change) [g CO2eq/MJ]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [g CO2eq/MJ]
$dCO2_{LUC}$	annualized CO2equ emission due to direct land use change [g CO2eq/MJ]
s_{min}	minimum GHG saving rate expressed as share of comparator [dimensionless]
T	length of accounting period [years]

When neither GHG criterion 1 or 2 can be met by a feedstock production in a given grid cell, then this grid cell is marked as unfit for cultivating the respective feedstock. When choosing among feedstocks and constructing an 'umbrella' database of best-performing biofuel crops, the selection is limited to the ones meeting GHG criterion 1 (termed 'umbrella 1') or respectively to feedstocks meeting criterion 1 or at least GHG criterion 2 (termed 'umbrella 2').

When the GHG criterion is met, the selection of feedstocks in a grid cell can either be based on maximizing fuel energy production or maximizing GHG emission savings. Note, by using, for instance, relative price weights for energy produced and emissions avoided, the two separate objectives could be combined into a more general weighted objective function. Results presented in this report are based on maximizing fuel energy production. In mathematical terms the grid cell level optimization can be written as in equation (12):

$$\max_{i} \{A_i * Y_i * [p_e + p_{CO2} * (eCO2_{fossil} - eCO2_{LCA,i} - dCO2_{LUC,i})], i \in I_{GHG}\}$$

where (12)

A_i	suitable area of projected land use [ha]
Y_i	attainable annual fuel yield of projected land use [MJ/ha]
p_e	fuel energy price weight [$/MJ]
p_{CO2}	GHG saving price weight [$/gCO2eq]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [g CO2eq/MJ]

$eCO2_{LCA,i}$ lifecycle emissions of biofuel pathway i (excluding land use change) [g CO2eq/MJ]

$dCO2_{LUC,i}$ annualized CO2equ emissions due to land conversion to land use i [g CO2eq/MJ]

I_{GHG} index set of feedstocks meeting required GHG criterion

When constructing an 'umbrella' crop database by grid cell according to equation (12), the specifically selected feedstock defines the suitability attributes, productivity and GHG outcomes of that grid-cell when mapping and tabulating the results.

3.6 Crop residues from food production

Agricultural residues can provide an additional contribution of biomass to ethanol production. Agricultural residues include straw, stubble, stalk, cob, husks and peelings. Residues from fruit trees and nuts include fibres, husks and shells. The availability of these residues for energy purposes is restricted by technical, environmental and economic factors rendering it difficult to precisely quantify. Crop residues fulfil also important ecosystem services essential to maintenance of soil fertility and erosion protection. Agricultural residues, processing by-products and wastes are readily available and can contribute significant amounts of feedstocks during the introduction phase for second generation biofuel production chains.

Cultivars of higher yielding varieties aim at a higher share of the total biomass to be stored in the harvested parts. As a consequence, the relative amount of crop residues (the RPR[19] factor) is less than for lower yielding breeds. For major cereals and oil crops a linear relationship is assumed between the upper and lower bounds of RPR values relative to the yield of the main produce. RPR estimates for individual crops were derived from literature (Jölli and Giljum, 2005, Koopmans and Koppejan, 1998, Ryan and Openshaw, 1991). Table 3.11. summarizes conversion factors for commodities where the RPR factor depends on yield. For the other crops included in the residue potential calculations a constant RPR is assumed: for other cereals, groundnut, cotton (lint), sugarcane bagasse and sugarcane tops the values used are respectively 1.5, 2.0, 5.4, 0.20 and 0.23 tons residues per ton of main produce.

Table 3.11. Residue-to-produce (RPR) factors for selected major crops [kg residues/kg produce]

Crop	lower yield boundary	higher yield boundary	RPR at lower yield boundary	RPR at higher yield boundary
Wheat	1.5	9.0	1.75	0.70
Rice, paddy	2.5	7.0	2.0	1.0
Maize	1.5	9.0	2.0	1.0
Sorghum	1.0	6.0	3.0	1.25
Millet	0.4	2.5	4.0	2.0
Barley	1.0	7.0	2.5	0.9
Soybeans	0.5	3.0	3.5	1.5
Rapeseed	1.0	3.5	3.5	2.0
Sunflower	0.5	3.0	3.5	1.75

Note: RPR factors indicate the amount of crop residues generated per unit of the main produce. A moisture content of 15% is assumed for crop residues, i.e. a DM conversion factor of 0.85.

19 Residue to Product Ratios (RPR)

The maximum amount of crop residues that can be removed from the field without significantly affecting soil fertility is debated. Some consider crop residues as currently unused waste material and make a strong case for its use for biofuel production, e.g. (Somerville, 2006). Others perceive crop residues as a valuable resource that provides irreplaceable environmental services (Smil, 1999) and argue removal of crop residues would exacerbate risks of soil erosion by water and wind, deplete soil organic matter, degrade soil quality, increase non-point source pollution, decrease agronomic productivity, and reduce crop yields per unit input of fertilizers and water (Lal and Pimentel, 2007). Moreover the importance of retaining residues on fields depends largely upon specific local conditions.

For the calculations in this study we applied a widely adopted assumption that amounts of crop residues exceeding 2 tons/ha could be removed without significant impacts on soil fertility or soil erosion (Batidzirai et al., 2016). Hence, the amounts of crop residues available have been calculated according to equations (13) and (14):

$$R_i^j = A_i^j * max\,(0, Y_i^j * RPR_i^j - R_{soil}) \qquad (13)$$

and

$$RPR_i^j = \begin{cases} RPR_{max}^i & when\ Y_i^j \leq Y_{min}^i \\ RPR_{max}^i + (RPR_{min}^i - RPR_{max}^i) * (Y_i^j - Y_{min}^i)/(Y_{max}^i - Y_{min}^i) & \\ RPR_{min}^i & when\ Y_i^j \geq Y_{max}^i \end{cases} \qquad (14)$$

where

R_i^j	available crop residues from crop i in grid-cell j [tons]
A_i^j	harvested area of crop i in grid-cell j [ha]
Y_i^j	yield of crop i in grid-cell j [tons/ha]
Y_{max}^i	higher yield threshold of crop i [tons/ha]
Y_{min}^i	lower yield threshold of crop i [tons/ha]
RPR_i^j	residue to crop yield factor of crop i in grid-cell j [tons residue/ ton produce]
R_{soil}	crop residues reserved for soil protection [tons residue/ha]
RPR_{min}^i	residue to crop yield factor of crop i at higher yield threshold [tons residue/ton produce]
RPR_{max}^i	residue to crop yield factor of crop i at lower yield threshold [tons residue/ton produce]

3.7 Estimation of sustainable future biofuel potentials

3.7.1 Ecological-economic modelling framework

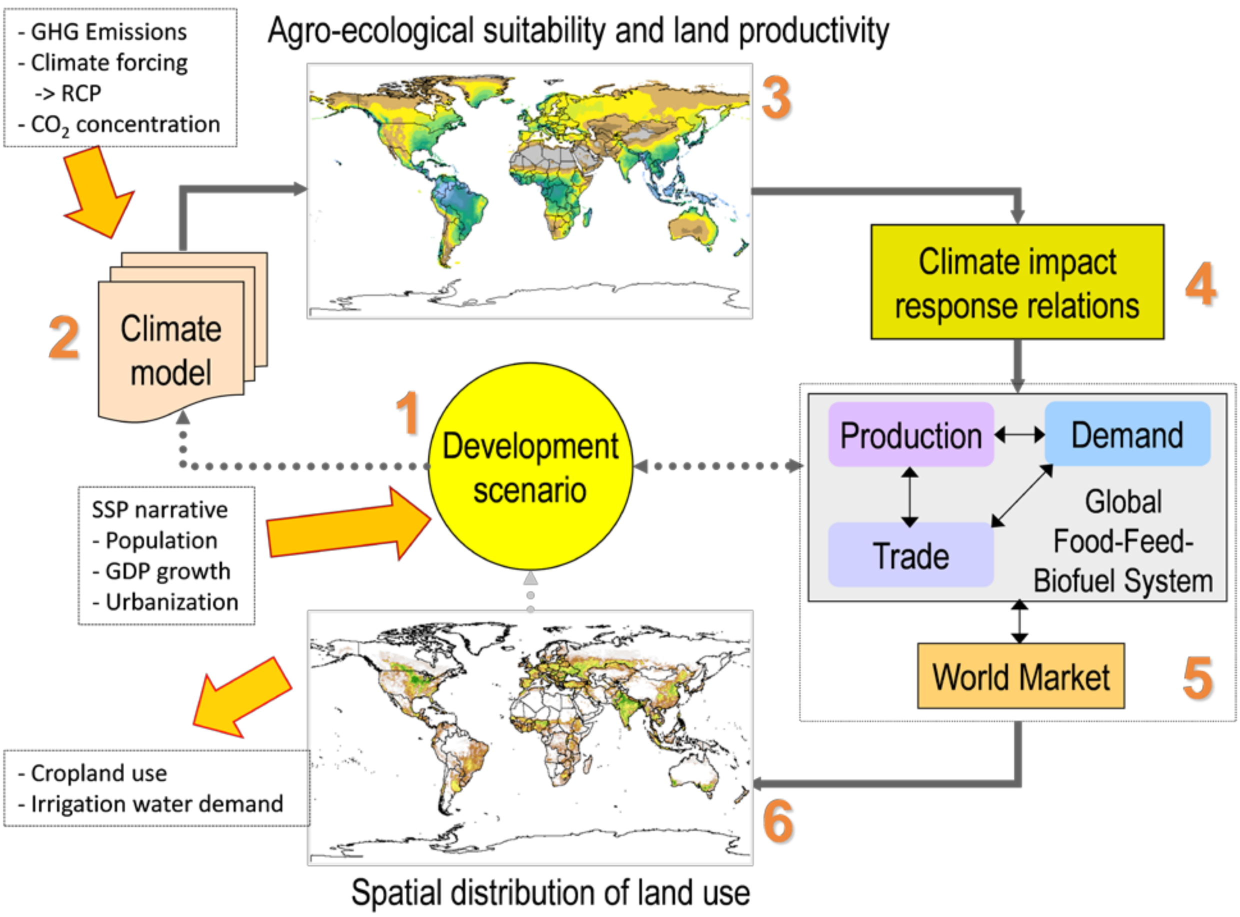
sub-Saharan Africa's current and future potential to supply biofuel feedstocks for the aviation industry depends to a large extent on the amount and quality of land available for biofuel feedstock production. The implementation of the food security sustainability criteria (Chapter 2.2 and 2.3) for future periods relies on the data and methodologies of IIASA's integrated ecological-economic modelling framework (Figure 3.8) used to analyse trajectories of sub-Saharan Africa's future land use, food and agriculture system. The modelling framework connects biophysical and socio-economic processes on a global scale and includes two main components:

i) the FAO/IIASA Global Agro-ecological Zone (GAEZ) model (Section 3.1)

ii) the IIASA World Food System (WFS) model (Section 3.6.2)

The modelling framework encompasses a state-of-the art representation of geospatial land use data, a range of CMIP5 climate scenarios, quantified country-wide scenario projections of demographic and socio-economic drivers, as well as the dynamics and linkages among production, consumption and world food trade of agricultural products. Incorporating the sustainability criteria related to food security into the assessment of biofuel feedstock potentials entails the analysis of land availability beyond current conditions to account for cropland requirements of food production in future periods. Due to data availability and for consistency with quantified socio-economic scenario drivers, we specify 'current' conditions based on a consistent set of data for the year 2010. Estimates of future conditions, here covering the period 2010 to 2050, follow a scenario approach in order to capture some of the key uncertainties pertaining to future developments.

Figure 3.8. Ecological-economic modelling framework for future projections applied in this study



The modelling framework (Figure 3.8) consists of six main elements:

1. A storyline and quantified macro-drivers of development, here chosen from among the Shared Socio-economic Pathways (SSP; see below), is selected to inform the world food system model of demographic changes in each region and of projected economic growth in the non-agricultural sectors. It also provides storyline assumptions characterizing in broad terms the international setting (e.g. trade liberalization; international migration), regarding technological progress, and the priorities of land use regulation.

2. A GHG concentration pathway (measured in CO2 equivalents) associated with the chosen development scenario is used to select among available and matching published outputs of simulation experiments with general circulation models (GCMs). The climate change signals derived from the GCM outputs are used to define applicable future climate scenarios.

3. The agro-ecological zones method (GAEZ) takes a climate scenario as input and estimates the likely agronomic impacts of climate change on crop suitability and crop yields on a spatial grid of 5 by 5 arc-minutes latitude/longitude (about 9 by 9 km).

4. Estimated spatial climate change impacts on crop yields are aggregated and incorporated into the parameterization of the national/regional crop production modules of the multi-region World Food System model.

5. The global general equilibrium World Food System model – informed by the development storyline, scenario-specific quantified drivers (population and economic growth) and estimated climate change yield impacts – is used to evaluate internally consistent global food system scenarios.

6. In a final step, results of the world food system simulations are 'downscaled' to the spatial grid of the resource database for spatial attribution of physical resource use and quantification of land cover impacts.

3.7.2 World Food System Model

IIASA released a first version of the World Food System (WFS) model in 1988 in response to the energy and food crisis of the 1970s and 1980s. The WFS model has been repeatedly calibrated and validated over past time windows. Several applications of the model to international agricultural policy analysis, trade liberalization, climate-change vulnerability, and to the food vs. fuel debate have been published (Fischer et al., 2009b, Fischer et al., 2005, Fischer et al., 2002, Prieler et al., 2013).

The WFS provides a framework for analysing how much food will be produced and consumed in the world, where it will be produced and consumed, and the trade and financial flows related to such activities. The WFS simulates alternative socio-economic development scenarios, to investigate impacts on cropland use, food price development and climate change impacts on food provision. It also has been used to assess the implications of alternative biofuel targets.

The WFS is an applied general equilibrium model. Simply put, its framework is a world market based on a series of linked national and regional agricultural economic models. In these models, national food and agricultural components are seen as embedded in national economies, which in turn interact with each other through international trade. Although the WFS focuses on agriculture, non-agricultural economic activities are also represented in the model so that the essential dynamics among capital, labour, and land are captured.

Within each country/region, the model considers three groups of actors: producers (supply), consumers (demand); government (market interventions). The model takes into account the budget constraints of each group. It is assumed that the actors in the system are rational and allocate their income to maximize their objectives subject to financial constraints.

In this virtual representation of the national and global commodity markets, international clearing prices are computed to equalize global demand with supply. Whatever is produced will be demanded, either for human consumption, feed, or industrial use (e.g., biofuels). Alternatively, it can be exported or put into storage. Working in annual time steps, the system is balanced simultaneously for all countries in each time period. Production in the next year is based on changes in demand and realized prices in the current one, making the WFS a recursively dynamic model.

Based on the above, WFS gives an essential overview of the food system at the national to international levels. It identifies potential gaps and gluts in the food system, their causes, how to address them through a better use of resources, as well as indicators of actual or potential environmental impacts caused by food production.

The WFS consists of 34 national and/or regional geographical components globally with individual models linked by means of a world market, i.e. an international linkage mechanism. Each individual country or region model covers the whole economy of the respective geographical area. For the purpose of international linkage, production, consumption, and trade are aggregated to nine agricultural sectors and one non-agricultural sector. All physical and financial accounts are balanced and mutually consistent: the production, consumption, and financial ones at the national level, and the trade and financial flows at the global level.

3.7.3 Development scenarios until 2050

The potential of large-scale aviation biofuel deployment is closely linked with the socio-economic development trends resulting, amongst others, in different demand patterns for agricultural products. From a sustainability/ food security perspective - a key focus of this study - competition for fertile land needed for the production of food, feed, fibre and fuel is of particular importance. Climate change is another factor that is highly relevant for future production potentials for food and feed as well as for potential biofuel feedstock production. We apply the economic-ecological modelling framework (see 3.6.1) to model future levels and geospatial patterns of food production and associated land demand including climate change impacts on crop production.

Scenarios enable to explore different possible development pathways against the background of uncertain futures. They help to understand long-term consequences of near-term decisions and therefore form an essential part of sustainability research. This study integrates into the widely applied new parallel process (Moss et al., 2010) characterized by a Scenario Matrix Architecture (Van Vuuren et al., 2014).

The two main axes of the scenario matrix are:

1) The level of radiative forcing of the climate system as characterised by the Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011), and

2) A set of alternative plausible trajectories of future demographic and economic development described as Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2017).

Each cell in the matrix combines an SSP with and RCP and represents possible scenarios that combine elements of mitigation and adaptation policy. Various Integrated Assessment Models (IAM) have been used to simulate possible combinations and to quantify resulting GHG emissions dependent on the type, degree and speed of policies implemented. For example, the emissions of an SSP2 world could follow the RCP6.0 trajectory, if only weak climate policies are implemented. With policies that are more ambitious, forcing levels of RCP4.5 or even RCP2.6 could be reached. In contrast, a combination of socio-economic development according to SSP1 in combination with RCP8.5 or RCP6.0 is not possible to occur. Based on consultations with colleagues at IIASA participating in the IAM modelling efforts and taking into account the priorities of WWF, this study has selected two (Table 3.12) of a range of plausible scenario combinations (Kram, 2012).

Table 3.12. Development scenarios applied in this study

Scenario name	Shared Socio-economic Pathway (SSP)	Climate Change
SC1	SSP1 (Sustainability - Taking the Green Road)	RCP 2.6
SC2	SSP2 (Middle of the Road)	RCP 6.0

The combination of SSP1 socio-economic development and RCP2.6 radiative forcing trajectory and resulting climate changes (henceforth termed scenario SC1) portrays an open and co-operative world oriented toward sustainability. GHG mitigation policies are ambitious and approximately sufficient to reach the Paris agreement of keeping global mean temperatures below 2°C by 2100.

The second combination, using SSP2 socio-economic drivers and RCP6.0 GHG concentrations (henceforth termed scenario SC2) represents a world following the patterns and behaviour of the past and generating business-as-usual trends.

The most important variables applied from the SSP quantifications include population numbers and economic growth projected at country level and obtained from the SSP Web-database (IIASA, 2016). For each RCP we apply geospatial meteorological conditions (i.e. temperature, precipitation, radiation, etc. and atmospheric CO_2 concentrations) of five general circulation models[20] (GCMs) and we use for characterization of future agronomic conditions the ensemble mean of GAEZ results obtained with these climate scenarios.

Both the climate and socio-economic scenarios that are used as input assumptions in this study are discussed in more detail below.

3.7.3.1 Climate scenarios

Four RCPs are used in the IPCC process to characterize the magnitude of future radiative forcing and resulting rate of climate change. They range from a target level of radiative forcing for the year 2100 of 2.6 Wm-2 to 8.5 Wm-2 (Table 3.13).

"Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850-1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2°C for RCP6.0 and RCP8.5, and more likely than not to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6." Source: (IPCC, 2013)

This study makes use of existing future climate quantifications of five Global Circulation Models (GCMs) based on the four RCPs. GCM outputs were processed in the context of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013, Warszawski et al., 2014) for bias-correction and geospatial harmonization at 0.5 degree latitude/longitude.

The RCP2.6 emission and concentration pathway is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2°C. These scenarios form the low end of the scenario literature in terms of emissions and radiative forcing. RCP2.6 thus is used here to represent compliance with the Paris agreement[21] (UN, 2015), i.e., to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C.

20 The GCMs include i) HadGem2-ES from Met office Hadley Centre, UK; ii) IPSL-CM5A-LR from Institute Pierre-Simon Laplace, France; iii) GFDL-ESM2M from NOAA Geophysical Fluid Dynamics Laboratory, United States; iv) MIROC-ESM-CHEM from JAMSTEC, AORI, University of Tokyo, NIES, Japan; and v) NorESM1-M from Norwegian Climate Centre, Norway.

21 See http://unfccc.int/paris_agreement/items/9485.php

RCP4.5 and RCP6.0 are scenarios in which total radiative forcing is stabilized shortly after 2100 (although at different levels) and mean temperature anomalies over pre-industrial levels increase by some 1.8°C and 2.2°C respectively. While deviating from each other in 2100, these RCPs are characterized by quite similar forcing levels at mid-century in 2050. RCP8.5 is characterized by increasing GHG concentrations throughout this century (and beyond 2100), leading to the highest GHG concentration levels and global mean temperature increases of nearly 4°C in 2100.

The corresponding atmospheric concentrations of carbon dioxide in 2100 range between 420 ppm (in RCP2.6) and over 930 ppm (in RCP8.5). For comparison, the current carbon dioxide concentration in the atmosphere is at 409 ppm[22], up from about 300 ppm at the end of the 19th century. Some characteristics of the four RCPs used for modelling the future climate are summarized in Table 3.13. Thus for the RCP2.6 pathway, CO2 concentrations in 2050 are about 30 ppm higher than current levels. For comparison, between 1959 and 2008 measurements at Mauna Loa showed an annual average growth rate of 1.4 ppm per year (Keeling et al., 2009).

Table 3.13. Characteristics of the Representative Concentration Pathways (RCPs)

Name	Radiative forcing[1]	AR5 global warming[2]	CO2 concentrations[3] (ppm)			
		Mean change and likely range in temperature change by 2081-2100 [degree Celsius]	2030	2050	2080	2100
RCP2.6	Peak of 3 Wm2 declining to 2.6 Wm2 by 2100	1.0 (0.3 to 1.7)	431	443	432	421[4]
RCP4.5	Peak around 2040, then decline to 4.5 Wm2 by 2100	1.8 (1.1 to 2.6)	435	487	531	538
RCP6.0	Peak around 2060, then decline to 6 Wm2 by 2100	2.2 (1.3 to 3.1)	429	478	594	670
RCP8.5	Rising to 8.5 Wm2 by 2100, and thereafter	3.7 (2.6 to 4.8)	449	571	758	936

1 Source: (Moss et al., 2010) **2** The figure provides mean change and likely range in global mean surface temperature changes for the period 2081-2100 relative to 1986-2005. The observed warming until the reference period 1986-2005 is 0.61 [0.55 to 0.67] degree Celsius from 1850-1900. Source: (Stocker (Ed.), 2014); **3** Source: (Meinshausen et al., 2011); **4** Peak before 2100 and then decline.

3.7.3.2 Shared Socio-economic pathways (SSPs)

In the analysis presented here, we make use of a new set of scenarios that was developed by the research community to harmonize and provide a common context for climate change impact, mitigation and adaptation assessments (Moss et al., 2010). A range of possible future socio-economic conditions are described in the Shared-Socio-economic Pathways (SSP) (O'Neill et al., 2017). On the most fundamental level, each SSP is described by a narrative. The SSP storylines describe socio-economic developments without the assumption of climate policies and climate change.

The SSPs provide a set of five storylines on possible trajectories for human development and global environmental change during the 21st century. They have been developed over the last few years as a joint community effort and form part of a larger set of community scenarios for analysis of climate change, global environmental change and sustainable development issues (van Vuuren et al., 2017). For each scenario quantitative descriptions for key scenario drivers such as population (Samir and Lutz, 2014), urbanization (Jiang and O'Neill, 2017), economic growth prospects (Dellink et al., 2015), have been compiled for harmonization and inter-comparability among ongoing integrated assessments, climate change impacts and adaptation studies. Quantified scenario drivers can be accessed and are available online in the SSP Web-database[23] (IIASA, 2016).

22 See https://www.co2.earth/
23 See https://secure.iiasa.ac.at/web-apps/ene/SspDb/

This study analyses two of the five[24] SSP scenarios with basic elements of the narratives described in Box 1 and 2. The Scenario 'Sustainability - Taking the green road' (SSP1), is the only possible pathway that can most likely meet the recently agreed Sustainable Development Goals. The 'Middle of the Road' Scenario (SSP2) largely maintains business-as-usual trends, uses a medium population growth, generates economic and food security improvements in all regions, but cannot achieve agreed climate targets.

Box 1. Narrative for SSP1 (adapted from (O'Neill et al., 2017))

SSP1 is a sustainability scenario ("Sustainability – Taking the green road") where the world shifts gradually, but pervasively, toward a more sustainable path, emphasising more inclusive development that respects perceived environmental boundaries. Increasing evidence of and accounting for the social, cultural, and economic costs of environmental degradation and inequality drive this shift. Rapid technological progress facilitates the reduction of resource intensity and fossil-fuel dependency. Consumption is oriented toward low material growth and lower resource and energy intensity. Low-income countries grow more rapidly, inequality between and within economies falls, and technology spreads. Educational and health investments accelerate the demographic transition, leading to a relatively low population. The world has an open trade economy, associated with increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions.

For scenario implementation, these general tendencies of development in the SSP1 storyline were interpreted to have the following specific agriculture/irrigation related implications:

- Improved agricultural productivity through more rapid reduction (compared to reference technological assumptions on yields) of prevailing yield gaps toward environmentally sustainable and advanced technology yield levels
- Progressive elimination of barriers and distortions in international trade of agricultural products
- Progress towards effective land use regulation especially for preventing deforestation caused by expansion of cropland
- Enforcement of legally protected conservation areas
- Large improvements of irrigation water use efficiency where possible
- Reliable water infrastructure and water supply
- Substantial improvements in food security globally, including the low-income countries in sub-Saharan Africa.

Box 2. Narrative for SSP2 (adapted from (O'Neill et al., 2017))

SSP2 is a continuation of current trends scenario ("Middle of the road"), where the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Fossil-fuel dependency decreases slowly. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth.

For food system scenario implementation this means continuation of past agricultural growth paths and policies, continued (albeit decreasing over time) protection of national agricultural sectors, and further environmental damages caused by agriculture, and includes:

- Progress of agricultural productivity in developing countries as portrayed in FAO perspective study "World Agriculture: Towards 2030/2050" (Alexandratos and Bruinsma, 2012)
- Increasing per capita consumption of livestock products with growing per capita incomes

24 The other three scenarios include SSP3 (Regional rivalry – A rocky road), SSP4 (Inequality – A road divided); SSP5 (Fossil-fueled development – Taking the highway)

- Barriers and distortions in international trade of agricultural products are reduced only slowly
- Some improvements of water use efficiency, but only limited advances in low-income countries
- Gradual reduction of food insecurity due to trickle down of economic development
- Food and water insecurity remain as problems in some areas of low-income countries
- No effective measures and protection to prevent deforestation due to cropland expansion

Population, food and agriculture development in SSP1 and SSP2

By 2050, between 1.54 and 1.73 billion people are projected to live in SSA countries, up from a current 0.85 billion (Table 3.14). Southern Africa is the only region with less pronounced growth rates amounting to 65% and 50% in SC 2 and SC 1 respectively. Countries with the highest relative population growth rates include Niger (+219% in SC 2), Liberia (+193%), Angola (+190%), Uganda (+178%), and Malawi (+165%). In absolute numbers, nine countries account for two-thirds of the population increase between 2010 and 2050 projected in scenario SC 2 (+917 million people). They include Nigeria (+213 million people), Democratic Republic of Congo (+80), Ethiopia (+76), Uganda (+59), Tanzania (+57), Kenya (+37), (former) Sudan (+37), Niger (+35), and Malawi (+25).

Table 3.14. Population in sub-Saharan Africa in 2010 and projected for 2050 in the development scenarios SC 1 and SC 2, by major region

million people	Current	Scenario SC 2		Scenario SC 1	
	2010	2050	Increase 2010-2050	2050	Increase 2010-2050
Eastern Africa	245	521	112%	448	83%
Central Africa	114	241	111%	215	88%
Southern Africa	119	197	65%	178	50%
Sudano-Sahelian Africa	134	292	117%	244	82%
Gulf of Guinea	233	513	120%	452	94%
TOTAL SSA	**846**	**1,763**	**108%**	**1,538**	**82%**

Table 3.15 summarizes the characteristics of the two development pathways and the main assumptions used in the implementation of the scenario simulations with regard to food and agriculture. The sustainability scenario SSP1 achieves land productivity improvements exceeding those in SSP2. These assumptions were implemented regarding crop yield increases, changes in cropping intensity (i.e, multi-cropping), and concerning the share of irrigated land in total cropland.

Table 3.15. Overview on assumptions for food and agriculture scenario simulations

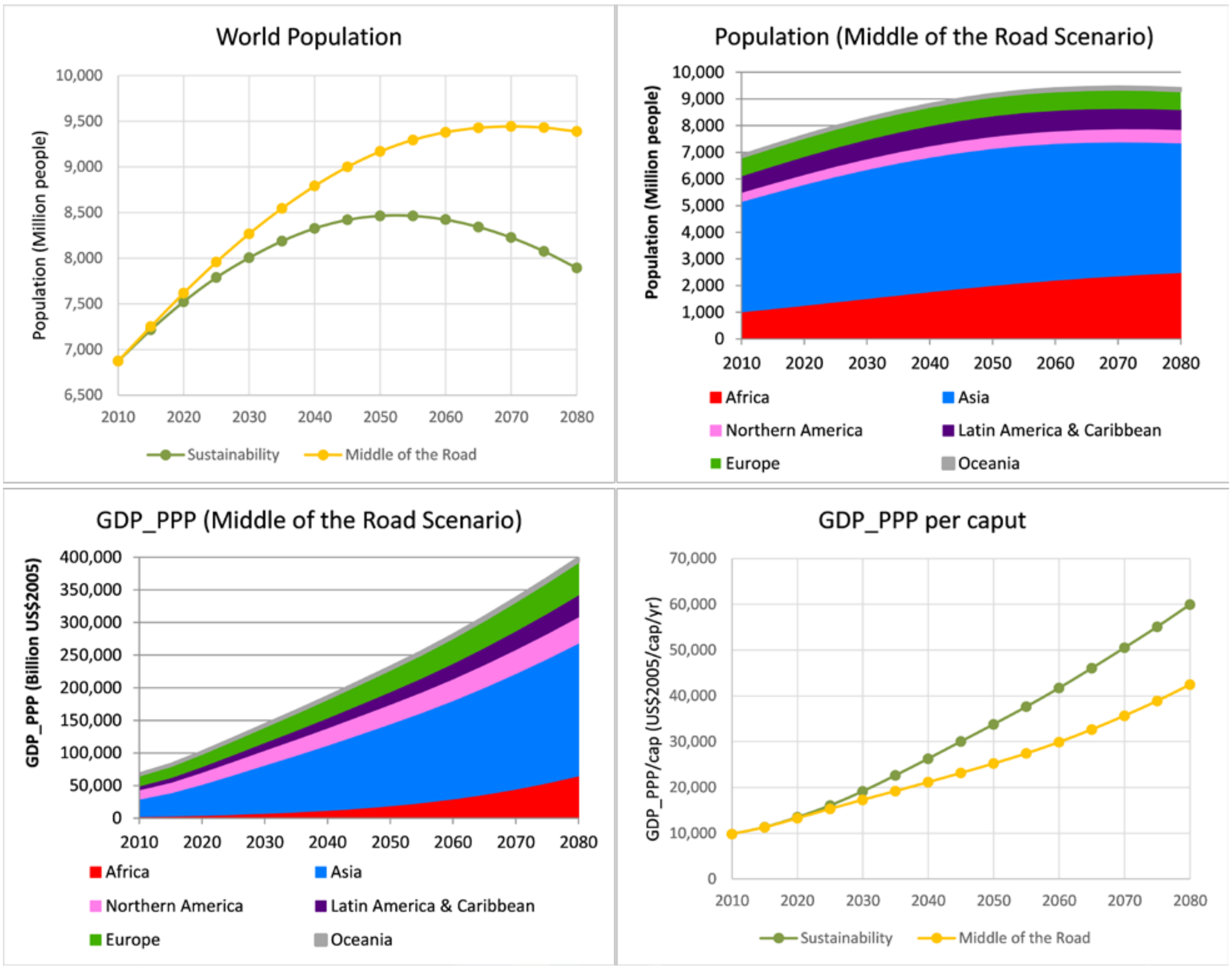
	SSP1 **Sustainability**	**SSP2** **Middle of the road**
Yield growth	Higher than medium	Medium
Irrigation share	Slightly increasing global irrigation share	Medium, approximately maintaining current global irrigation share
Trade liberalization	Full liberalization by 2040	Incomplete and slower path toward liberalization
Land use changes	Strong regulation	Some regulation
Protected areas	Fully enforced	Incomplete enforcement

As to institutional factors affecting the food and agriculture sector, it was assumed that agricultural protection measures would be fully eliminated by 2040 in SSP1 and would be reduced, but incompletely and at a slower pace, in SSP2. Concerning land use change regulation it was assumed that legally protected conservation areas would be fully enforced in SSP1 and some leakages of land conversion encroaching on protected or high biodiversity areas would be tolerated in SSP2. Also, there is strong regulation and concern to prevent deforestation by agricultural land conversion in SSP1; yet, some deforestation still takes place due to urban development or lack of alternatives.

The total number of people, their wealth and dietary preferences are principle drivers of future global food demand. Availability and suitability of land and water resources, access to advanced technologies, and institutional settings and land use regulations are essential means to satisfy future demands. Figure 3.9 shows the range of projected global population development and economic growth in the two development pathways over the period 2010 to 2080 analysed in this study. Starting from 6.9 billion people in 2010, the world population in SSP1 reaches 8.0 billion in 2030 and its peak of about 8.5 billion around 2050. Beyond mid-century global population decreases in scenario SSP1 and by 2080 amounts to 7.9 billion people. Global population also peaks in scenario SSP2, but later (about 2070) and at a higher level of 9.4 billion.

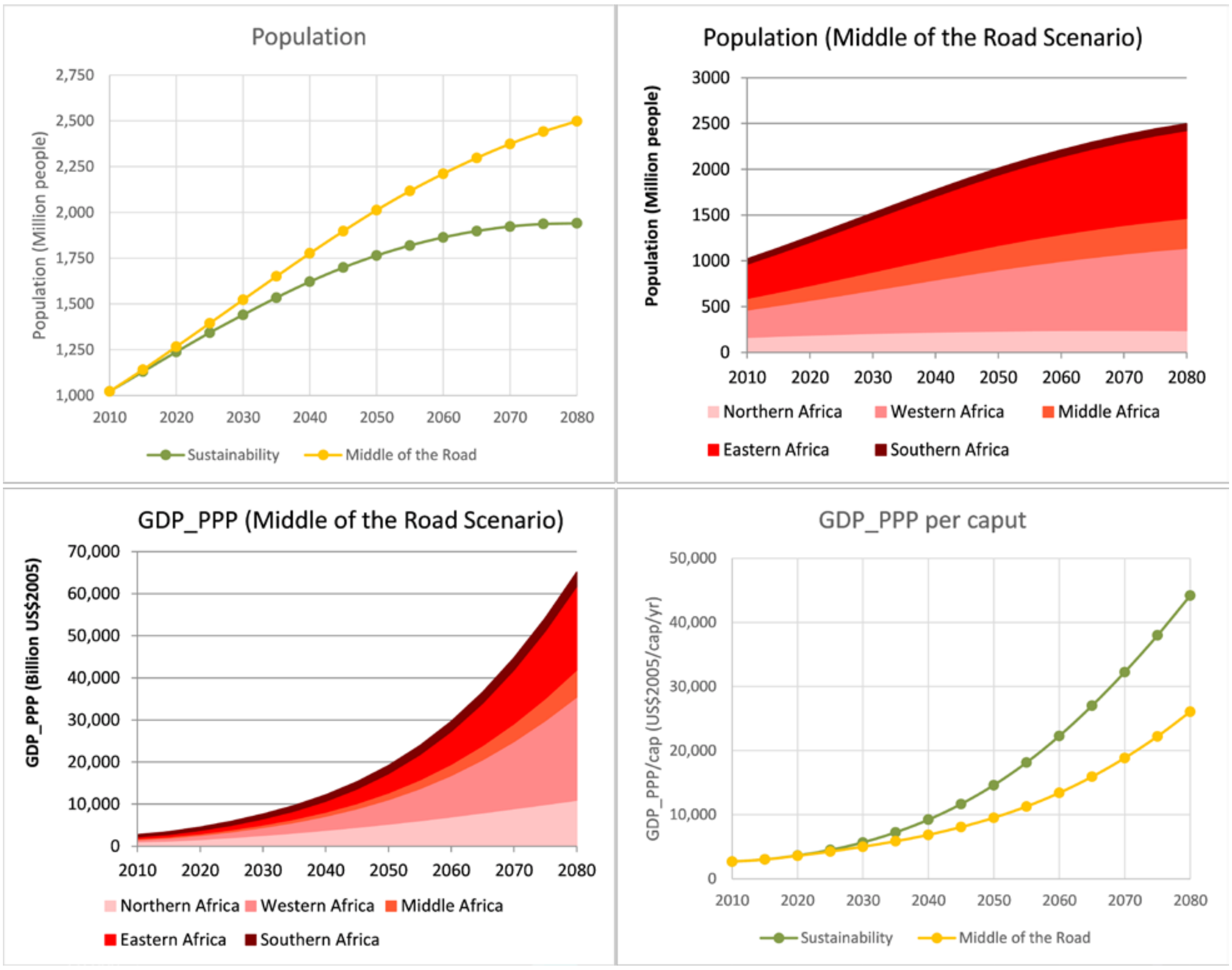
The global economy in the Middle of the Road scenario (SSP2) in 2050 is 3.4 times its size of 2010 (in terms of purchasing power parity (PPP)) and is up 4.2 times in the Sustainability scenario (SSP1). In 2080 the GDP growth factors are respectively 5.9- and 7-fold compared to 2010.

Figure 3.9. Major drivers of global food system development under the different SSPs



For Africa, the portrayed development is fairly dramatic. Population in Africa reaches a peak in this century only in the Sustainability scenario, at 1.95 billion and as late as 2080, i.e. nearly a doubling compared to 2010 African population of about 1.0 billion. In the Middle of the Road scenario the African population keeps increasing throughout to the end of the century, reaching 2.0 billion in 2050 and 2.5 billion in 2080. Fuelled by these rapid demographic changes, both development pathways envisage substantial economic growth in Africa, at average annual GDP growth rates over the period 2010 to 2050 of respectively 5.8% (Sustainability scenario) and 5.0% (Middle of the Road scenario) resulting in a size of the African economy in 2050 being 9.4 times and 7.0 times the size in 2010. For the 70 years from 2010 to 2080 the average annual African GDP growth projected in the development pathways is 5.0% (in SSP1) and 4.6% (in SSP2). As a consequence, average annual per capita GDP growth rates for the 40 years to 2050 are respectively 4.3% and 3.2%, which means a 5.4 to 3.5 fold increase of per capita GDP compared to 2010 (Figure 3.10).

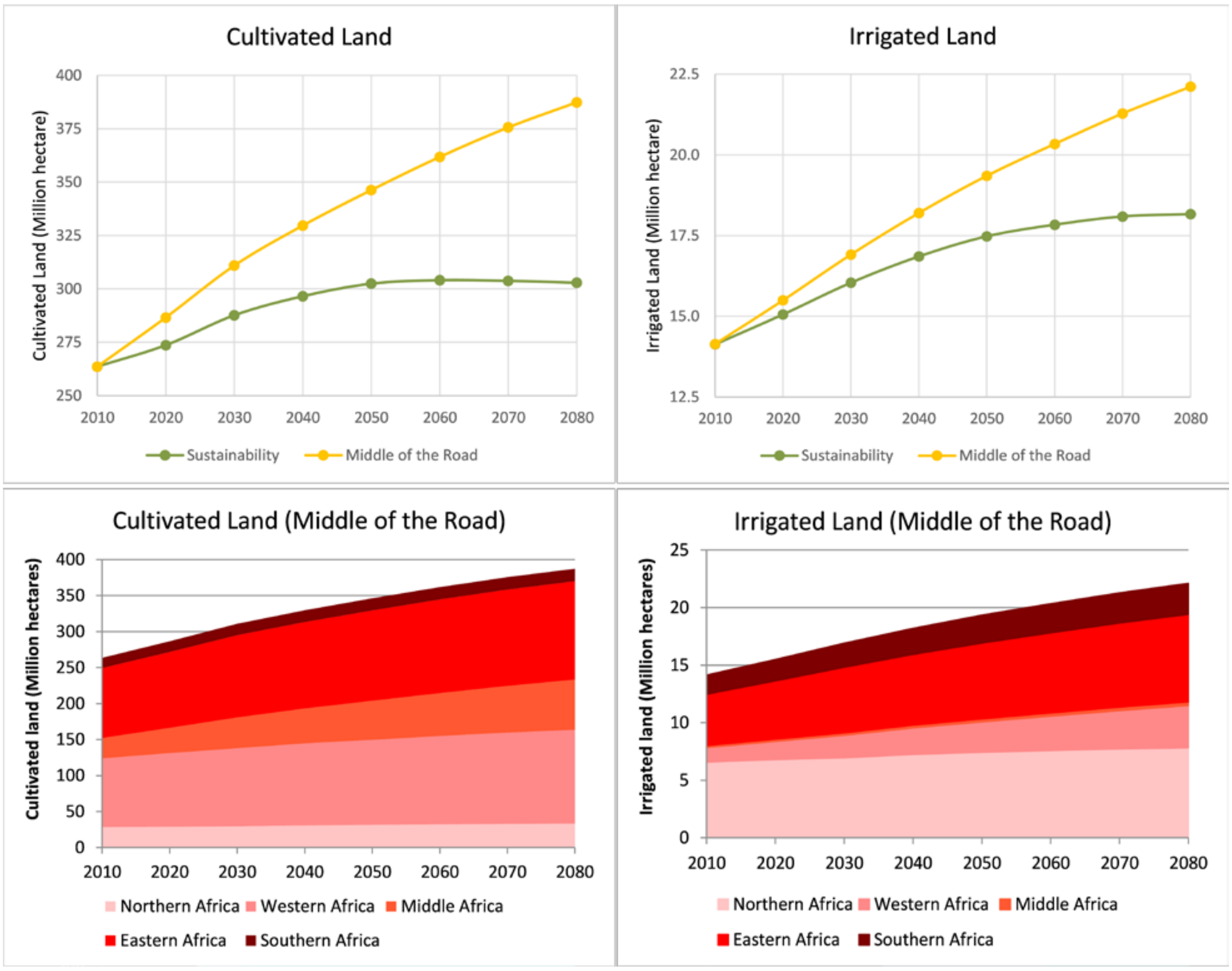
Figure 3.10. Demographic and economic drivers of African food system development



Driven by population growth and substantial income gains, cereal food demand in the Africa region is rapidly increasing, from 128 Million tons in 2010 to between 290 Million tons (scenario SSP1) and 310 Million tons (scenario SSP2) in 2050, and between 375 Million tons (scenario SSP1) and 425 Million tons (scenario SSP2) in 2080. The assumed swift economic growth in African countries, as portrayed in the storylines of scenario SSP1 and SSP2, results in greatly improved diets and food energy supply, exceeding an average 2800 kCal/cap/day in 2050 and 3100 kCal/cap/day in 2080.

By 2080, hunger is almost completely eliminated in the SSP1 and SSP2 scenarios. It does not come as a surprise that this macro-driver development is resulting in rather dynamic trajectories of agricultural production and resource use, as shown in Figure 3.11.

Figure 3.11. Evolution of cultivated land and area equipped with irrigation in Africa



African cultivated land use in 2010 is estimated at 264 Million hectares, increasing to extents between 288 Million hectares (scenario SSP1) to 331 Million hectares in 2030, to a range of 302 to 387 Million hectares in 2050, and between 303 and 481 Million hectares in 2080. Only under the conditions of the Sustainability scenario (SSP1) cultivated land is projected to stabilize at about 300 Million hectares, whereas land conversion for agricultural expansion continues throughout the simulation period in the other two development pathways.

Irrigation, although expanding swiftly as well, plays an important role only in two sub-regions, Northern Africa and Southern Africa. Cultivation in the other sub-regions remains foremost rain-fed with irrigation shares below 5%, albeit of a rapidly growing cultivated land base.

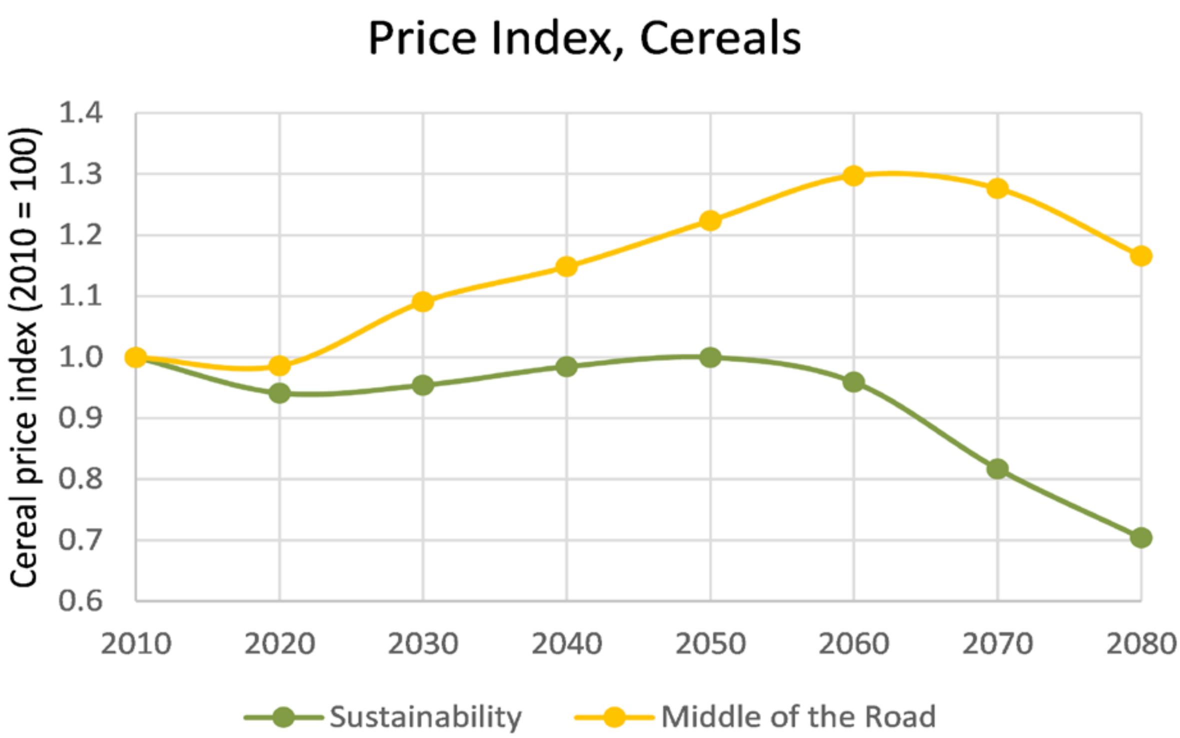
The quantified scenarios presented in this report illustrate the magnitude of challenges facing the regional and global food and agricultural systems in the next decades. The analysis suggests that due to the dynamics of demographic and economic development the required production increases in the next two to three decades will fall within a relatively narrow range of outcomes if hunger is to be successfully eliminated by mid-century. Beyond 2050, the differences in population numbers and economic growth among scenarios become large and the scenarios portray quite different demands for agricultural products and associated resource use and environmental risks.

Production increases in all scenarios mainly rely on intensification, i.e. substantial increases of output per unit of cultivated land. While this is possible and achievable due to large prevailing yield gaps in Africa and developing Asia, it cannot be taken as given and will require major efforts by the countries and the international community.

In the world food system model the various national/regional components are linked together by means of a world market, where international clearing prices are computed to equalize global demand with supply. The indexes of cereal prices generated in each scenario are shown in Figure 3.12. The cereal price index can be interpreted as a stress indicator of the world food system. Under the Sustainability scenario, cereal prices remain initially quite stable. A clear downward trend occurs beyond mid-century, coinciding with the decline of world population numbers, progressive technological development and maintenance of the resource base in this scenario. Price development in the Middle of the Road scenario signals that meeting food demand is more difficult in this scenario, at least until mid-century when global demographic growth comes to a halt.

Cropland expansion and intensification, if not regulated and managed well, increase the risk of environmental damages. Intensification inevitably means intensified application of nutrients and other agro-chemicals, which may result in pollution and over-exploitation of water resources to meet irrigation requirements, and may cause excessive deforestation when yield improvements do not materialize as needed. Such specific assumptions can be tested in the modelling framework but have not been explored in the current analysis. Also, the scenario implementations of the analysis presented here have used empirical relationships of enriching diets with livestock products as per capita incomes rise. In follow-up work we will explore the differential impacts of widely adopting healthier and less environmentally burdening diets, e.g. involving less livestock products than currently and putting an extra emphasis on reducing food wastes.

Figure 3.12. Cereal price index (2010=100) under the different SSP scenarios



4 RESULTS AND DISCUSSION

This section estimates the current and future extents and quality of REMAIN land and the associated sustainable production potentials of selected biofuel feedstocks for the current (2010) and future (2050) land use and climate conditions based. The results are based on the assessment methodology described in Chapter 3.

4.1 Database specifications

We first summarize some key concepts used to present the study results. The spatially detailed feedstock assessment operates on a geospatial grid of 5 arc-minute resolution (about 9x9 km) with sub-grid cell information (derived from 30 arc-second datasets) retained for selected variables (e.g. land use, soil information, terrain slopes). For presenting results, we tabulate grid-level data by region and country-level administrative unit (4.1.1) for defined land suitability classes (4.1.2). The potential biofuel assessment presents results for individual biofuel feedstocks, subject to meeting sustainability GHG criteria (4.1.3). Results were also compiled for an 'umbrella' of best-yielding feedstock crops, which was constructed by selecting in each grid-cell a feedstock to maximize potential output in terms of biofuel energy (4.1.4).

4.1.1 Country boundaries and country groupings

This study applies the Global Administrative Unit Layers (GAUL) distributed by the Food and Agricultural Organization of the United Nations. Original GAUL 2014 polygons were converted to a 30 arc-second grid database (about 1x1 km) for aggregation and reporting of data. Country extents and regional grouping are listed in Annex II-1.

4.1.2 Land suitability and productivity

Areas of REMAIN land vary significantly in land quality and suitability for biofuel feedstock production. Only a relatively small fraction of REMAIN land can support economic biofuel feedstock production due to differences in prevailing agro-climatic, soil and terrain conditions. GAEZ reports the distribution of land quality for biofuel feedstock production expressed in terms of agronomically attainable crop yields and grouped in five suitability classes, as described in Table 4.1.

Table 4.1. Suitability classes reported in GAEZ

Acronym	Suitability description	Farm economics
VS	Very suitable land (80-100 % of maximum achievable yield in sub-Saharan Africa)	Prime land offering best conditions for economic feedstock production
S	Suitable land (60—80%)	Good land for economic feedstock production
MS	Moderately suitable land (40-60%)	Moderate land with substantial climate and/or soil/terrain constraints requiring high product prices for profitability
mS	Marginally suitable land (20-40%)	Commercial production not viable. Land could be used for subsistence production when no other land is available
VmS	Very marginally suitable (< 20%)	Economic production not feasible
NS	Not suitable	Production not possible

Farm economics depend on the relationship between input costs for labour and agro-inputs (seeds, fertilizer, pest, disease and weeds control and energy for mechanized field operations and investment costs) and achievable crop yields and prices. Experience has shown that economic production is feasible on prime and good land where achievable yields are respectively 80-100% and 60-80% of maximum attainable yields. Moderately suitable land where 40-60% of best yields can be achieved are often not economically viable for commercial production, but may become so with high commodity demand and resulting high raw material prices.

The GAEZ geospatial assessment applied in this study reports the distribution of land quality and attainable yields for the selected biofuel feedstocks in terms of area extents and crop yields. We assume rain-fed cultivation of biofuel feedstocks under advanced input/management regimes (i.e. sufficient nutrients and adequate pest control). From a farm-economic perspective, very suitable (VS) and suitable (S) land is well suited for commercial feedstock production. Economic production conditions on moderately suitable land (MS) may be risky and would likely depend on product prices being high. Henceforth we use the term 'prime and good land' for VS and S land, and 'moderate land' for MS extents. Also, note that the designation of suitability is not an attribute of physical land per se but always applies to a combination of land and land utilization type (LUT; crop cultivated under a certain management assumption).

4.1.3 GHG emission saving criteria

Suitability and production potentials of biofuel feedstocks in individual grid-cells are analysed for GHG saving potentials vis-à-vis fossil oil-based fuels (see 3.5) based on IPCC criteria for GHG accounting, as follows:

i) For life-cycle GHG emissions (3.5.1) we assume best practice management compliant with 60% saving requirements, as listed in Table 3.4.

ii) GHG emissions caused by direct land use change, i.e. here the conversion of shrub- or grass land to cropland for cultivating respective biofuel feedstocks. Most losses occur at the time of conversion but are annualized for a 20-year accounting period (see 3.5.2).

iii) Sustainability oriented, yet feasible, land management options assume no tillage or reduced tillage and high or intermediate input of organic matter depending on feedstock and climate region (Table 3.6).

The RSB guidelines for sustainable biofuel certification require a minimum GHG emissions saving of 60% compared to the use of fossil fuels, henceforth termed here GHG 1 criterion (Table 4.2). The fossil fuel comparator is set at 94 g CO_2eq/MJ. Therefore to achieve the minimum 60% saving criterion, the maximum possible amount of the combined GHG emissions, from fuel chain life-cycle assessment (LCA) and the annualized direct land use change (dLUC) emissions, amounts to 37.6 g CO_2eq/MJ. Considering that the best-practice life-cycle GHG emissions assumed here range between 14 and 37 g CO_2eq/MJ (Table 3.4), it is obvious that any additional emissions from direct land use change play a crucial role for achieving, or not, the GHG 1 criterion.

For comparison and sensitivity analysis, we also apply an alternative form of GHG criterion, which uses the concept of pay-back time and is somewhat less strict for recuperating carbon losses from direct land use changes. As for GHG 1, in this alternative GHG 2 criterion, the emissions from LCA must be less than 40 % relative to fossil fuel comparator. In addition, the repay period for the dLUC carbon debt must be less or equal to half the accounting period, i.e. repay must be achieved within 10 years. Thus, the GHG 2 criterion requires the assessed biofuel activity to become carbon neutral at least within 10 years of conversion. Thereafter a minimum 60% saving is achieved every year.

The permissible annualized dLUC carbon releases depend on achievable fuel energy yields and range from 0 gCO_2eq/MJ (when life-cycle emissions approach the 60% saving threshold) to a theoretical maximum of 37 gCO_2eq/MJ. In comparison, for compliance with the GHG 2 criterion, the permissible annualized dLUC emissions are at minimum 28 gCO_2eq/MJ and have a theoretical maximum of 47 gCO_2eq/MJ. Although achievable cumulative net GHG emission savings are similar for both criteria in the long term, the GHG 1 criterion helps minimizing the risk of net carbon losses in case of terminating biofuel production shortly after converting REMAIN land to arable use for biofuel feedstock production. A detailed comparison of the two GHG criteria can be found in Annex IV.

Table 4.2. Greenhouse Gas (GHG) criteria applied in this study

Criterion	GHG savings
GHG 1	GHG emissions from life-cycle assessment (LCA) and direct land use changes (dLUC), annualized for a 20-year accounting period, amount to less than 40 % of the fossil fuel comparator. This criterion is fully conforming to RSB requirements.
GHG 2	GHG emissions from LCA amount to less than 40 % of the fossil fuel comparator. In addition, the repay period for GHG emissions resulting from dLUC must be less than 10 years, i.e. the annual GHG savings calculated without considering dLUC must exceed 1/10 of the total calculated dLUC emissions.

4.1.4 Comparison across different biofuel feedstocks

The assessment calculates for each feedstock the biofuel production potential using energy conversion factors as shown earlier in Table 3.2. In any particular grid-cell several biofuel feedstocks may qualify for economic production and compliance with GHG 1 and/or GHG 2 criteria. Selecting in each grid-cell the best performing feedstock in terms of fuel energy production potential results in an 'umbrella' dataset of maximum biofuel potential. Comparing each crop's feedstock potential with the 'umbrella' potential casts light on the comparative advantage of a particular biofuel feedstock. Note, the focus here is on fuel energy content of potential biofuel feedstock production and the economic values of other co-products were not considered in the selection (however, they were accounted for in the attribution of dLUC emissions).

Example 3: To illustrate the mechanism of crop selection used in the construction of the 'umbrella' dataset we assume a 5 arcmin grid cell (8,000 ha) with the following characteristics: (1) agro-climatic conditions (temperature regime and precipitation) allow rain-fed jatropha cultivation without limitations (i.e. very suitable) and for miscanthus cultivation the agro-climatic conditions are sub-optimal (i.e., suitable), and (2) the grid cell comprises of two soil types. Soil type one, covering one-third of the grid cell, poses no limitations to cultivation and soil type two, on two-thirds of the land, results in some yield reductions for both jatropha and miscanthus. From the evaluation of agro-climatic (1) and agro-edaphic (2) conditions we conclude that the land in this grid-cell is rated very suitable (VS; one-third) and suitable (S; two-thirds) for jatropha with estimated class yields of respectively 50 GJ/ha and 35 GJ/ha. For miscanthus one-third of the grid cell is assessed as suitable (S) and two-thirds as moderately suitable (MS) with estimated class yields of 105 GJ/ha and 75 GJ/ha.

In this grid cell the potential fuel energy production using jatropha amounts to (50x1/3 + 35x2/3) x 8000 = 320 TJ, all of which is from VS or S land. For miscanthus (105x1/3 + 75x2/3) x 8000 = 680 TJ could be produced, but only 280 TJ from the part rated suitable (S). As a consequence, if only land with prime and good suitability is considered, jatropha will be selected as the crop offering the highest energy production (320TJ) and all land is recorded as VS+S land. If moderately suitable land is considered as well, then miscanthus will be chosen to define results of this grid cell due to highest total energy production (680 TJ), with one-third of the land recorded as S land and two-thirds as MS land.

4.2 Sustainable biofuel production potential under current conditions

Guided by the principles and criteria of the Roundtable on Sustainable Biomaterials (RSB), the first step in the assessment has been to delineate and quantify the land extents potentially available for sustainable biofuel feedstock production. For this purpose exclusion layers have been defined (see section 3.3, Table 3.3, Figure 3.2) to address food security and environmental sustainability criteria. Once food and environmental criteria have been accounted for, the remaining tracts of land were termed as REMAIN land and were included in the suitability assessment of potential biofuel feedstock production.

4.2.1 Current land use and REMAIN land

sub-Saharan Africa's total land area amounts to 24.2 million km2, from which we deduct various land extents in order to comply with the RSB principles. RSB principle seven regarding "Conservation" lists forests (according to the FAO definition) as 'no conversion' areas. We therefore exclude from potential biofuel feedstock production areas all Sub-Saharan forests, some 6.1 million km2. In addition to this, we set aside protected areas and areas of high biodiversity value found on other current land covers, as listed in the various databases in Table 3.3

Full exclusion of forests is also justifiable under RSB principle three on "Greenhouse Gas Emissions" because the GHG debt resulting from the conversion of forests to cropland will make any biofuels produced from feedstock grown on previously forested areas non-compliant with the minimum GHG emission reduction requirement. In addition, we have excluded land with organic soils (Histosols) because of the very high carbon losses that would occur if these soils were to be converted to agricultural land.

RSB principle six, dealing with "Local food security", is strictly interpreted by reserving all cropland for food security and therefore excluding it from biofuel feedstock production. Currently, some 2.3 million km2 or 10% of the total land area in sub-Saharan Africa are cultivated for crop production. These areas represent the statistically reported cultivated land extents and may include some fallow land in rotation cycles. The density of cropland is highest in the region 'Gulf of Guinea' where one third of total area is under cultivation for crop production. In Eastern Africa, the share of cropland in total land is 15%, followed by Southern Africa and Sudano-Sahelian Africa with 7% each. In Central Africa, where almost two thirds of all areas are forest land, cropland amounts to only 4% of total land.

Feed balance calculations suggest that about 1 million km2 shrub- and grassland are currently required to meet feed requirements of ruminants. This leaves a balance of 2.8 and 2.7 million km2 for shrub- and grassland respectively as REMAIN land, which we consider to be potentially available for biofuel feedstock production (Table 4.3).

Cropland, forest land, built-up areas and water account for about 40% of the SSA land and were excluded from being considered for biofuel feedstock production. The land use category 'bare and sparsely vegetated land' covers 21% of the land surface and was excluded due to severe biophysical limitations for rain-fed feedstock production. About 9.4 million km2 (39%) of SSA land is classified as grassland or shrub land of which 3.9 million km2 is set aside for nature conservation and livestock feeding, leaving a balance of 5.5 million km2 which is considered potentially available for biofuel feedstock production. These areas enter the next step of the potential assessment as "REMAIN land".

Table 4.3. Land balance and exclusions for sub-Saharan Africa, 2010

	1000 km²	Land use category area	% of total	Excluded	Reason for exclusion	REMAIN land[1]
		[1]		[2]		[1-2]
1	Cropland	2,353	10 %	2,353	Food security	0
2	Forest	6,901	28 %	6,901	Environment[2]	0
3	Built-up land	270	1 %	270	Not for farming	0
4	Water	281	1 %	281	Not for farming	0
5	Shrub land	4,538	19 %	1,270	Environment (Env)	
				454	Livestock (Lvst)[3]	
				1,724	Env & Lvst	2,813
6	Grassland	4,856	20 %	1,608	Environment (Env)	
				558	Livestock (Lvst)[3]	
				2,166	Env & Lvst	2,691
7	Sparsely veg. & bare	5,068	21%	5,068	Not considered for commercial farming	0
	TOTAL	24,266	100%	18,759		5,504

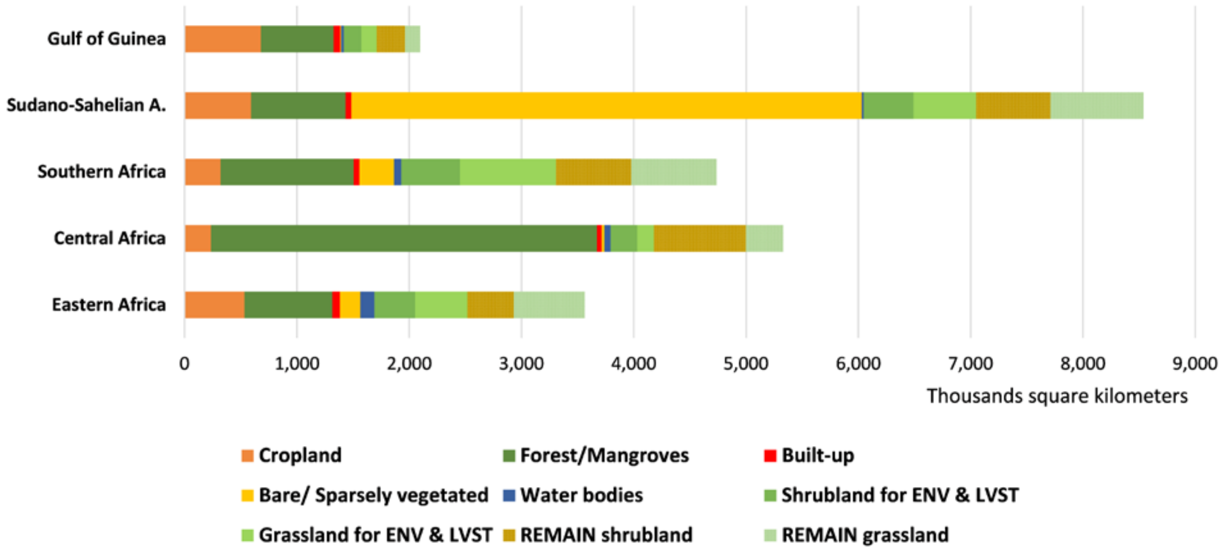
1 REMAIN land is explored in this study for potential biofuel feedstock production. It covers the remaining areas once food security and environmental sustainability criteria have been accounted for; **2** Excluded to protect environment and biodiversity; **3** Reserved for grazing ruminant livestock.

Figure 4.1 shows land balances by major regions, which are also summarized in Table 4.4. Large tracts of REMAIN land are found in Southern Africa and Sudano-Sahelian Africa (about 1.4 million km2 each) followed by Central (1.14 million km2) and Eastern (1.0 million km2) Africa. In the Gulf of Guinea region, REMAIN land amounts to less than 0.4 million km2.

Table 4.4. Extents of REMAIN land by region, in 2010

Region	Total land	REMAIN land In 2010	
	1000 km²	1000 km²	%
Eastern Africa	3,562	1,042	29
Central Africa	5,329	1,152	22
Southern Africa	4,737	1,431	30
Sudano-Sahelian Africa	8,541	1,493	17
Gulf of Guinea	2,097	386	18
Total sub-Saharan Africa	24,266	5,504	23

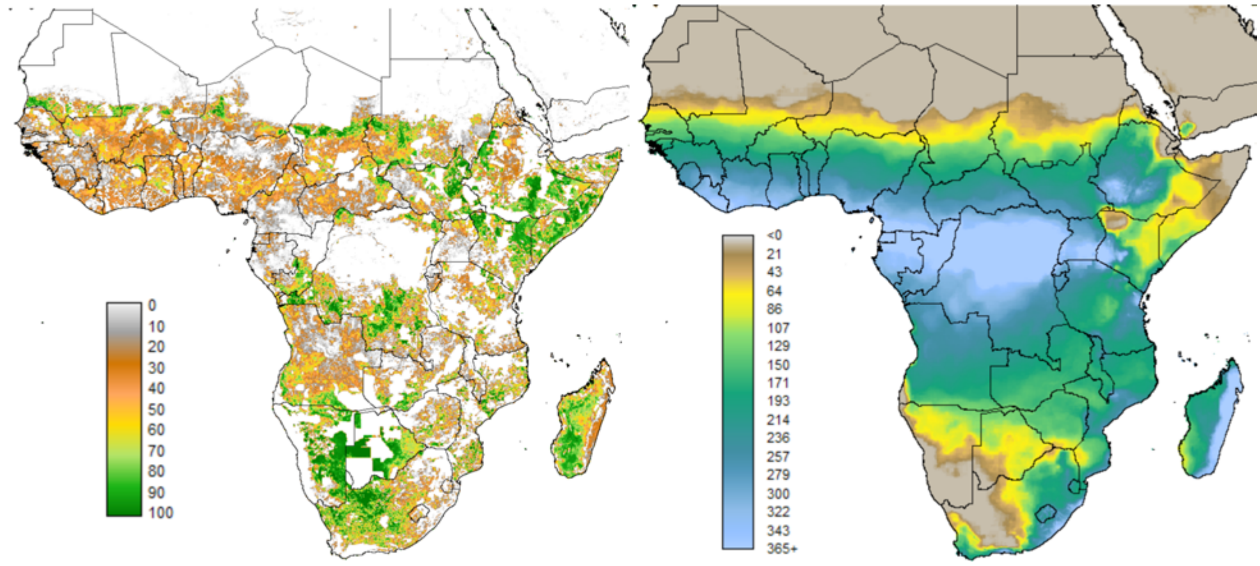
Figure 4.1. Land balances in sub-Saharan Africa, by major region, in 2010



In Figure 4.2 the map on the left side shows the percentage of REMAIN land in each 5 arc-minute grid cell, based on land use, protected areas, additional exclusion layers and ruminant livestock distribution in 2010. On the right side of Figure 4.2 the estimated number of annual growing period days (number of days when temperature and soil moisture permit rain-fed cropping) is shown under reference climate conditions of the period 1981-2010.

The maps indicate that a high density of REMAIN land usually coincides with limiting climatic conditions; exceptions occur mainly in parts of Central Africa, Mozambique and South Sudan. At the country level the extents of REMAIN land vary between less than 10% of total area in smaller countries (Rwanda, Equatorial Guinea, Djibouti, Gambia) or densely populated ones (Rwanda, Gabon) to some 40-50% in South Africa, Somalia and Madagascar. Annex II-2 lists extents of REMAIN land by country.

Figure 4.2. Intensity and spatial distribution of REMAIN land and number of annual growing period days, in 2010



4.2.2 Current biofuel potential (2010)

REMAIN land suitability for the production of biofuel feedstocks varies widely. First, we discuss land quality of REMAIN land in terms of suitability separately for each of the different biofuel feedstocks (see 4.2.2.1, 4.2.2.2 and Annex III). Finally we do a comparison across all biofuel feedstocks, select the highest yielding one in terms of fuel energy produced and present a respective 'umbrella' biofuel potential for SSA (see 4.2.2.3). Results highlight the importance of GHG criteria specification and of the minimum quality of REMAIN land considered viable in the calculation of feedstock potentials.

4.2.2.1 Suitability for sugar and starch based biofuels

The suitability of REMAIN land for rain-fed production of biofuel feedstocks has been assessed under assumptions of advanced level inputs and management. Figure 4.3 presents suitability maps for respectively: sugarcane, maize, cassava, sweet sorghum, triticale and miscanthus. These maps show the occurrence of suitability classes by means of a suitability index SI[25].

Figure 4.3 shows for different sugar/starch producing feedstocks and miscanthus the spatial pattern of crop suitability for grid-cells with (at least 5%) REMAIN land in 2010. Grid-cells where the share of REMAIN land in 2010 is less than 5% are shown as "Not assessed".

The largest suitable extents can be found for maize, sweet sorghum and cassava. Suitable rain-fed sugarcane areas are limited to the sub-humid zone and triticale is found suitable only in cooler highland environments. Very suitable areas for miscanthus require good rainfall such as in parts of Central Africa and Easter Africa region; a large part of Africa is however assessed as only moderately suitable or suitable.

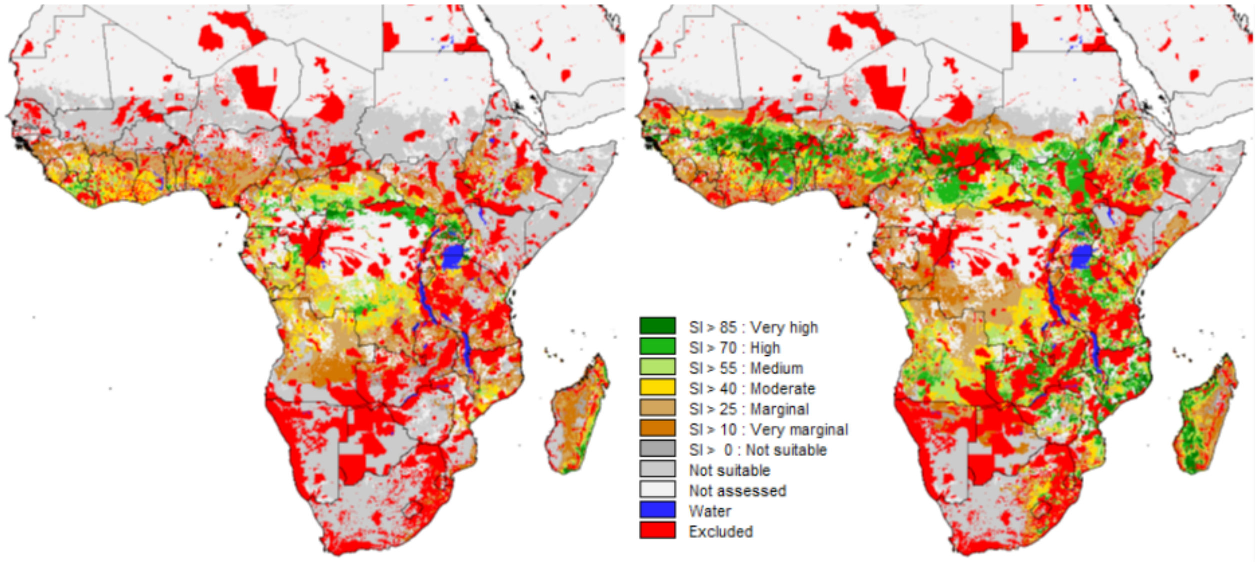
Depending on feedstock and considered land quality varying amounts of REMAIN land are suitable for crop cultivation. Between only 1% (triticale) and 29% (sweet sorghum) of SSA's REMAIN land is of prime or good quality for the cultivation of sugar and/or starch producing crops. About 4.5% of REMAIN land or 0.25 million km2 is of prime or good quality for the cultivation of rain-fed sugarcane.

25 SI is representing the suitability distribution in individual grid cells according to the occurrence of suitability classes as follows: SI=(VS*90+S*70+MS*50+mS*30+V mS*15)/0.9. The resulting values are classified as very high productive grid cells with SI >85, high productivity with SI>70, medium productivity SI> 55, moderate productivity SI > 40, marginal productivity SI > 25, very marginal productivity SI >10, and not suitable SI ≥0.

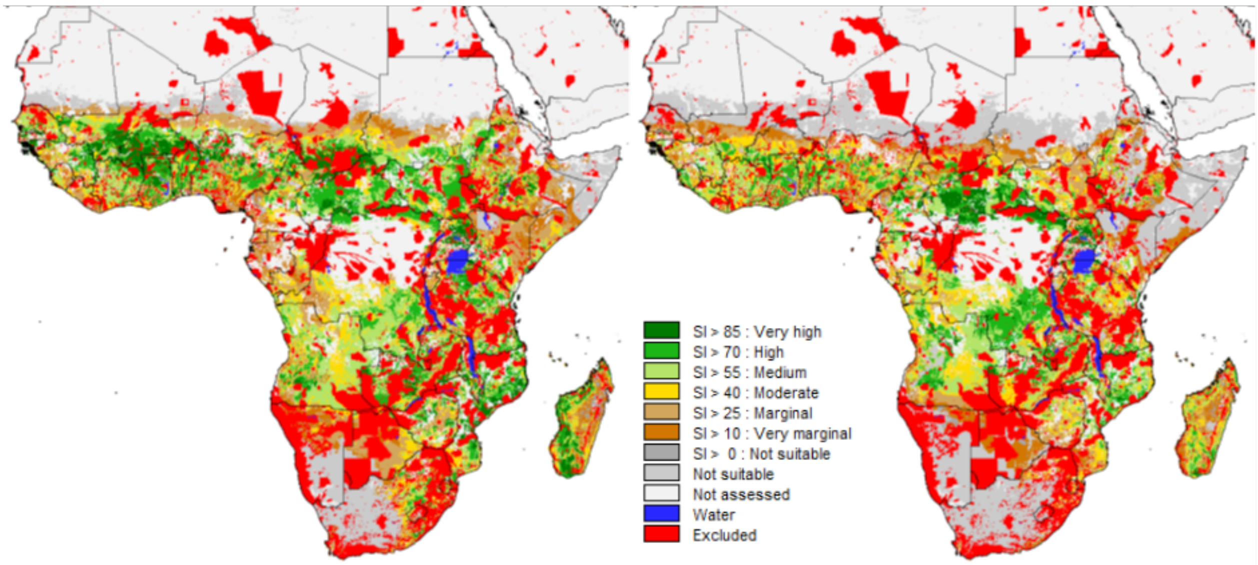
When assessing REMAIN land for biofuel feedstock production, sustainability criteria with regard to GHG emission savings must also be considered. As shown in Figure 4.4, this has a large effect on the applicability of annual crops for feedstock production as only a small fraction of total extents can meet the GHG criteria. Due to carbon stored in the vegetation and better protection of soil carbon, perennial crops generally meet the strict GHG 1 criterion. For instance, miscanthus can potentially produce 736 million tons of GHG 1 compliant biomass on 0.39 million km2 prime and good quality REMAIN land. As indicated in the figure, two-thirds of these potentials can be found in Eastern and Central Africa. In comparison, sugarcane would yield 89 million tons sugar on 0.11 million km2 of prime and good land.

Figure 4.3. Suitability of REMAIN land for sugar/starch based biofuel feedstocks

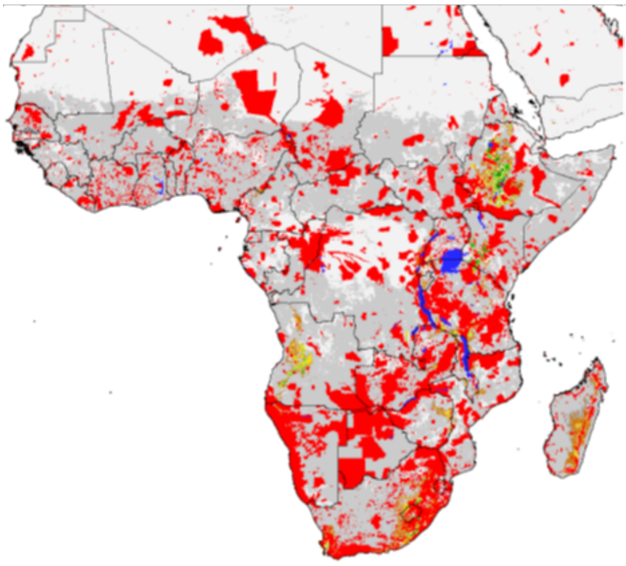
a. Agro-ecological suitability of rain-fed sugarcane *b. Agro-ecological suitability of rain-fed maize*



c. Agro-ecological suitability of rain-fed sweet sorghum *d. Agro-ecological suitability of rain-fed cassava*



e. Agro-ecological suitability of rain-fed triticale



f. Agro-ecological suitability of rain-fed miscanthus

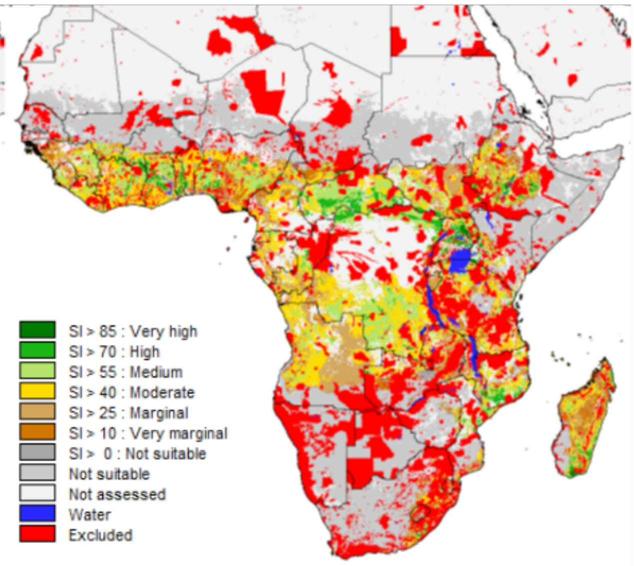
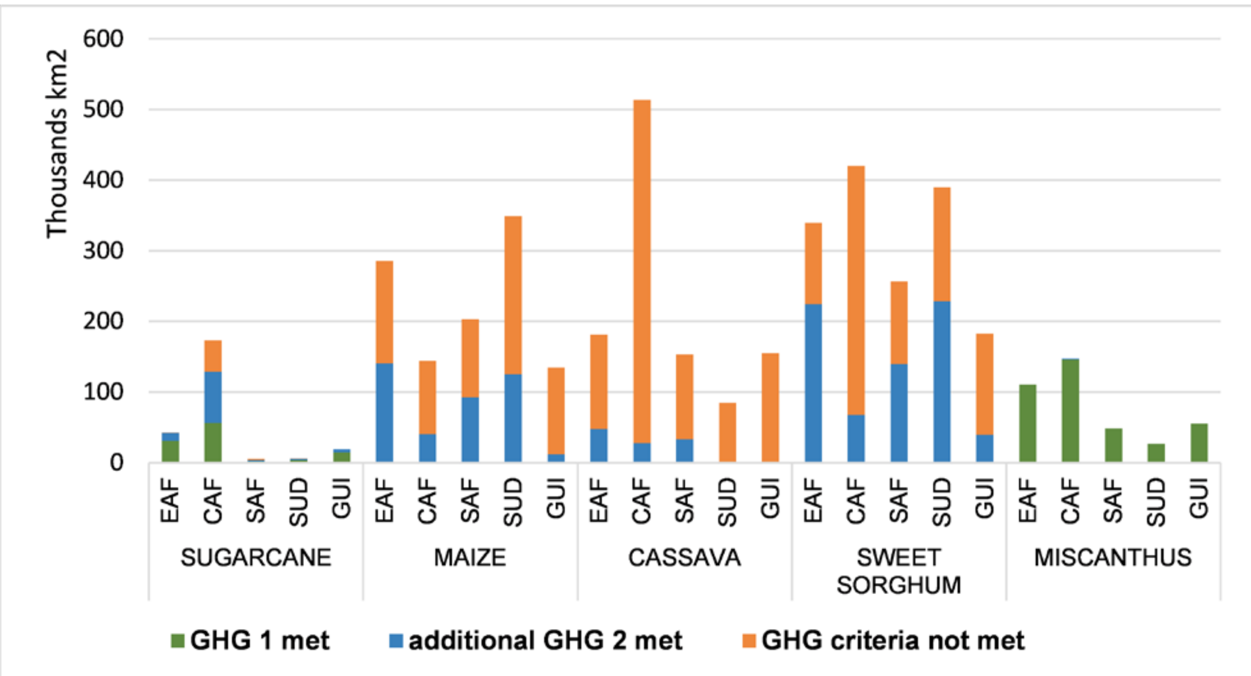


Figure 4.4 presents a summary of the extents of REMAIN land in sub-regions (East Africa, Central Africa, Sudano-Sahelian Africa, Southern Africa and Gulf of Guinea) suitable for sugar and/or starch (sugarcane, maize, cassava, sweet sorghum[26]) based biofuel production chains and for ligno-cellulosic biomass from miscanthus and highlights the impact of applying GHG emission criteria. Regional details of area extents and biomass production for each feedstock are shown in Annex III. Results at the country-level have been compiled in an accompanying Excel file “CurrentClimate_By-Individual-Feedstock.xlsx”.

Figure 4.4. Suitability of REMAIN land for the cultivation of sugarcane, maize, cassava, sweet sorghum and miscanthus, in 2010

a) Suitability on prime and good land (VS+S)



26 Triticale is not shown. Only 0.7 % of REMAIN land in SSA is prime or good land for Triticale, and 1.4 % if moderate land is added.

b) Suitability on moderate land (MS)

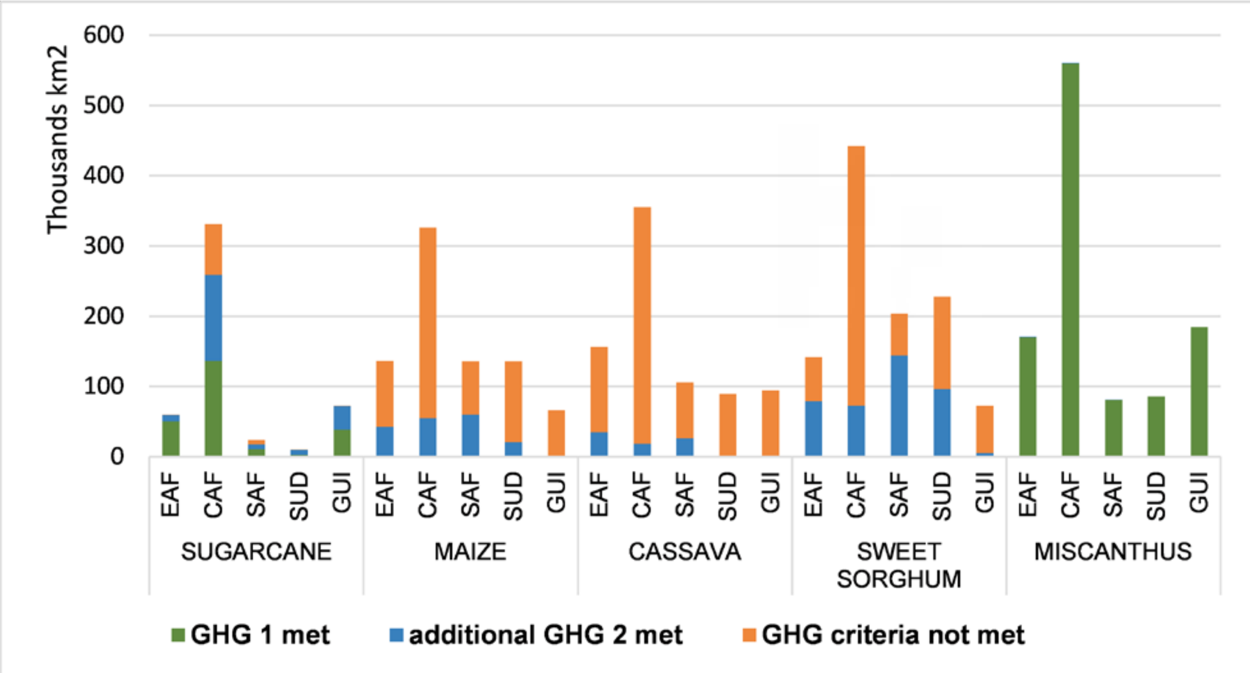


Table 4.5 presents by individual feedstocks the total extents of prime and good quality land occurring in REMAIN land of sub-Saharan Africa as well as the extents compliant with respectively GHG 1 and GHG 2 criteria. Annex III provides this information by region.

Table 4.5. Suitability of REMAIN land for rain-fed feedstock production of sugar/starch based biofuels

Crop	Total VS+S (km²)	Compliance with GHG criteria					
		GHG 1		GHG 2		GHG not met	
		VS+S (km2)	%	VS+S (km2)	%	VS+S (km2)	%
Sugarcane	245,569	106,415	43	199,330	81	46,239	19
Maize	1,116,310	0	0	409,575	37	706,735	63
Cassava	1,088,298	0	0	108,422	10	979,876	90
Sweet sorghum	1,588,795	0	0	699,304	44	889,490	56
Triticale	34,168	0	0	1,824	5	32,344	95
Miscanthus	388,951	387,520	100	388,951	100	0	0

Note: Total REMAIN land in sub-Saharan Africa is 5,504,270 km²

Of the crops considered here only sugarcane and miscanthus can meet the strict GHG 1 criterion on a part (sugarcane) or nearly all (miscanthus) of the assessed prime and good REMAIN land. Annual crops, foremost sweet sorghum and maize, although widely suitable, become feasible only under the GHG 2 criterion.

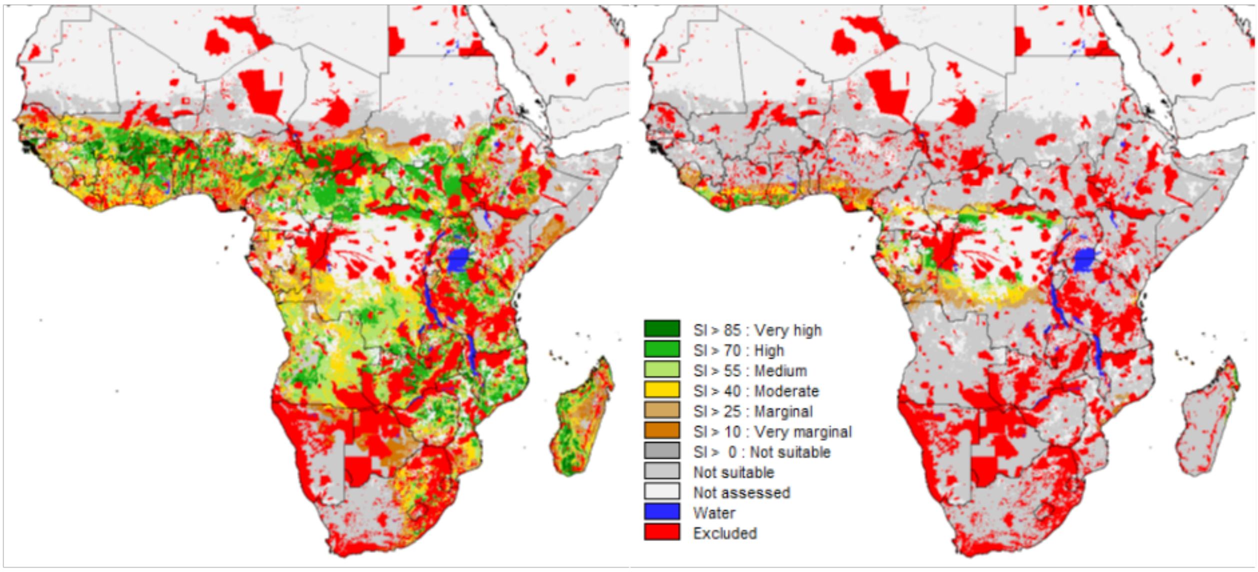
4.2.2.2 Suitability for oil producing feedstocks

The suitability of REMAIN land for rain-fed production of oil crops has also been assessed under assumptions of advanced level inputs and management. Figure 4.5 presents suitability maps for respectively soybean, oil palm, jatropha, Solaris tobacco and camelina. These maps show the occurrence of suitability classes by means of a suitability index SI[27].

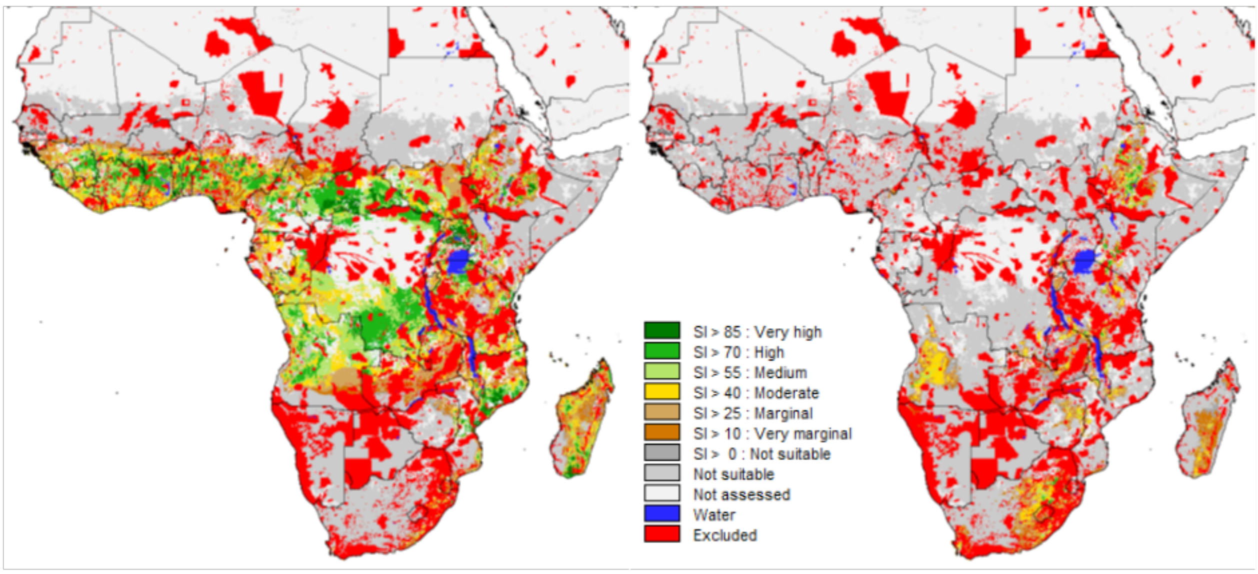
Figure 4.5 shows the widely varying spatial patterns of crop suitability for the five oil producing feedstocks assessed in this study. Solaris tobacco and especially camelina are confined to tropical and sub-tropical highland areas, whereas oil palm is suitable for rain-fed cultivation only in pockets at the fringe of the tropical forest zone. The maps clearly show that widest geographical coverage of suitability is achieved by soybeans and jatropha, for which 25% and 17% of remain land are considered suitable or very suitable for rain-fed cultivation, respectively. For Solaris tobacco this figure is 7%, for oil palm 1.5% and for camelina only 1%.

Figure 4.5. Suitability of REMAIN land for oil based biofuel feedstocks

a. Agro-ecological suitability of rain-fed soybean *b. Agro-ecological suitability of rain-fed oil palm*



c. Agro-ecological suitability of rain-fed jatropha *d. Agro-ecological suitability of rain-fed camelina*



27 SI is representing the suitability distribution in individual grid cells according occurrence of suitability classes as follows: SI=(VS*90+S*70+MS*50+mS*30+VmS*15)/0.9. The resulting values are classified as very high productive grid cells with SI >85, high productivity with SI>70, medium productivity SI> 55, moderate productivity SI > 40, marginal productivity SI > 25, very marginal productivity SI >10, and not suitable SI ≥0.

e. Agro-ecological suitability of rain-fed Solaris tobacco

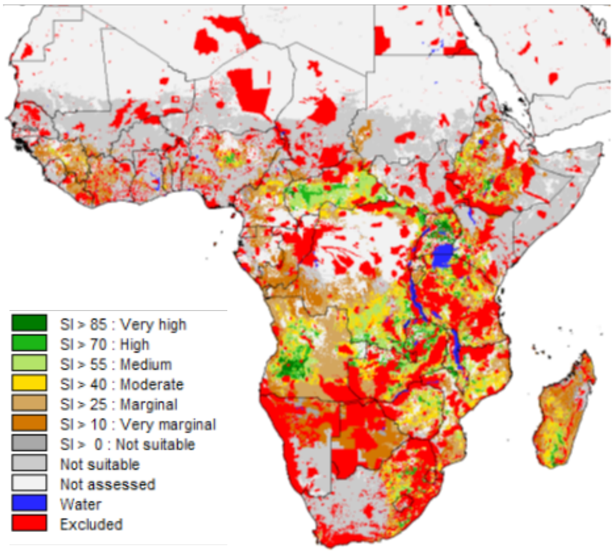


Figure 4.6 presents a summary of the extents of REMAIN land suitable for oil crop (soybean, oil palm, jatropha, Solaris tobacco and camelina). It also provides indications of the effect of compliance of oil crop production with GHG 1 and GHG 2 criteria. Regional details of both area extents and productivity for each crop are shown in Annex III. Country-level results are available from the accompanying Excel file "CurrentClimate_By-Individual-Feedstock.xlsx".

As shown in Figure 4.6 and as was observed for sugar/starch based production, annual oil crops (soybean, Solaris tobacco, camelina) generally cannot meet the GHG 1 criterion for sustainable biofuel production if land use change is considered (or in other words, if virgin shrub- or grassland is converted to agricultural land for the cultivation of annual biofuel feedstocks), and only to some extent comply with GHG 2. Perennial crops generally meet the strict GHG 1 criteria well. For instance, rain-fed oil palm and rain-fed jatropha can potentially produce respectively 38 million tons oil and 239 million tons jatropha seeds on prime and good quality land.

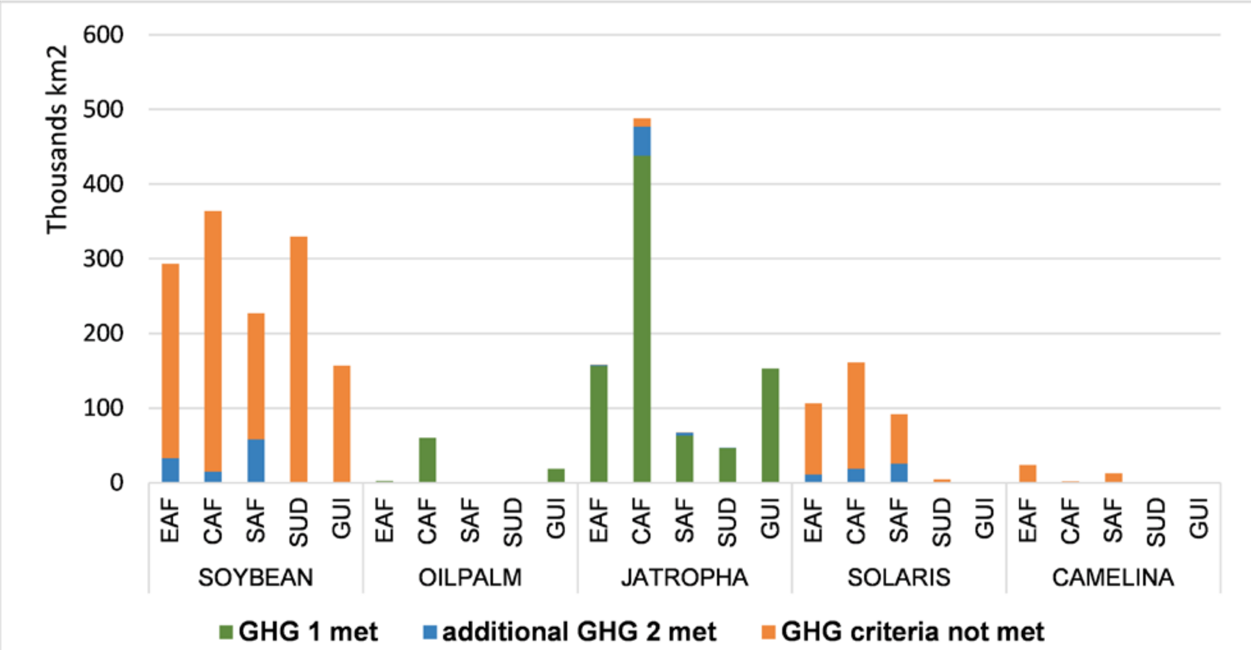
Table 4.6 presents for the assessed oil crops the total extents of prime and good quality REMAIN land in sub-Saharan Africa as well as the extents compliant with respectively GHG 1 and GHG 2 criteria. Of the crops considered here, only oil palm and jatropha can meet the strict GHG 1 criterion for nearly all the assessed prime and good REMAIN land. Solaris tobacco meets the strict GHG 1 criteria on a small area of land in Southern Africa; however, annual crops would by and large be more feasible under the GHG 2 criterion. Annex III provides the details by region.

Table 4.6. Suitability of REMAIN land for rain-fed feedstock production of oil based biofuels, 2010

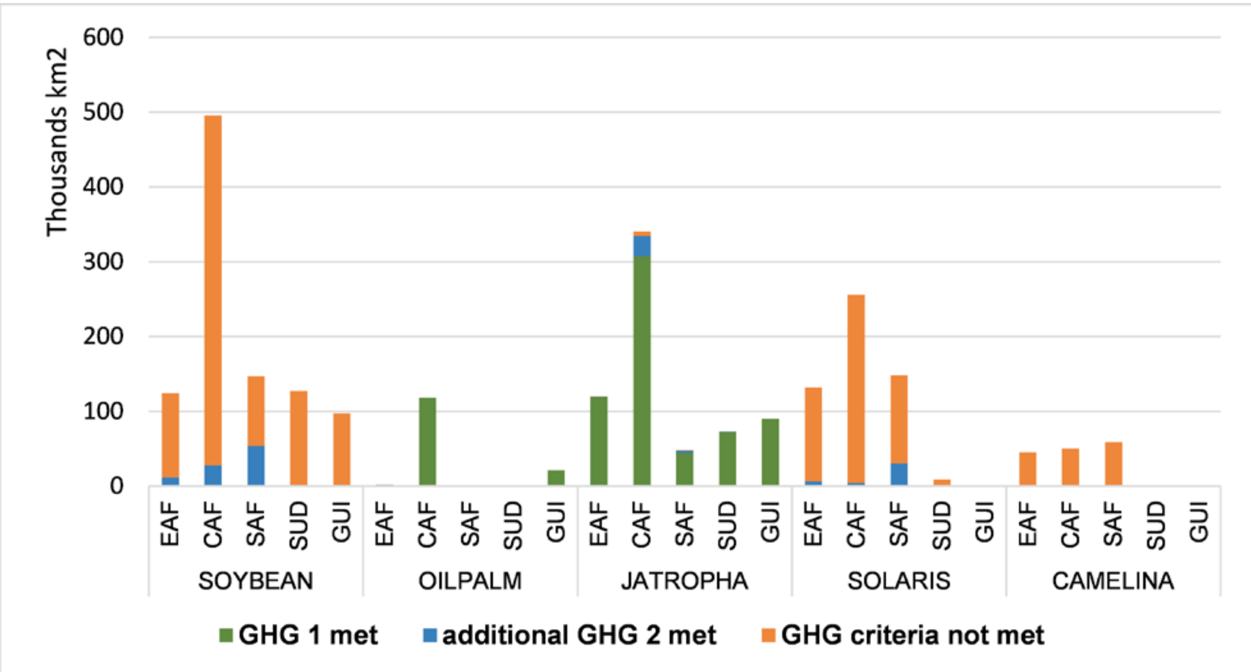
Crop	**Total VS+S (km²)**	**Compliance with GHG criteria**					
		GHG 1		GHG 2		GHG not met	
		VS+S (km2)	%	VS+S (km2)	%	VS+S (km2)	%
Soybean	1,371,281	0	0	106,852	8	1,264,429	92
Oil palm	80,194	80,194	100	80,194	100	0	0
Jatropha	913,155	857,303	94	901,042	99	12,113	1
Solaris tobacco	366,652	215	0	54,363	15	312,289	85
Camelina	38,153	0	0	0	0	38,153	100

Figure 4.6. Suitability of REMAIN land for the cultivation of soybean, oil palm, jatropha, Solaris tobacco and camelina, in 2010

a) Suitability on prime and good land (VS+S)



b) Suitability on moderate land (MS)



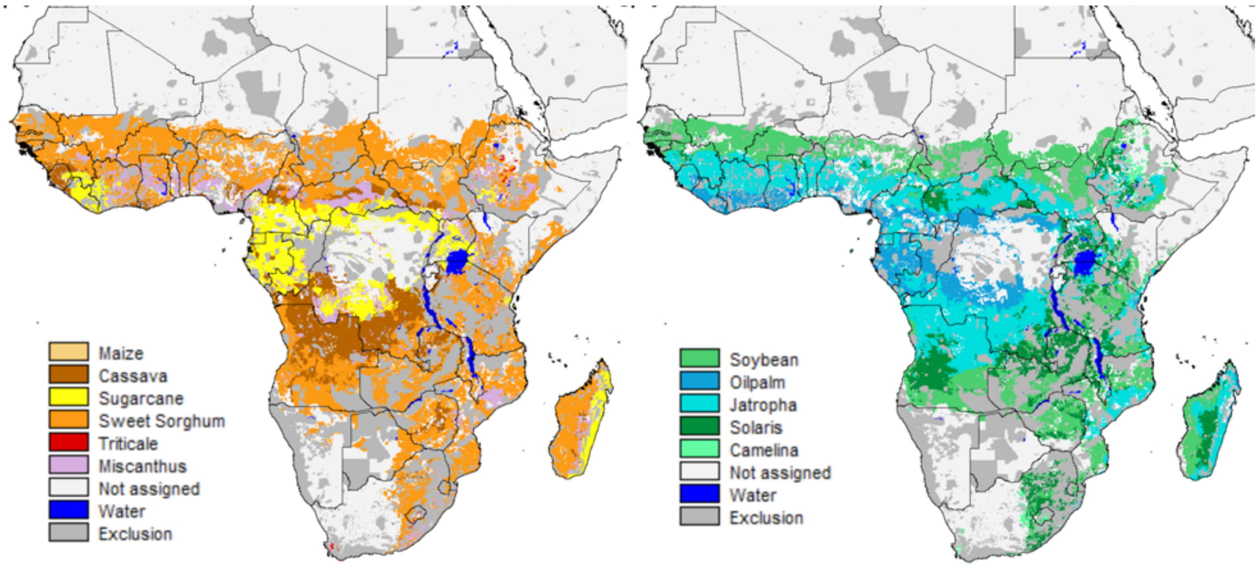
4.2.2.3 Combined potentials across different biofuel feedstocks

As more than one biofuel feedstock may qualify for economic production and compliance with GHG 1 and/or GHG 2 criteria in a 5 arc-minute grid-cell, we undertake as a last step the comparison across all feedstock types included in this analysis. Selecting in each grid-cell the best performing feedstock in terms of fuel energy production potential results in a combined potential termed as the 'umbrella' dataset, which defines the maximum achievable biofuel potential on the identified REMAIN land.

To explore the comparative advantage of different feedstocks in terms of fuel energy equivalent production, we first construct 'umbrella' datasets taking into account the applicable energy conversion factors without applying the dLUC emissions criteria. Figure 4.7 shows the results separately for sugar/starch producing and for vegetable oil producing feedstocks. It clearly shows a spatial differentiation of the chosen feedstocks which strongly correlates with the spatial gradients of precipitation and temperature in sub-Saharan Africa.

Figure 4.7. Defining feedstocks of fuel energy 'umbrella' on REMAIN land without dLUC GHG criteria

a) Sugar/starch based biofuel feedstocks



Applying the dLUC GHG emission criteria significantly reduces the choices available for selection on REMAIN land, especially regarding selection of annual crops. Figure 4.8 presents the maps indicating which of the sugar/starch feedstocks would produce best in terms of fuel energy equivalents. The maps show respectively, by grid cell, the best performing feedstock (a) subject to compliance with the GHG 1 criterion, and (b) accounting for compliance with the GHG 2 criterion. Figure 4.9 provides the same kind information for oil-producing feedstocks.

Figure 4.8. Defining feedstocks of sugar/starch based biofuel potentials from REMAIN land

a) subject to GHG 1 Criterion *b) subject to GHG 2 Criterion*

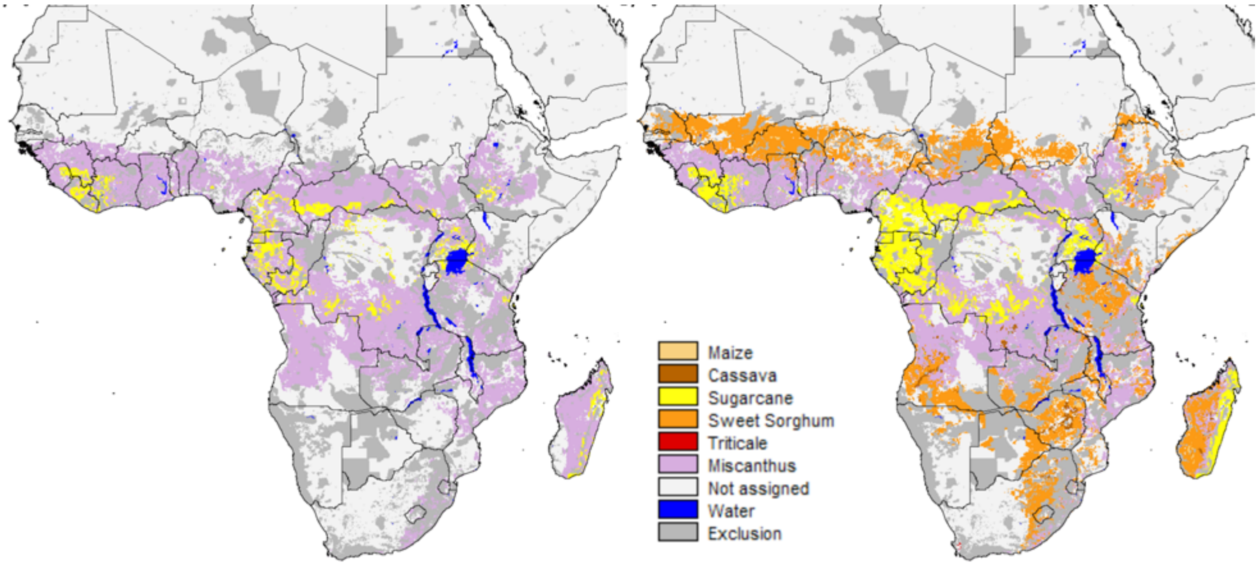
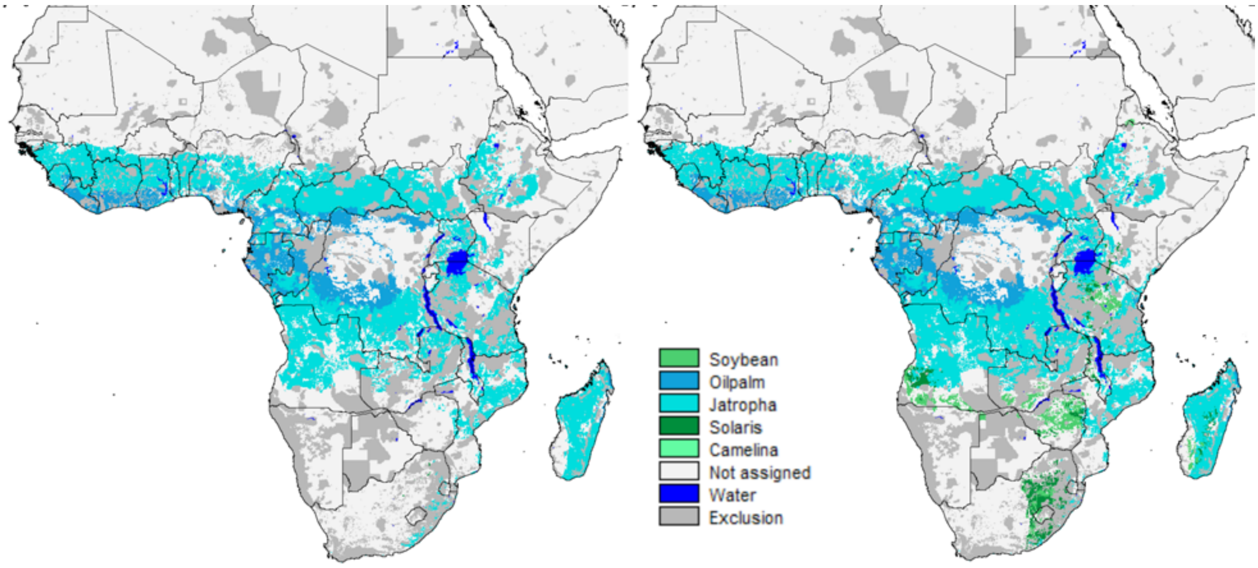


Figure 4.9. Defining feedstocks of vegetable oil based biofuel potentials from REMAIN land

a) subject to GHG 1 Criterion *b) subject to GHG 2 Criterion*

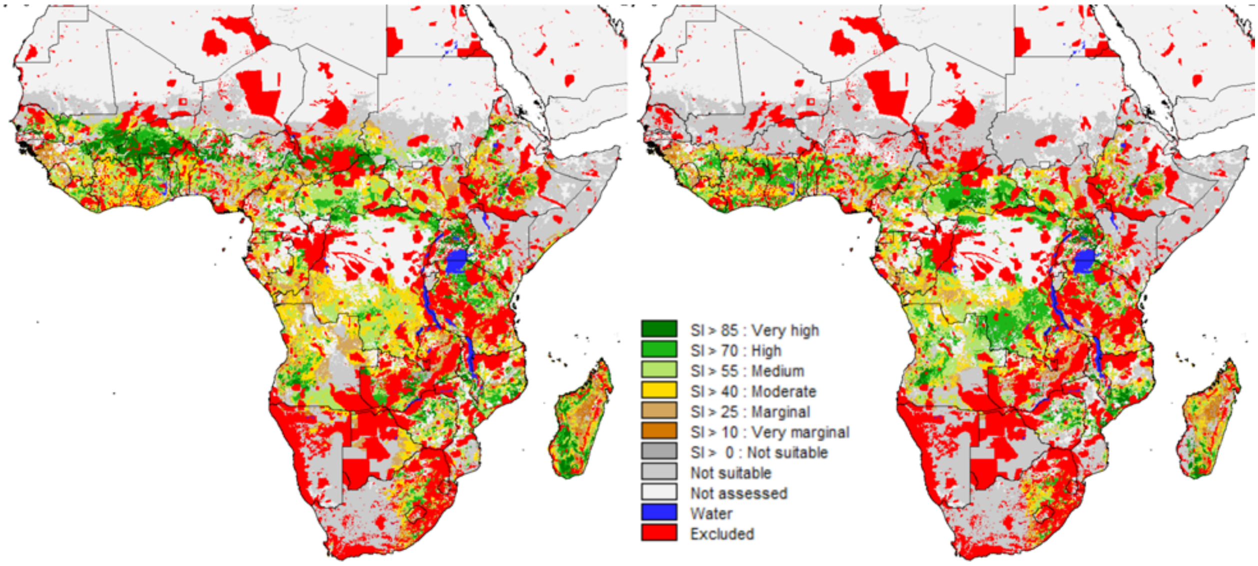


The analysis clearly demonstrates the crucial importance of the exact details used for the specification of GHG criteria as well as the technical coefficients used in their evaluation, e.g. for co-product allocation and for soil carbon loss factors.

The resulting spatial suitability distributions for sugar/starch feedstocks and oil-producing feedstocks grown under rain-fed conditions are shown in Figure 4.10. The suitability in each grid cell is represented by the suitability of the selected best performing feedstock in terms of fuel energy equivalents. These maps are referred to as biofuel ‘umbrella’ crops.

Figure 4.10. Agro-ecological suitability of rain-fed 'umbrella' crops on REMAIN land

a) Sugar/starchy feedstocks *b) Oil-producing feedstocks*



The maps indicate the occurrence of some suitable areas in parts of Western Africa (albeit shares of REMAIN land are quite small in that region), in the eastern part of Southern Africa, and mostly in the Central Africa grassland and shrub land areas.

Table 4.7 presents the extents (a) and corresponding biofuel potential (b) of prime and good quality land and the extents (c) and corresponding biofuel potential (d) of prime, good and moderately suitable quality land in SSA. Results in Table 4.7 are presented for three different sets of feedstocks and different levels of compliance with GHG criteria. Both biofuel energy yield and compliance with GHG criteria is assessed for all feedstocks of the respective crop group. Agro-climatic conditions usually allow the cultivation of more than one possible feedstock crop. For each feedstock group, the crop achieving the highest biofuel energy yield and meeting the GHG criteria in the respective 5 arc-minute grid-cell (about 9 x 9 km) is selected to define potential biofuel production.

Table 4.7. Suitability and productivity of REMAIN land for rain-fed biofuel feedstock production in SSA, by compliance with GHG criteria, 2010

a) Extents of prime and good REMAIN land (VS+S) (1000 km²)

Groups of feedstock types considered on REMAIN land (VS+S)	Total VS+S REMAIN Land[4]	Compliance with GHG criteria					
		GHG 1		GHG 2[5]		GHG not met	
		Area	%	Area	%	Area	%
(1) Sugar/starch/biomass producing crops[1]	1,857	422	23	1,086	59	771	41
(2) Vegetable oil producing crops[2]	1,670	907	54	1,051	63	619	37
(3) All feedstocks[3]	1,915	838	44	1,469	77	446	23

b) Biofuel production potential on prime and good REMAIN land (Petajoules)

Groups of feedstock types considered on REMAIN land (VS+S)	Potential in REMAIN VS+S land	Compliance with GHG criteria					
		GHG 1		GHG 2[5]		GHG not met	
		Prod.	%	Prod.	%	Prod.	%
(1) Sugar/starch/biomass producing crops	18,072	5,172	29	11,617	64	6,455	36
(2) Vegetable oil producing crops	6,197	4,077	66	4,548	73	1,649	27
(3) All feedstocks	18,650	7,064	38	13,305	71	5,346	29

c) Extents of prime, good and moderate REMAIN land (VS+S+MS) (1000 km²)

Groups of feedstock types considered on REMAIN land (VS+S+MS)	Total VS+S+MS REMAIN Land[4]	Compliance with GHG criteria					
		GHG 1		GHG 2[5]		GHG not met	
		Area	%	Area	%	Area	%
(1) Sugar/starch/biomass producing crops[1]	18,072	5,172	29	11,617	64	6,455	36
(2) Vegetable oil producing crops	6,197	4,077	66	4,548	73	1,649	27
(3) All feedstocks	18,650	7,064	38	13,305	71	5,346	29

d) Biofuel production potential on prime, good and moderate REMAIN land (Petajoules)

Groups of feedstock types considered on REMAIN land (VS+S+MS)	Potential in REMAIN VS+S+MS land	Compliance with GHG criteria					
		GHG 1		GHG 2[5]		GHG not met	
		Prod.	%	Prod.	%	Prod.	%
(1) Sugar/starch/biomass producing crops	24,270	14,598	60	21,103	87	3,167	13
(2) Vegetable oil producing crops	9,040	6,611	73	7,232	80	1,808	20
(3) All feedstocks	24,799	15,510	63	21,901	88	2,898	12

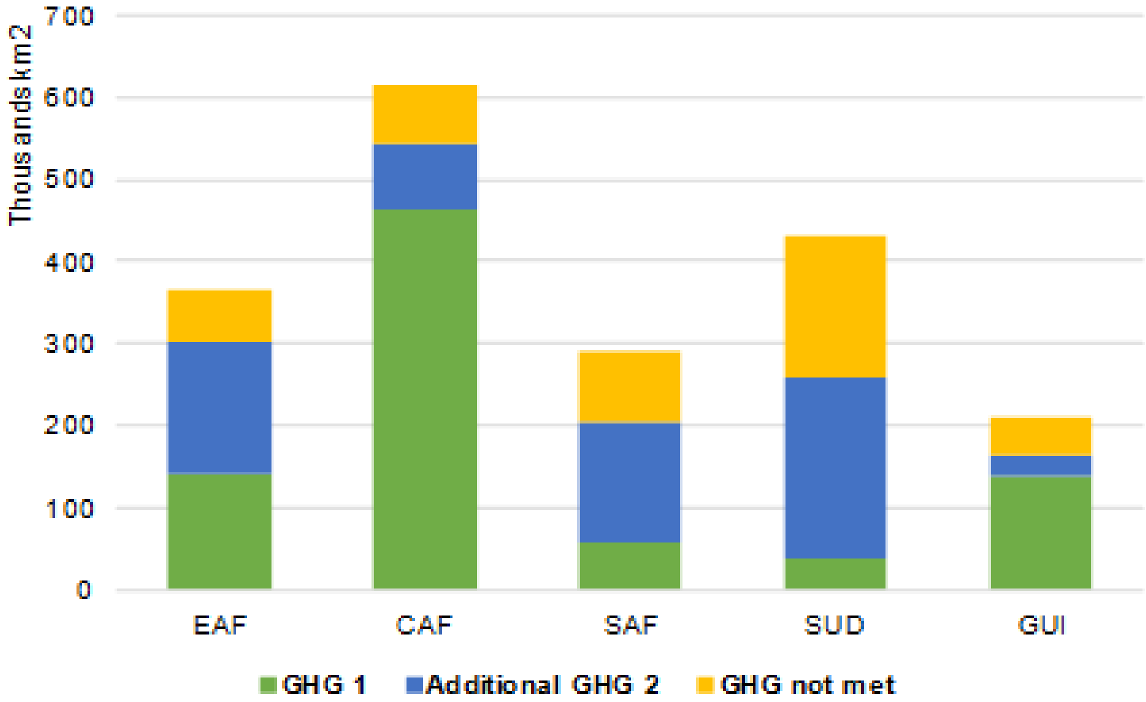
Results indicate that sub-Saharan Africa's REMAIN land varies greatly in suitability and biofuel production potential[28]. Depending on which of the GHG criteria is applied and which group of biofuel feedstocks is considered, between 8% and 27% of the total SSA REMAIN land (some 5,504 thousand km2; see Table 4.3) qualify for biofuel feedstock cultivation with prime and good suitability conditions in 2010. On about a quarter of the REMAIN land assessed to be of prime and good agronomic suitability for feedstock cultivation (of 1,915 thousand km2; Table 4.7) none of the suitable feedstock crops in these locations can meet the GHG criteria and this land is not considered in the potential. Figure 4.11 shows the regional distribution of prime and good REMAIN land by compliance with GHG criteria.

28 Biofuel production potential refers to the combination of the 11 feedstocks assessed in this study.

Large areas qualify as GHG compliant prime and good quality land for the production of both jatropha and miscanthus. Typically, the vegetable oil based conversion route of jatropha seeds has somewhat better agronomic suitability but yields significantly lower biofuel energy yields compared to the second-generation conversion route of miscanthus. Because of this (and other but smaller extents of overlap between crops), the very suitable and suitable area extents of GHG 1 compliant crops of the feedstock group (2), oil producing crops, is larger (907 thousand km2) compared to the area allocated when all 11 feedstocks are considered (838 thousand km2).

This outcome is due to (a) the goal of maximising fuel energy production rather than planted area, (b) the fact that less of the identified REMAIN land is VS + S for sugar/starch/lignocellulosic crops than for oilseeds, and (c) ethanol pathways generally achieve much higher energy yields than vegetable oil-based pathways (except for oil palm). This means that in a grid cell of 5 arc minutes (approximately 9 x 9 km), due to the presence of different soil types and terrain slopes there might be less land suitable for the production of sugar/starch/lignocellulosic crops than for oilseeds, but the former may still achieve a higher energy yield than oilseeds would on a larger area in the same grid cell, and therefore the model chooses them; see also example given earlier in section 4.1.4.

Figure 4.11. Prime and good REMAIN land in 2010 for all 11 biofuel feedstocks considered, by region and compliance with GHG criteria



At the lower end, when applying the GHG 1 criterion, considering all feedstocks and only REMAIN land of prime and good suitability, some 838 thousand km2 (or 15%), out of total 5,504 thousand km2 REMAIN land, qualify for the cultivation of biofuel feedstocks. Table 4.8, Figure 4.12 and Figure 4.13 highlight details of the composition and regional distribution of individual feedstocks contributing to the biofuel potential when considering all biofuel feedstocks (i.e. group (3) in Table 4.7). They show extents of REMAIN land separately for prime and good land (VS+S) and extents when considering prime, good and moderate land (VS+S+MS).

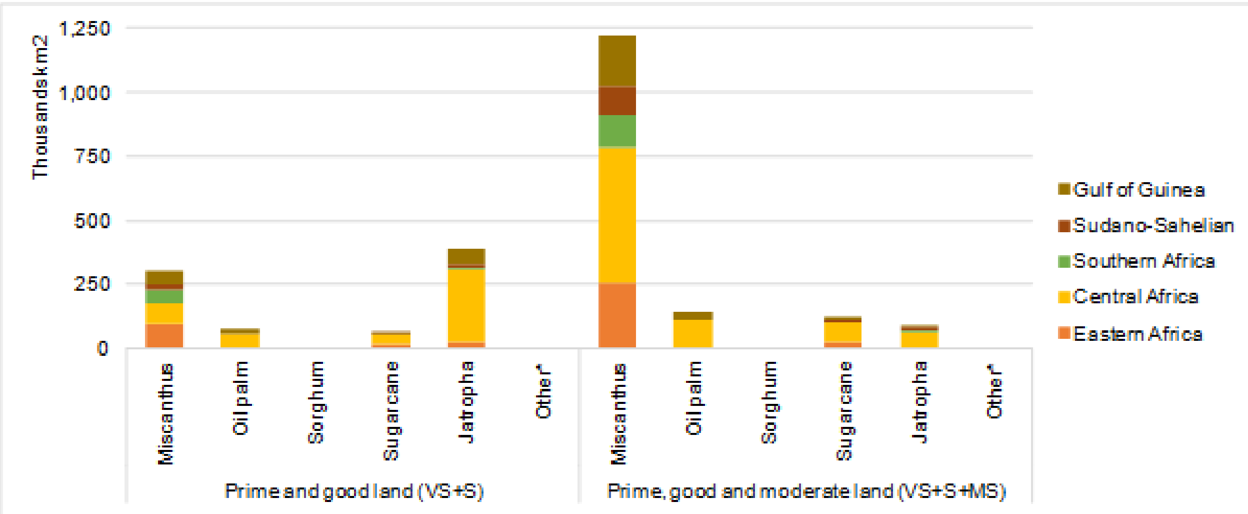
Table 4.8. Suitability of REMAIN land for biofuel feedstock production, by GHG criteria, 2010

1000 km²	TOTAL REMAIN	VS+S[1]				VS+S+MS[2]			
		GHG 1	%	GHG 2	%	GHG 1	%	GHG 2	%
Eastern Africa	1,042	141	143	302	29	287	28	439	42
Central Africa	1,152	463	40	542	47	781	68	886	77
Southern Africa	1,431	59	4	203	14	131	9	388	27
Sudano-Sahelian	1,493	38	3	259	17	126	8	414	28
Gulf of Guinea	386	137	35	163	42	244	63	253	66
SSA	5,504	838	15	1,469	27	1,570	29	2,379	43

1 VS + S: Very suitable (>80% of maximum yield) and Suitable (60-80% of max); i.e. prime and good land. **2** Very suitable, suitable and moderately suitable land; MS: Moderately suitable land (40-60% of max); **3** Share in total REMAIN land of respective region

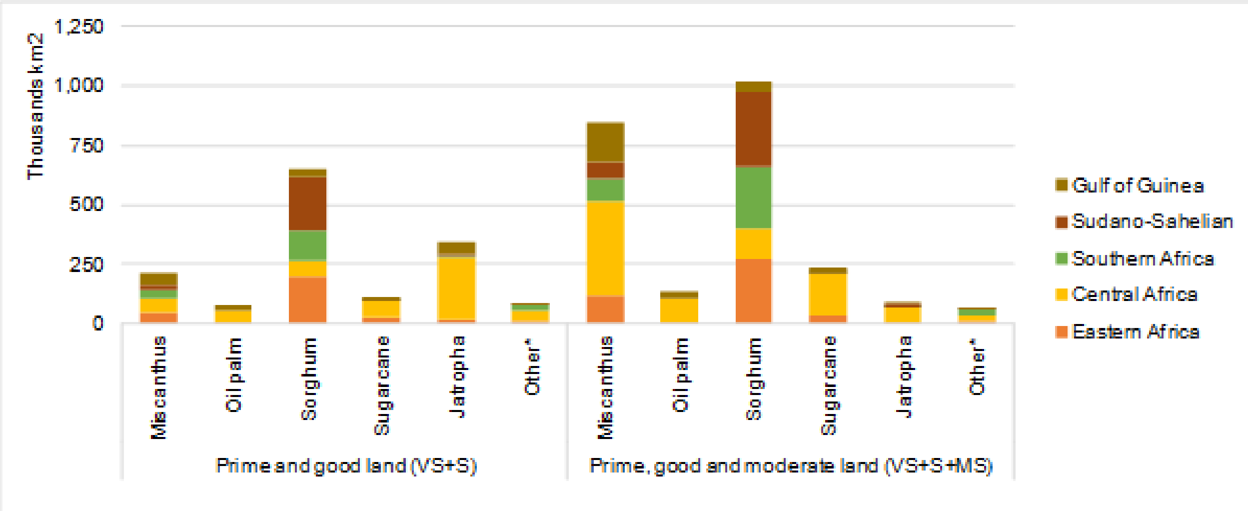
The majority (52%) of the prime and good REMAIN land extents in the biofuel 'umbrella' are associated with miscanthus, followed by oil palm (18%), jatropha (17%) and sugarcane (13%). When moderately suitable areas are also considered, the GHG 1 compliant extents increase to 1,570 thousand km2 (or 29%) of total REMAIN land (Table 4.8). Including moderately suitable areas would further increase the share of miscanthus in the feedstock mix, then accounting for 77% of these VS+S+MS land extents (Figure 4.12).

Figure 4.12. Geographical distribution of best performing feedstocks subject to GHG 1 criterion, 2010



** These extents include very small amounts of Solaris tobacco that meet GHG 1 in Southern Africa*

Figure 4.13. Geographical distribution of best performing feedstocks subject to GHG 2 criterion, 2010



** Other crops include maize, cassava, soybean, jatropha, Solaris tobacco and triticale.*

Applying the somewhat less stringent GHG 2 criterion instead of GHG 1 significantly increases the potential areas qualifying for the production of biofuels. In this case, more than a quarter (27 %) of the REMAIN land is of prime and good quality for biofuel crops and a total of 43% if moderate land quality is also considered for the production of biofuel feedstocks. In addition to the perennial feedstocks qualifying under GHG 1, a number of annual crops can meet the GHG 2 criterion. As a result, the composition of the selected best performing feedstocks becomes more differentiated. The most important feedstocks on prime and good land include sweet sorghum (47%), followed by miscanthus (19%), sugarcane (14%) and oil palm (9%). When including also moderate land qualities, sweet sorghum and miscanthus together would contribute three quarters of the extents allocated in the 'umbrella' (Figure 4.13).

Complementing the presentation of potentially suitable extents in the available REMAIN land, Table 4.9 summarizes the results obtained for potential production in terms of fuel energy equivalent compliant with GHG criteria 1. Respective results compliant with GHG criterion 2 for SSA are summarized in Table 4.10.

Across sub-Saharan Africa we estimate a total biofuel energy production potential of 7.1 thousand PJ from feedstocks cultivated on prime and good quality REMAIN land. If REMAIN land of moderate quality is included, 15.5 thousand PJ can be produced. These potentials comply with the GHG 1 criterion and are mainly derived from four crops (miscanthus, oil palm, jatropha and sugarcane). Annual crops rarely comply with the GHG 1 criterion. Sugarcane can in part meet the GHG 1 requirements due to its relatively low life cycle emissions, lower dLUC burden and its high yields and Solaris tobacco can meet the criteria in a very limited area in Southern Africa.

Biofuel potentials vary substantially across regions throughout sub-Saharan Africa. Sugarcane is concentrated in Eastern Africa (Madagascar, Ethiopia, Uganda, Tanzania), Central Africa (Congo DR, Central African Rep., Congo Rep., Cameroon), and Gulf of Guinea (Liberia, Guinea). Oil palm plantations require the hot and moist tropical climates prevalent in Central Africa (foremost Congo DR, Congo Rep., Gabon, Cameroon) and the Gulf of Guinea (Cote d'Ivoire, Liberia, Ghana). Almost the entire potential for jatropha cultivation on REMAIN land occurs in a few countries only, including parts of Congo DR, Angola, and South Sudan. Suitability of miscanthus defines the biofuel potential mostly in the sub-humid regions of SSA. Finally, Solaris tobacco enters under the GHG 1 criterion only in some pockets of Southern Africa.

Table 4.9. Biofuel potential on REMAIN land compliant with the GHG 1 criterion, in 2010

Regions	**Eastern Africa**	**Central Africa**	**Southern Africa**	**Sudano-Sahelian**	**Gulf of Guinea**	**SSA TOTAL**
Prime and good land (VS+S) production potential (Petajoules)						
Sugarcane	253	513	0	26	115	907
Miscanthus	1,188	959	584	291	594	3,645
Oil palm	38	989	0	0	297	1,294
Jatropha	84	882	33	36	183	1217
Solaris	0	0	1	0	0	1
TOTAL VS+S	**1,564**	**3,342**	**617**	**353**	**1,188**	**7,064**
Prime, good and moderately suitable land (VS+S+MS) production potential (Petajoules)						
Sugarcane	301	898	0	27	167	1,394
Miscanthus	2,644	4,923	1,293	1058	1,990	11,908
Oil palm	47	1,293	0	0	437	2,023
Jatropha	11	126	3	30	2	184
Solaris	0	0	1	0	0	0.3
TOTAL VS+S+MS	**3,003**	**7,499**	**1,297**	**792**	**2,596**	**15,510**

Source: own calculations; Country-level results is available upon request.

When adopting the GHG 2 criterion, sub-Saharan Africa's biofuel potential nearly doubles on prime and good land from 7.1 thousand PJ under the GHG 1 to 13.3 thousand PJ and to 21.9 thousand PJ under the GHG 2 criterion when moderate land is included (Table 4.10).

The significant increase compared to GHG 1 results is due to the wider range of biofuel feedstocks (and number of grid cells) passing this GHG 2 criterion. In particular, annual crops can also often meet this criterion, which employs a different, somewhat less stringent requirement for the recuperation of the dLUC GHG burden on REMAIN land. All but one biofuel feedstock qualify for biofuel production on REMAIN land under GHG 2. The exception is camelina, an oilseed producing annual crop adapted to tropical highland conditions as, for example, prevailing in Ethiopian highlands. Camelina does not pass the GHG 2 criterion mainly due to achieving only rather low crop yields resulting in a relatively high dLUC emission burden per MJ of fuel energy equivalent.

When GHG 2 is applied, sweet sorghum emerges as a crop with a large and competitive (among the crops considered) feedstock potential. Under GHG 2 this crop alone would account for almost half of SSA's total biofuel potential on prime/good REMAIN land. Sweet sorghum's wide adaptation to the biophysical conditions in SSA permits cultivation throughout the continent's semi-arid and sub-humid regions. In the Sudano-Sahelian region, it by far dominates the feedstock selection. Miscanthus remains an important feedstock candidate, but unlike in the case of the GHG 1 'umbrella' is not the dominating crop.

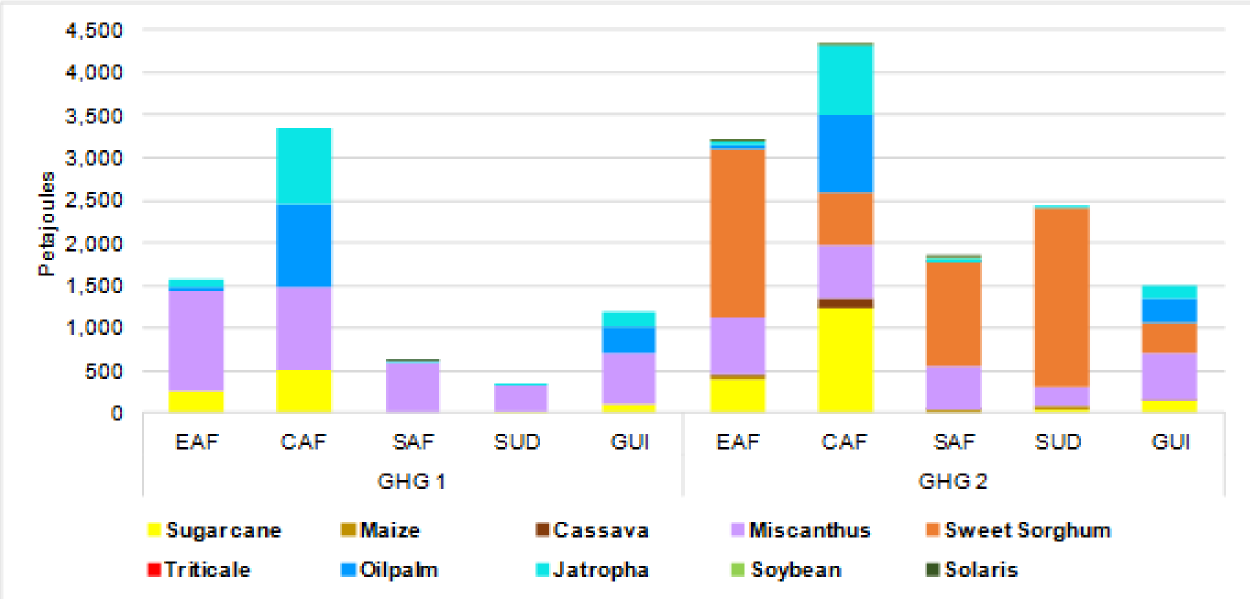
Table 4.10. Biofuel potential on REMAIN land compliant with GHG criterion 2, in 2010

Regions	Eastern Africa	Central Africa	Southern Africa	Sudano-Sahelian	Gulf of Guinea	SSA TOTAL
Prime and good land (VS+S) production potential (Petajoules)						
Sugarcane	385	1,226	0	44	156	1,810
Maize	56	13	28	33	2	132
Cassava	28	109	16	0	0	153
Sweet sorghum	1,983	616	1,234	2,099	355	6,288
Triticale	0	0	1	0	0	1
Miscanthus	646	615	500	237	548	2,546
Soybean	1	2	25	0	0	28
Oil palm	37	913	0	0	294	1,244
Jatropha	50	817	28	26	155	1,076
Solaris	3	1	23	0	0	28
TOTAL VS+S	**3,189**	**3,612**	**1,855**	**2,439**	**1,510**	**13,305**
Prime, good and moderately suitable land (VS+S+MS) production potential (Petajoules)						
Sugarcane	470	1,955	0	47	234	2,705
Maize	36	16	27	27	2	108
Cassava	36	126	32	0	0	194
Sweet sorghum	2,430	1,017	2,013	2,628	368	8,456
Triticale	0	0	1	0	0	1
Miscanthus	1.291	3,661	976	713	1,641	8,282
Soybean	0	5	25	0	0	30
Oil palm	45	1,436	0	0	430	1,911
Jatropha	6	145	3	30	2	186
Solaris	2	0	25	0	0	27
TOTAL VS+S+MS	**4,316**	**8,362**	**3,103**	**3,444**	**2,677**	**21,901**

Source: own calculations; Country-level results is available upon request.

The previous tables indicate that the application of the GHG 2 criterion allows for a larger potential biofuel production from prime and good REMAIN land (about twice the quantity obtainable under the GHG 1 criterion) based on a somewhat more varied set of feedstock sources, as is also shown in Figure 4.14.

Figure 4.14. Regional biofuel potentials from REMAIN land with prime and good suitability, in 2010



4.3 Sustainable biofuel production potential under future conditions

A major challenge confronting the agricultural sector today is to supply crops for a variety of future agricultural demands — food, animal feed, fibre, chemicals and bio-energy — without jeopardizing food supply. In Africa, cropland has been mostly used for the cultivation of staple crops to meet food demands. Agricultural production for export and the non-food industry has been relatively small. Today, only some 2 % of harvested area (52 thousand km2) is used to grow non-food cash-crops including rubber (7,310 km2), tobacco (6,680 km2), and other industrial crops (38,150 km2; mainly cotton).

sub-Saharan Africa includes regions where population growth rates are among the highest in the world. In addition, many African countries are also expected to achieve strong economic growth. Both population growth and economic development trends will trigger an ever increasing food demand and will require some expansion of cropland in addition to narrowing existing large yield gaps.

This study has analysed two possible development scenarios (see 3.7.3):

- Scenario SC 1, a combination of the socio-economic development pathways described as SSP1 (Sustainability – Taking the Green Road) and climate change impacts calculated for the concentration pathway RCP2.6, representing the lower end for the range of future climate change scenarios.

- Scenario SC 2, a combination of factors according to the socio-economic development pathway SSP2 (Middle of the Road) and climate change impacts calculated for the concentration pathway RCP6.0 (i.e., medium climate change).

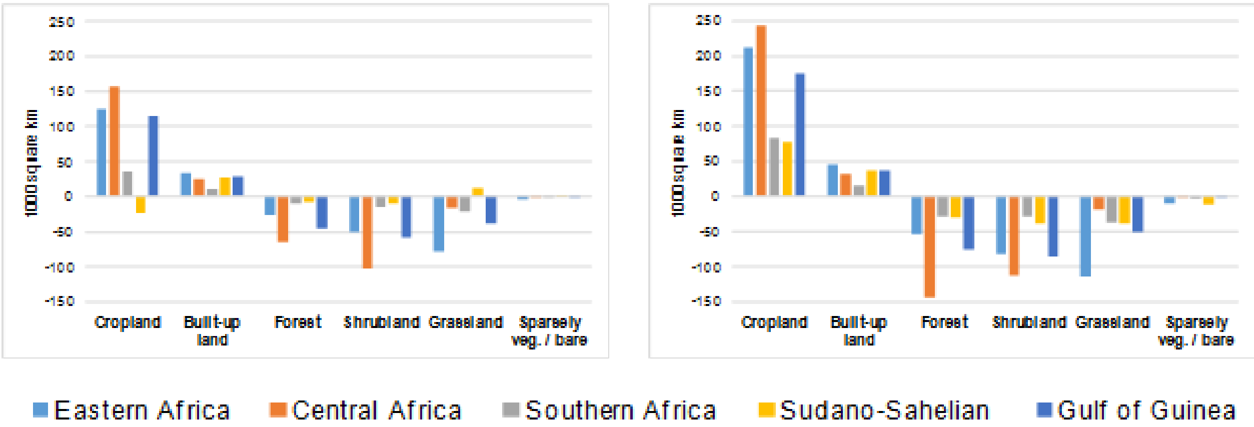
Between 2010 and 2050, the Sub-Saharan population will more than double in scenario SC 2 and increase by 82% in scenario SC 1 (see Table 3.14). In view of the rapid population growth in SSA, there is a twofold challenge. First, to reduce the number of food insecure in absolute and relative terms (currently 218 million people undernourished) (FAO, 2015) and second, to satisfy the additional demand for food production due to an additional 700 to 900 million people (depending on scenario) between 2010 and 2050. In this study we apply a "food first" approach by assessing future food demand in each scenario and explicitly setting aside the projected cropland needed for the food sector before assessing remaining land resources for potential biofuel feedstock production.

4.3.1 Land use changes until 2050

The general trend in land use changes in the two development scenarios, due to population growth and the required expansion of agricultural production, is an increase in both cropland and built-up areas, which depending on the assumed strength of land use regulation will expand more or less into forests, shrub land and grassland (Figure 4.15). The harsh conditions of sparsely vegetated and bare land impede expansion of cropland use or built-up land for human settlements. Therefore, extents of this land use category change little over time.

Figure 4.15. Land use changes in the development scenarios, 2010 to 2050

a) Scenario SC 1 "Sustainability" *b) Scenario SC 2 "Middle of the Road"*



Source: own calculations

Between 2010 and 2050, cropland for food production and built-up land are projected to increase by respectively 792 thousand km2 and 168 thousand km2 in scenario SC 2 (Middle of the Road). Scenario SC 1 (Sustainability) achieves a higher crop yield growth than experienced in scenario SC 2 while at the same time population grows less compared to SC 2. Thus, the demand for expanding food land is less in scenario SC 1 than under scenario SC 2. In addition, for the Sustainability scenario SC 1 stricter rules are assumed to apply for forest conversion. Consequently, the projected expansion of cropland and built-up areas (and conversion of forest land) is less pronounced in SC 1, amounting for the period 2010 to 2050 to respectively 409 thousand km2 and 126 thousand km2. During the same period, forest land decreases by 332 thousand km2 in scenario SC 2, and significantly less, 154 thousand km2, in the Sustainability scenario SC 1.

Because of these required land conversions in the development process, by 2050 the total shrub land and grassland extents are reduced by 374 thousand km2 (scenario SC 1) and 603 thousand km2 (scenario SC 2) resulting in the loss of REMAIN land, which decreases during 2010 to 2050 by between 320 thousand km2 (scenario SC 1) and 501 thousand km2 (scenario SC 2), see Table 4.11.

Table 4.11. Changes in extents of REMAIN land between 2010 and 2050, by region

1000 km²	2010	2050		Change 2010 to 2050			
Scenario		SC1 (Sustain-ability)	SC2 (Middle of the Road)	SC1 (Sustainability)		SC2 (Middle of the Road)	
Eastern Africa	1,042	944	893	-99	(-10%)	-149	(-14%)
Central Africa	1,152	1,040	1,027	-112	(-10%)	-125	(-11%)
Southern Africa	1,431	1,402	1,377	-29	(-2%)	-54	(-4%)
Sudano-Sahelian	1,493	1,485	1,426	-8	(-1%)	-68	(-5%)
Gulf of Guinea	386	314	280	-72	(-19%)	-107	(-28%)
SSA Total	5,504	5,185	5,003	-320	(-6%)	-501	(-9%)

Source: own calculations

The magnitude of the land use changes varies across regions and countries due to differences in population growth and quality of resource endowments. Pronounced land use changes in Eastern and Central Africa result in a reduction of the REMAIN land by 10% to 14%. In the Gulf of Guinea region, already today a region with relatively small extents of REMAIN land, the model simulations suggest a significant further reduction of the REMAIN land over the coming decades in the order of 20% to 30% (Table 4.11). The least reductions of 1% to 5% occur in the Southern Africa and Sudano-Sahelian region.

4.3.2 Future biofuel potentials (2050)

As discussed previously, over time the extents of REMAIN land available in 2010 will be declining (Table 4.11) due to growing food demand and progressing climate change which affects land productivity. Furthermore, the additional cropland use for food production is likely to expand where possible into areas with the most suitable biophysical conditions (climate, terrain, soil) for agriculture. This means that the REMAIN land area is not only reduced in size due to the development process to 2050 but also loses some of its agronomically better suited parts.

Table 4.12 and Table 4.13 present a summary for sub-Saharan Africa comparing current with future biofuel potentials for the two scenarios explored in this study (for details see 3.7.3). A potentially positive environmental impact of climate change is the direct effect of increased atmospheric CO2 concentrations on crop yields, known as the CO2 fertilization effect, because of the enhancement of photosynthesis rates and plant water use efficiency (Kimball et al., 2002). Under RCP2.6 conditions, which represents the lower end concentration pathway of the IPCC scenarios, the average atmospheric CO2 concentrations in the 2050s (period 2041-2070) amount to 443 ppm. The respective value for RCP6.0 is 493 ppm (see section 3.7.3).

By 2050, under constraints posed by GHG criterion 1, the biofuel potential on prime and good land amounts to about 4,000 PJ compared to the potential estimated for current REMAIN land and current climate conditions of about 7,000 PJ. If REMAIN land of moderate suitability for energy crop production is included, then the overall GHG 1 compliant potential in 2010 of about 15,500 PJ decreases to some 11,165 PJ. The strong decline of the biofuel potential results from a combination of two factors, namely the reduction of available REMAIN land extents due to growing food demand (and hence expansion of cropland for additional food production) and the impacts of climate change on crop suitability and yields.

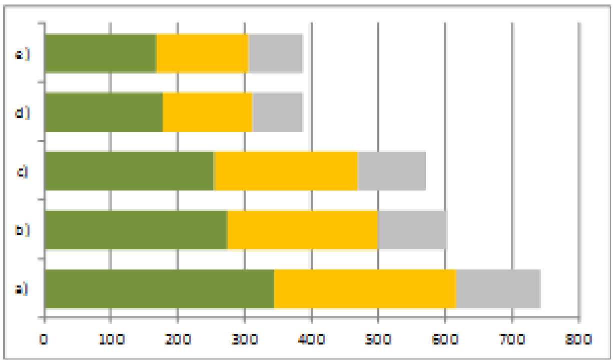
Figure 4.16 highlights the impacts of scenario induced changes of REMAIN land and the impacts of climate change on the total land extents assessed as very suitable, suitable or moderately suitable for rain-fed cultivation, for major crops contributing to the estimated biofuel potentials in sub-Saharan Africa. The bars refer to different combinations of the effect of land use changes and climate change and are labelled as:

a) Reference climate (1981-2010); REMAIN land in 2010
b) Reference climate; REMAIN land in 2050 under scenario SC 1
c) Reference climate; REMAIN land in 2050 under scenario SC 2
d) Ensemble of RCP2.6 climate; REAMIN land of SC1 in 2050
e) Ensemble of RCP6.0 climate; REAMIN land of SC1 in 2050

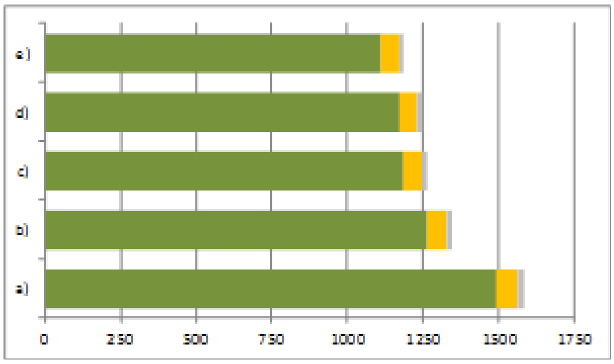
Each diagram indicates the suitable extents (i.e. the sum of prime, good and moderate land) where the GHG 1 criterion is met (shown in green), additional extents where only the GHG 2 criterion can be met (shown in orange), and the suitable extents where both GHG criteria cannot be met (shown in grey) due to carbon losses in soil and vegetation that would result from grassland or shrub land conversion to crop cultivation.

Figure 4.16. Suitable extents on REMAIN land, by scenario and compliance with GHG criteria

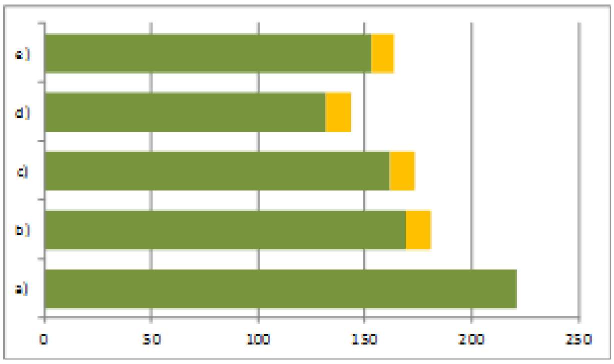
Sugarcane, suitable area (1,000 km²)



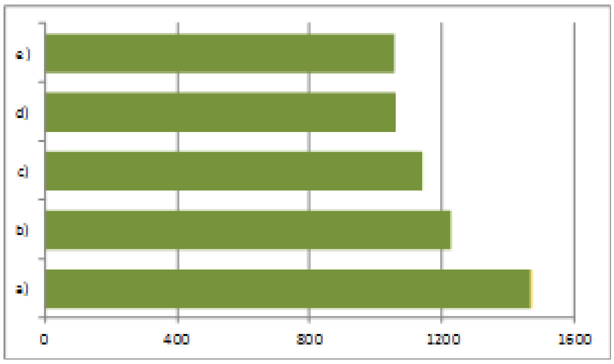
Jatropha, suitable area (1,000 km²)



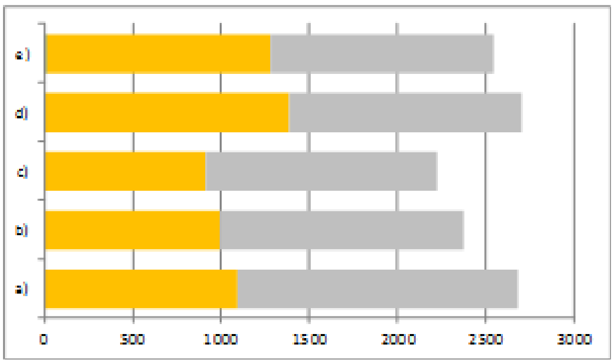
Oil palm, suitable area (1,000 km²)



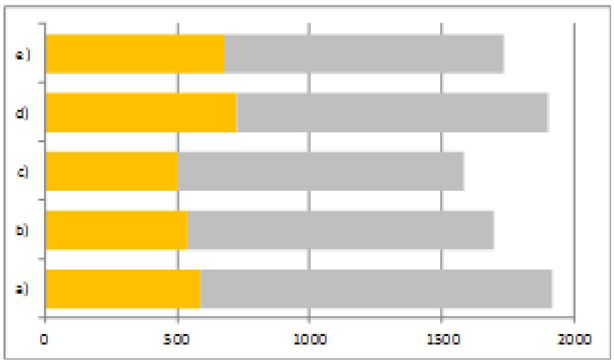
Miscanthus, suitable area (1,000 km²)



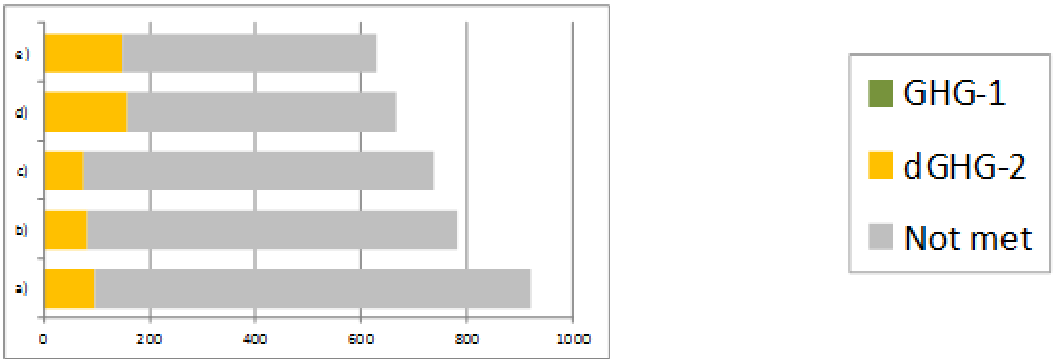
Sweet Sorghum, suitable area (1,000 km²)



Maize, suitable area (1,000 km²)



Sweet Sorghum, suitable area (1,000 km²)



Notes: Bars in diagrams refer to a) Reference climate, REMAIN land of 2010; b) Reference climate; REMAIN land of SC1 in 2050; c) Reference climate; REMAIN land of SC2 in 2050; d) ENSEMBLE of RCP2.6 climate; REMAIN land of SC1 in 2050; e) ENSEMBLE of RCP6.0 climates; REMAIN land of SC2 in 2050. Green: suitable areas meeting GHG 1 criterion; Orange: additional suitable areas meeting GHG 2 criterion; Grey: additional suitable areas not meeting GHG criteria.

For perennial feedstocks, most of the agronomically suitable areas can also meet the GHG criteria (see diagrams for jatropha, oil palm, miscanthus and sugarcane in Figure 4.16). By contrast, almost none of the annual crops can meet the GHG 1 criterion and only a part of the suitable areas of annual crops can meet the GHG 2 criterion. For all crops the suitable extents on REMAIN land are reduced in the future due to land conversions for food production foreseen in the development scenarios SC 1 and SC 2; see bars in Figure 4.16 labelled as a), b) and c). The remaining bars d) and e) show results when combining both land use change and climate change impacts under SC1 and SC2.

Table 4.12. Biofuel potential of REMAIN land compliant with GHG 1 criterion, contribution by crop

Climate	Reference (1981-2010)			Ensemble RCP2.6 (2041-2070)		Ensemble RCP6.0 (2041-2070)	
CO_2 concentration[1]	360ppm			443ppm		493ppm	
Land use	2010	SC1-2050	SC2-2050	SC1-2050	SC1-2050	SC2-2050	SC2-2050
CO_2 fertilization[2]	reference			with	without	with	without
	1	2	3	4	5	6	7
Prime and good land (Petajoules)							
Maize	0	0	0	0	0	0	0
Sorghum	0	0	0	18	14	38	25
Triticale	0	0	0	0	0	0	0
Cassava	0	0	0	0	0	0	0
Sugarcane	907	692	647	222	208	150	133
Miscanthus	3,645	2,773	2,444	1,890	1,515	1,963	1,392
Oil palm	1,294	1,081	1,030	801	649	920	659
Jatropha	17	961	909	1,001	852	906	785
Soybean	0	0	0	0	0	0	0
Camelina	0	0	0	0	0	0	0
Solaris	1	1	1	30	14	28	11
TOTAL VS+S	**7,064**	**5,508**	**5,030**	**3,962**	**3,252**	**4,003**	**3,004**

Prime, good and moderately suitable land (Petajoules)							
Maize	0	0	0	0	0	0	0
Sorghum	0	0	0	37	27	71	51
Triticale	0	0	0	0	0	0	0
Cassava	0	0	0	0	0	0	0
Sugarcane	1,394	1,141	1,082	422	416	306	289
Miscanthus	11,908	9,814	9,050	8,934	8,505	8,848	8,139
Oil palm	2,023	1,734	1,663	1,545	1,373	1,754	1,523
Jatropha	184	171	166	204	194	150	139
Soybean	0	0	0	0	0	0	0
Camelina	0	0	0	0	0	0	0
Solaris	1	1	1	28	13	30	13
TOTAL VS+S+MS	**15,510**	**12,860**	**11,962**	**11,171**	**10,528**	**11,159**	**10,154**

Source: own calculations;

Country-level and regional results is available upon request.

1 The shown CO2 concentrations refer to the midpoint of the respective climate period; e.g. 1995 is the mid-point of the period 1981-2010 and the CO2 concentration in 1995 was 360 ppm. (The concentration in 2010 was 409 ppm).

2 "Without" CO2 fertilization refers to assuming crop photosynthesis as under reference conditions of 360 ppm.

Here perennial crops experience additional reductions due to changing climate, whereas the results are more varied for annual crops due to more flexibility and many existing adaptation options.

While REMAIN land is reduced in scenario SC 1 between 2010 and 2050 by -6% (see Table 4.11) the corresponding reduction of the GHG 1 compliant potential derived from prime, good and moderate quality land is -17% due to the fact that some better quality REMAIN land is converted to cropland for food production. Similarly, in the scenario SC 2 the reduction of REMAIN land between 2010 and 2050 is -9% whereas the associated reduction of the overall GHG 1 compliant biofuel potential is -23%.

When changes in crop suitability and attainable yields due to climate change, including the positive CO2 fertilization effects on yields, are taken into account in addition to land use changes, then the simulated combined impact in both scenarios is a reduction of the overall biofuel potential by about -28%. Note that the percentage reduction when only considering prime and good land is even more severe, about -43%, as some of this land is shifted to the moderate class due to climate change impacts.

Table 4.13. Biofuel potential on REMAIN land compliant with GHG 2 criterion, contribution by crop

Climate	Reference			Ensemble RCP2.6		Ensemble RCP6.0	
CO2 concentration	360ppm	360ppm	360ppm	443ppm	360ppm	493ppm	360ppm
Land use	2010	SC1-2050	SC2-2050	SC1-2050	SC1-2050	SC2-2050	SC2-2050
CO2 fertilization	reference			with	without	with	without
	1	2	3	4	5	6	7
Prime and good land (Petajoules)							
Maize	132	121	112	108	95	74	83
Sorghum	6,288	5,572	5,081	7,602	6,999	6,984	6,120
Triticale	1	1	1	0	0	0	0
Cassava	153	130	126	104	55	113	49
Sugarcane	1,810	1,342	1,268	399	369	286	252
Miscanthus	2,546	1,966	1,713	1,358	1,101	1,508	1,086
Oil palm	1,244	1,047	997	791	640	910	653
Jatropha	1,076	848	803	879	740	787	685
Soybean	28	27	24	0	0	4	2
Camelina	0	0	0	0	0	0	0
Solaris	28	24	23	116	108	45	42
TOTAL VS+S	**13,305**	**11,076**	**10,146**	**11,358**	**10,108**	**10,709**	**8,972**
Prime, good and moderately suitable land (Petajoules)							
Maize	108	100	93	80	61	48	45
Sorghum	8,456	7,633	7,040	10,743	10,094	9,923	9,004
Triticale	1	1	1	0	0	0	0
Cassava	194	169	163	122	76	132	65
Sugarcane	2,705	2,189	2,099	730	727	551	538
Miscanthus	8,282	6,827	6,294	6,266	6,065	6,427	6,027
Oil palm	1,911	1,644	1,577	1,486	1,312	1,721	1,479
Jatropha	186	174	169	207	196	154	142
Soybean	30	29	27	1	1	1	0
Camelina	0	0	0	0	0	0	0
Solaris	27	24	23	76	68	35	32
TOTAL VS+S+MS	**21,901**	**18,790**	**17,485**	**19,711**	**18,600**	**18,991**	**17,331**

Source: own calculations;
Country-level and regional results is available upon request.

When applying the GHG 2 criterion instead of GHG 1 in the selection of feedstocks at grid-cell level, which allows more flexibility to adapt to local conditions due to a wider base for crop selection than GHG 1, the resulting changes in biofuel potential of prime and good land between 2010 and 2050 are somewhat less pronounced (Table 4.13).

The simulated reductions are between -15% to -33% depending on the scenario considered. By 2050 some 8,972 PJ (scenario SC 2, without CO2 fertilization) to 11,358 PJ (scenario SC 1, with CO2 fertilization) from feedstocks cultivated on prime and good REMAIN land can meet the GHG 2 criterion, compared to 13,305 PJ in 2010. If the potential from REMAIN land of moderate suitability is included, the overall potentials in 2050 range between 17,331 PJ (scenario SC 2, without CO2 fertilization) to 19,711 PJ (scenario SC 1, with CO2 fertilization), down from 21,901 PJ estimated for REMAIN land under conditions in 2010, i.e. reductions in the range of -21% to -10%.

It is interesting to note that the specific pattern of projected climate changes combined with the CO2 fertilization effect can trigger net overall yield increases for some crops, resulting in slightly higher potentials under the GHG 2 criterion and future climate compared to reference climate conditions. This can be seen, for instance, when comparing results for SC1-2050 land use in column 2 (without climate change) and column 4 (with climate change) of Table 4.13, or columns 3 and 6 for SC2-2050 land. When the CO2 fertilization effect is not taken into account the overall impact of climate change is a reduction of the GHG 2 criterion compliant potentials on prime and good land in the order of -9% to -12% compared to the simulations using the historical reference climate.

Table 4.14 summarizes by region the various scenario results of GHG 1 compliant biofuel potentials respectively from prime and good REMAIN land and for prime, good and moderately suitable REMAIN land. As a starting point in 2010, the countries of the Central and Eastern Africa regions contribute more than two thirds of the assessed biofuel potential on REMAIN land; this holds for the potential on prime and good land (VS+S) as well as for prime, good and moderate land (VS+S+MS). About one-sixth (around 17%) of the GHG 1 potential can be produced in the Gulf of Guinea region, less than 10% in the Southern Africa region. The Sudano-Sahelian region contributes the least (about 5%-7%) to the SSA total.

Table 4.14. Biofuel potentials of REMAIN land compliant with the GHG 1 criterion, by region

Climate	Reference			Ensemble RCP2.6		Ensemble RCP6.0	
CO2 concentration	360ppm	360ppm	360ppm	443ppm	360ppm	493ppm	360ppm
Land use	2010	SC1-2050	SC2-2050	SC1-2050	SC1-2050	SC2-2050	SC2-2050
CO2 fertilization	reference			with	without	with	without
	1	2	3	4	5	6	7
Prime and good land (Petajoules)							
Eastern Africa	1,564	1,086	914	872	769	810	668
Central Africa	3,342	2,637	2,571	2,099	1,748	2,236	1,704
Southern Africa	617	540	504	329	261	400	297
Sudano-Sahelian	353	336	313	262	198	273	185
Gulf of Guinea	1,188	909	727	400	276	285	150
TOTAL VS+S	**7,064**	**5,508**	**5,030**	**3,962**	**3,252**	**4,003**	**3,004**
Prime, good and moderately suitable land (Petajoules)							
Eastern Africa	3,003	2,283	1,977	1,988	1,883	1,843	1,691
Central Africa	7,499	6,347	6,230	5,513	5,167	5,907	5,339
Southern Africa	1,297	1,169	1,099	922	864	1,010	911
Sudano-Sahelian	1,115	1,071	1,003	1,018	960	961	875
Gulf of Guinea	2,596	1,990	1,653	1,731	1,654	1,439	1,339
TOTAL VS+S+MS	**15,510**	**12,860**	**11,962**	**11,171**	**10,528**	**11,159**	**10,154**

Source: own calculations

In terms of scenario induced reductions of GHG 1 compliant prime, good and moderate REMAIN land, the regional biofuel potentials are most affected in Eastern Africa and Gulf of Guinea regions, in the order of -25% (scenario SC 1) to -35% (scenario SC 2), followed by Central Africa region (-15% to -17%), the Southern Africa region (-10% to -15%) and the Sudano-Sahelian region (-4% to -10%).

In addition, climate change has a negative impact on GHG 1 compliant biofuel potentials in all regions. Climate change impacts on regional GHG 1 potentials vary somewhat across regions and depend on assumptions regarding CO2 fertilization, but are negative in all regions and in most cases will cause a further reduction of overall biofuel potentials from prime, good and moderate REMAIN land falling in a range of -7% to -18%.

We now turn to the regional biofuel potentials that can be achieved when applying the GHG 2 criterion for soil carbon recuperation requirements instead of the GHG 1 criterion which due to soil carbon losses rules out annual crops on almost all REMAIN land. As annual crops can now be selected in certain environments, especially where rain-fed perennial crops cannot be cultivated or are only moderately suitable, e.g. due to moisture deficits during part of the year, this increases the achievable potentials and particularly so in drier regions like Southern Africa and the Sudano-Sahelian region. A summary of GHG 2 compliant scenario results by region is given in Table 4.15.

When applying the GHG 2 criterion to REMAIN land in 2010, the countries of Central and Eastern Africa regions would contribute more than half of the assessed biofuel potential. About 30% of the GHG 2 compliant potential, much more than under the GHG 1 criterion conditions, could be produced in the Southern Africa and Sudano-Sahelian region. The Gulf-of-Guinea region would contribute the least (about 12%) to the SSA total potential compliant with the GHG 2 criterion. While the loss of REMAIN land due to socio-economic development in both scenarios results in a significant loss of biofuel production potential, the use of annual crops in the feedstock mix facilitates adaptation and helps to mitigate negative impacts of climate change.

Table 4.15. Biofuel potentials on REMAIN land compliant with the GHG 2 criterion, by region

Climate	Reference			Ensemble RCP2.6		Ensemble RCP6.0	
CO2 concentration	360ppm	360ppm	360ppm	443ppm	360ppm	493ppm	360ppm
Land use	2010	SC1-2050	SC2-2050	SC1-2050	SC1-2050	SC2-2050	SC2-2050
CO2 fertilization	reference			with	without	with	without
	1	2	3	4	5	6	7
Prime and good land (Petajoules)							
Eastern Africa	3,189	2,488	2,184	2,848	2,622	2,621	2,307
Central Africa	4,312	3,513	3,429	3,002	2,572	3,109	2,482
Southern Africa	1,855	1,690	1,582	2,055	1,865	1,913	1,647
Sudano-Sahelian	2,439	2,269	2,051	2,706	2,468	2,484	2,145
Gulf of Guinea	1,510	1,116	901	746	581	582	391
TOTAL VS+S	**13,305**	**11,076**	**10,146**	**11,358**	**10,108**	**10,709**	**8,972**
Prime, good and moderately suitable land (Petajoules)							
Eastern Africa	4,316	3,451	3,058	3,875	3,674	3,559	3,273
Central Africa	8,362	7,183	7,055	6,386	6,008	6,765	6,141
Southern Africa	3,103	2,886	2,731	3,440	3,250	3,373	3,097
Sudano-Sahelian	3,444	3,248	2,962	4,215	3,957	3,789	3,426
Gulf of Guinea	2,677	2,021	1,680	1,796	1,712	1,505	1,395
TOTAL VS+S+MS	**21,901**	**18,790**	**17,485**	**19,711**	**18,600**	**18,991**	**17,331**

Source: own calculations

In summary, the biofuels potential of the REMAIN land in 2010 will likely be significantly reduced, in the order of -15% to -30% (depending on development path, applicable GHG criterion and the suitability classes considered) due to land conversion for food production needed in response to future demographic changes and improved diets due to the expected economic development process and income growth between 2010 to 2050. Beyond the impacts of socio-economic drivers, the land suitability and yield impacts of climate change will further reduce potential biofuel production, especially when only based on perennial crops due to imposing the strict GHG 1 criterion for soil carbon recuperation. Under the alternative and somewhat less strict GHG 2 criterion, the achievable potential from prime and good REMAIN land nearly doubles compared to GHG 1 conditions. More important, allowing annual crops to participate in feedstock selection would result in more flexibility to use available resources with a wider base and better adaptation options to respond to climate change.

4.4 Crop residues from food production

Agricultural residues such as straw, stalks, stover[29], husks and shells are generated as by-products of crop cultivation. Crop residues of some crops can be used as ligno-cellulosic feedstock for second-generation biofuel production pathways. At the same time crop residues, especially straw, have alternative uses such as animal feeding and bedding and in part need to be returned to the fields as they provide important ecosystem services essential for the maintenance of soil fertility and for erosion protection.

Factors that determine the quantity of crop residues produced include the crop type and yield (see 3.6) and related factors of crop residues to crop main produce. The GAEZ database includes year 2010 actual crop production data based on FAOSTAT harvested area and crop production statistics (average of 2009-2011), which were spatially attributed ('downscaled') to year 2010 cropland areas. Resulting actual crop yields together with crop specific residue-to-produce (RPR) factors were used for the estimation of the crop residues supply from the production of cereals, oil crops and sugarcane in 2010 (Table 4.16).

An estimated 235 million tons DW of crop residues (stalks and straw) were generated in 2009-11 as by-products from growing cereals on about 940 thousand km2. More than one third of this potential is from maize production (37%), followed by sorghum (24%), millet (17%), and rice (14%). Major oil crops and cotton generate another 41 million tons DW of crop residues from growing on about 180 thousand km2. Nearly half of the oil crop residues originate from groundnut production. Sugarcane harvesting (on 13 thousand km2) produces in addition to sugar also some 4.3 million tons DW biomass from tops and leaves (currently mostly being burnt at harvest) and 7.5 million tons DW as bagasse, the pulpy residues left after extraction of the juice from sugarcane stalks. Bagasse is often used as primary fuel source in sugar mills.

Table 4.16. Crop residues from cereals, oil crops and sugarcane production, SSA, 2010

1000 tons DW	Eastern Africa	Central Africa	Southern Africa	Sudano Sahelian	Gulf of Guinea	SSA Total
CEREALS						
Wheat	4,914	0	2,511	721	0	8,146
Rice	11,333	906	684	4,611	14,895	32,428
Maize	25,326	6,750	29,929	5,078	21,046	88,129
Sorghum	11,618	2,765	1,974	22,409	17,566	56,332
Millet	3,217	502	717	23,661	12,302	40,399
Barley	3,375	0	439	135	0	3,949
Other Cereals	4,431	3	88	669	500	5,691
Total, cereals	64,213	10,926	36,341	57,285	66,308	235,073

29 Stover is the field residues (stalks and leaves) of large cereals such as maize and sorghum.

OIL CROPS						
Soybean	615	96	1,730	50	1,195	3,686
Groundnut	1,563	2,126	1,333	5,736	7,549	18,306
Rapeseed	112	0	134	0	0	246
Sunflower	1,966	31	1,960	370	0	4,328
Cotton	1,942	962	2,485	4,644	4,106	14,139
Total, oil crops	6,199	3,215	7,641	10,800	12,850	40,705
SUGARCANE						
Bagasse	2,336	484	3,356	931	381	7,489
Tops+Leaves	1,343	278	1,930	535	219	4,306
Total, sugarcane	3,679	763	5,286	1,467	601	11,795
TOTAL	**74,091**	**14,904**	**49,268**	**69,552**	**79,759**	**287,573**

Source: own calculations based on FAO reported harvested areas and average annual production of 2009-2011

As a rule, it is recommended that 2 tons of crop residues per hectare should remain on the field as cover to reduce soil loss risks (Andrews, 2006, Batidzirai et al., 2016, Papendick and Moldenhauer, 1995) and to maintain soil fertility. When adopting this rule, the current relatively low levels of achieved crop and residue yields in large parts of SSA significantly reduce the potential availability of crop residues for alternative uses including biofuel production. Allowing 2 tons of residues per hectare to remain on the field, results in a current usable crop residue potential of 75.7 million tons DW from cereals, 11.8 million tons DW from oil crops and 9.6 million tons DW from sugarcane (Table 4.17).

Accordingly, about two thirds or 190 million tons DW of SSA's total production of crop residues in 2010 are required for soil protection, leaving one third or 97 million tons DW potentially available for other uses. The highest potential crop residue removal rate is found in the Southern Africa region for cereals due to relatively high crop and residue yields. Up to 45 % of total crop residues from cereals could potentially be available for other uses when 2 tons/ha remain in the fields for soil fertility management.

Collection of available crop residues from food production will need substantial investments in logistics, transportation and storage and requires a sufficient spatial density of available residues for economic feasibility of the supply chain. In this regard, the map in Figure 4.17 highlights the spatial distribution of crop residues (stalks, straw, sugarcane bagasse, tops & leaves) from cereals, oil crops, cotton and sugarcane in 2010. The map shows net amounts of crop residues (1000 tons DW) available in each 5 arc-minute grid cell after allowing 2 tons/ha to remain in the fields for soil protection.

Table 4.17. Crop residues from cereals, oil crops and sugarcane production in 2010, allowing 2 tons/ha to remain on fields

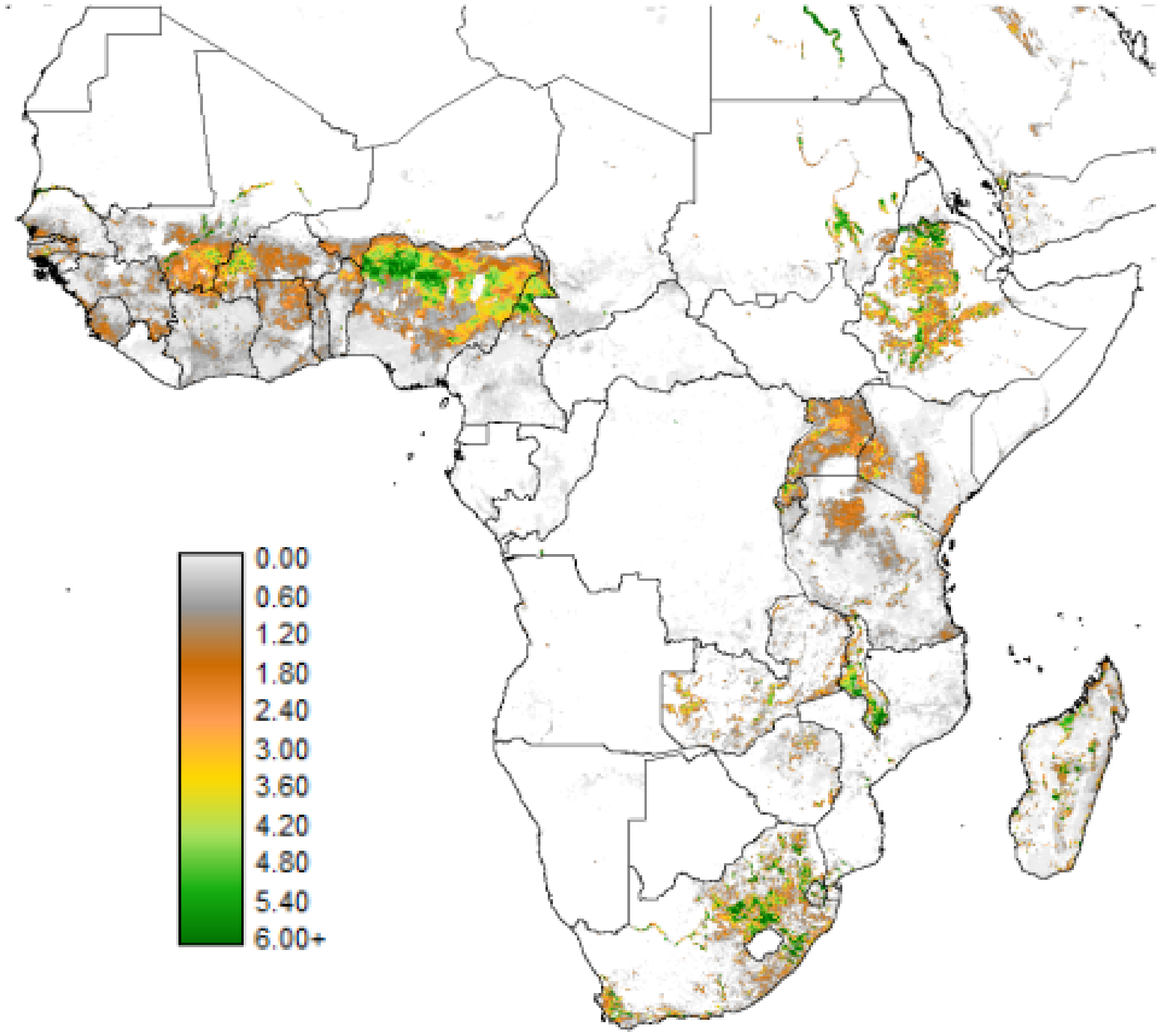
1000 tons DW	Eastern Africa	Central Africa	Southern Africa	Sudano Sahelian	Gulf of Guinea	SSA
CEREALS						
Wheat	1,357	0	1,205	177	0	2,739
Rice	5,845	107	171	2,423	5,849	14,395
Maize	8,684	1,116	14,330	1,603	6,588	32,320
Sorghum	5,104	1,208	257	2,772	6,889	16,230
Millet	1,186	122	52	2,713	4,071	8,143
Barley	1,287	0	260	39	0	1,587

Other Cereals	274	0	1	35	0	310
Total cereals	23,736	2,553	16,275	9,762	23,397	75,724
OIL CROPS						
Soybean	183	7	710	17	202	1,117
Groundnut	41	172	40	175	1,357	1,784
Rapeseed	55	0	54	0	0	109
Sunflower	487	3	677	90	0	1,257
Cotton	724	546	1,089	2,713	2,482	7,554
Total oilseeds	1,489	727	2,570	2,995	4,040	11,822
SUGARCANE						
Bagasse	2,336	484	3,356	931	381	7,489
Tops+Leaves	688	45	1,013	340	63	2,149
Total sugarcane	3,024	529	4,369	1,271	444	9,638
TOTAL	28,249	3,809	23,215	14,028	27,882	97,183

Additionally, crop residues are also a major feed source in large parts of SSA, especially in a context where the availability of natural grazing decreases and livestock numbers grow. Crop residues are widely used as lean-season feed, especially in small-scale production systems where grain stovers are sometimes grazed. While grazing of stover is sometimes considered wasteful, this practice can save on labour input and helps to return nutrients to the fields (Suttie, 2000).

Although we acknowledge large uncertainties in the magnitude of the available crop residue potential for biofuel production, up to 480 PJ biofuel equivalent could be produced from the estimated 76 million tons DW of cereal crop residues not required for soil fertility management (Table 4.17).

Figure 4.17. Spatial distribution of crop residues from current cropland, in 2010



Note: The map shows net amounts of straw, stalks, tops and leaves (in 1000 tons DM per 5 arc-minute pixel) available from the production of major crops in 2010 (cereals, oil crops, cotton, sugarcane) and when allowing 2 tons of residues per hectare to stay on the field for soil protection and fertility maintenance.

The estimated biofuel potential from prime and good REMAIN land compliant with the GHG 1 criterion amounts to 7,064 PJ (Table 4.18). Therefore cereal crop residues would add around 7% to these potentials from REMAIN land, and around 9% if all crop residues listed in Table 4.17 were used for biofuel production.

Table 4.18. Comparing biofuel potentials of REMAIN land and of available crop residues in 2010

REGION	Biofuel potential of prime and good REMAIN land (PJ fuel equivalent)		Biofuel potential of available crop residues (PJ fuel equivalent)	
	GHG 1 compliant	GHG 2 compliant	Cereals	All crops
Eastern Africa	1,564	3,189	151	179
Central Africa	3,342	4,312	16	24
Southern Africa	617	1,855	103	147
Sudano-Sahelian	353	2,439	62	89
Gulf of Guinea	1,188	1,510	149	177
SSA Total	**7,064**	**13,305**	**481**	**617**

Note: Amounts of available crop residues listed in Table 4.17 were converted to biofuel equivalent assuming that 300 litres of fuel can be produced per ton DW at 21.17 MJ per litre.

By comparison, miscanthus, the feedstock type considered in this study for ligno-cellulosic second-generation biofuel production, would produce significantly larger amounts of biomass when cultivated on REMAIN land. If some 388 thousand km2 REMAIN land, assessed to be of prime and good quality for miscanthus cultivation (see Table 4.5), would be fully utilized for biofuels then estimated 738 million tons DW ligno-cellulosic feedstock could be harvested. At 300 litres per ton DW, this potential amounts to 4782 PJ or about 10 times the potential from available cereal residues.

Despite the relatively moderate additional biofuel potential from crop residues in SSA compared to the potential from REMAIN land, in some regions crop residues could provide a significant contribution. Important regions where the utilization of available crop residues from the food sector could contribute substantially for biofuel production, compared to the potential from REMAIN land, include countries in Southern Africa (South Africa, Malawi, Zambia), Sudano-Sahelian Africa (Mali, Burkina Faso), Gulf of Guinea (Nigeria) and Eastern Africa (Ethiopia). For example, the potentials of prime and good quality REMAIN land (year 2010) in South Africa and Malawi amount to 73 PJ and 8 PJ compared to available cereal crop residue potential in 2010 of respectively 70 PJ and 16 PJ.

Unlike REMAIN land, where the potential will be decreasing toward the 2050s because of the expanding food sector (see discussion in 3.7.3) and climate change, the amount of crop residues potentially available from future food production will be increasing. Even though the amount of crop residues per unit of grain production will become somewhat less due to the fact that intensification will lower the crop-residue RPR factor, future volumes of crop residue supply will nevertheless increase significantly. As a result, in several SSA countries the future biofuel potential of crop residues available from food production may exceed the future GHG 1 compliant potentials from REMAIN land.

4.5 Supply chain considerations

Various economic opportunities and challenges exist along biofuel supply chains. Among the social benefits considered in biofuel production is the generation of new jobs. Employment is generated at the stage of agricultural production, the industrial processing stage, and for transport and distribution of the raw materials and final fuel products from ‘field to fuel use’. The objective in this study is to provide an estimate of potential agricultural job creation.

4.5.1 Potential agricultural job creation

Increased biofuel production is considered a great opportunity for job creation in rural areas, especially in less developed regions with a large share of the population employed in the agricultural sector and with the comparative advantage of a relatively cheap, abundant labour force. Generation of income and employment from biofuel feedstock cultivation will require stable economic conditions and the number and kind of jobs created will depend on crop type and applied management scheme. Activities involve field preparation, planting, fertilizing, management of pests, diseases and weeds and harvesting. A crucial factor for labour intensity is whether the harvest is manual or mechanical using harvest machines. Full mechanization of feedstock cultivation can reduce labour inputs substantially and therefore is a critical consideration with regard to employment generation.

For most annual biofuel feedstocks (maize, soybean, sweet sorghum, triticale, camelina), where mechanization can provide large efficiency improvements and production cost advantages, farm activities are assumed to be fully mechanized. The exception is Solaris tobacco where seeds are usually harvested using manual labour. Some perennial crops (oil palm, jatropha, cassava) involve substantial labour inputs especially for manual harvesting. Miscanthus, a perennial grass, is assumed to be fully mechanized including field preparation/planting (once per rotation period of 15 to 20 years) and annual harvesting.

Sugarcane production traditionally uses manual labour. It usually involves burning the spiky leaves of the sugarcane crop, to reduce the risk of injuries during harvest and allow a faster cane collection process after burning. However, burning fields before harvest causes significant amounts of GHG emissions, impedes air quality and is affecting human health. Therefore mechanization and green harvesting are increasingly promoted as a beneficial an environmentally more benign harvest practice. It eliminates harmful emissions from smoke and increases the utilization of biomass in terms of energy generation when the green tops are collected and used for electricity cogeneration.

Although the poor working conditions of the sugarcane cutters are well known and widely acknowledged, cane cutting provides an important source of income for workers lacking formal education or qualification (Kaup, 2015). While in principle manual cutting would be a possibility for green harvesting of sugarcane, there are additional risks of injury to workers harvesting “green”, when cutting off the sugarcane tops, and also a significant slow-down in the collection process. This usually necessitates the adoption of a mechanized process for green harvesting. For example, in Brazil’s sugar and ethanol industries, adopting mechanized green-cane harvesting was an important factor for increasing the eco-efficiency of ethanol production. It required up-front capital investment in harvesters and high pressure boilers and resulted in reduced labour requirements. Adopting mechanisation improved the energy balance, increased production income and reduced environmental damages (ELLA, 2012).

For commercial biofuel feedstock production we assume advanced management regimes including, to the extent possible, mechanization. For South Africa, where advanced agricultural production schemes predominate, cereals (e.g. maize, wheat) and oil crops (soybean, canola) are classified as non-labour intensive crops with a labour requirement of 0.01 person per hectare per year. In contrast, sugarcane, tobacco, cotton, various fruit trees and vegetables are labour-intensive with labour requirements of 1 person per hectare (e.g. sugarcane) up to 3.5 (tomatoes) persons per hectare (Meyer et al., 2011). As South Africa’s sugarcane is currently predominantly harvested manually with about 85%-90% of the sugarcane being burnt at harvest (Meyer, 2005), the stated 1 person/ha labour requirement apparently reflects traditional manual sugarcane harvesting and would be much reduced by mechanization.

As discussed, the labour requirements for green-cane harvesting differ considerably depending on whether machines or manual labour[30] are used for cutting and collecting the cane. There are various estimates for the number of workers that are prone to losing their employment in the sugarcane complex due to the increase in mechanization. It is estimated that one harvester can substitute 80 to 100 workers (Kaup, 2015). The shift to mechanization for sugarcane production in Brazil has definitely resulted in fewer jobs, reducing the number of employed workers by 54 % (ELLA, 2012, Guilhoto et al., 2004).

30 See also http://www.sasta.co.za/wp-content/uploads/2017/Drought%20Kevin%20Drew.pdf

For jatropha plantations, the collection and dehulling of seeds is usually manual and varies from case to case, requiring repeated visits as fruits do not reach maturity at the same time. Nevertheless, in general terms it can be said that four hectares in full season (three months) will require one to two workers per day for harvest (Rosillo-Calle and Johnson, 2010). For year-round employment this translates into 0.08 to 0.15 persons per hectare. Other sources (Nielsen and de Jongh, 2009, FACT, 2009) suggest that a worker can harvest 40-60 kg of seeds per day. Assuming a good yield of 2500 kg seeds per hectare this would require about 40-60 person days of harvesting time, or on an annual basis about 0.14-0.20 persons per hectare. Subsequent dehulling of seeds approximately doubles the labour requirements. Furthermore, establishment of jatropha plantations requires substantial additional labour inputs in the first two years. As a reference value we use an employment coefficient of 0.4 persons per hectare of prime and good quality land for jatropha seed harvesting and dehulling.

Estimates of the intensity of employment in palm oil cultivation vary widely from 1 person required for every 2 to 3.5 hectares (Rutz and Janssen, 2014). These figures translate into a labour input of 0.3 to 0.5 persons per hectare. Studies in Malaysia estimate a labour to land ratio of nearly 1:10 for Malaysian oil palm production in 2010, i.e. a comparatively low requirement coefficient of 0.1 persons per hectare. An economic assessment of palm oil production in Indonesia by World Agroforestry Centre states labour requirements during the operational phase of palm oil plantations in the range of 50 to 90 person-days per hectare per year. Annual labour requirements during the plantation establishment period (5-12 years) were in the order of 100 to 200 person-days per hectare. This translates into average labour requirement coefficients of some 0.30-0.40 person-years per hectare, similar to the estimates given by Rutz and Janssen.

Table 4.19 summarizes labour requirement coefficient for each biofuel feedstock adopted in this study. We apply these labour requirement factors to the estimated biofuel potential of rain-fed REMAIN land in 2010, as presented in section 4.2, to estimate the jobs potentially generated in agriculture. When only agronomically very suitable and suitable land (VS+S) is considered in the allocation of land to feedstock cultivation, jatropha is chosen in 46% (under the GHG 1 criterion) to 23% (under the GHG 2 criterion) of the total allocated and compliant REMAIN land. Since mechanization is not assumed for jatropha this would result in 20.3 to 21.6 million jobs of which three quarter to two-thirds would be required for jatropha cultivation and harvesting. Alternatively, when crop selection is based on energy production on agronomically very suitable, suitable and moderately suitable land then miscanthus, having a somewhat lower agronomic suitability but giving a higher fuel energy yield, replaces jatropha in many locations and labour requirements decrease due to mechanization to 11.3 to 15.3 million jobs with sugarcane and oil palm dominating the labour demand. The estimates show that job creation is quite uncertain and highly depends on the chosen mix of feedstock crops, which in turn depends on agronomic and GHG selection criteria used.

Table 4.19. Labour input requirements for biofuel feedstock cultivation

Biofuel feedstock	Labour input [Person / ha / year]	Source
Maize, Soybean	0.01 (mechanized)	Greyling et al (2010)
Sweet sorghum, Triticale, Miscanthus	0.01 (mechanized)	own estimate (same as cereals)
Cassava	0.25 (national average)	Phillippine Statistics Authority (2014)
Solaris	1.0 (manual)	Sunchem (personal communication)
Sugarcane	0.2 (mechanized)	Kaup (2015)
	1.0 (manual)	Greyling et al (2010)
Oil palm, Jatropha	0.4 (manual; good land) 0.3 (manual; moderate land)	Rutz (2014); Rosillo-Calle & Johnson (2010); GAEZ for ratio between VS+S and MS land

Table 4.20. Agricultural employment potential of biofuel feedstock production on 2010 REMAIN land

1000 person-years	Eastern Africa	Central Africa	Southern Africa	Sudano Sahelian	Gulf of Guinea	SSA Total
GHG 1						
Prime & good land	1,602	14,415	485	536	3304	20,342
Prime, good & moderate land	961	7,952	206	596	1,581	11,295
GHG 2						
Prime & good land	1,653	14,462	1,260	651	3,031	21,058
Prime, good & moderate land	1,439	10,020	1,276	912	1,684	15,331

Source: own calculations based on labour input factors in Table 4.19;
Note the estimates assume mechanized green-cane harvesting of sugarcane.

If sugarcane were harvested manually (i.e. assuming a labour input of 1 person-year per hectare) the labour input for prime and good land would increase to 25.8 million to 29.8 million jobs and for crop selection based on prime, good and moderate land to a range of 21.1 to 34.1 million jobs for feedstock potentials subject to GHG 1 and GHG 2, respectively.

4.5.2 Spatial concentration of feedstock production potentials

For biofuel production to be viable, a minimum cumulative concentration of biomass raw materials must be available around a biofuel production plant. In this context, cumulative energy production potentials were calculated for each grid-cell assuming a radius of 50 km, 100 km and 200 km for collection of biomass around a location.

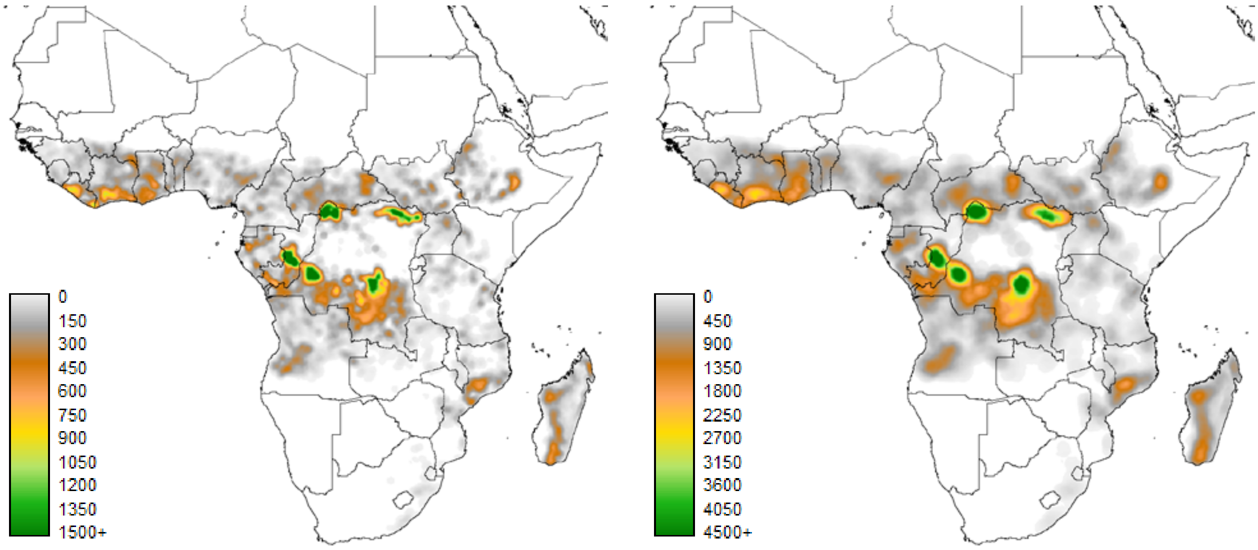
The map in Figure 4.18 shows the cumulative feedstock potential (in TJ of biofuel equivalent) from prime, good and moderate REMAIN land for vegetable oil producing feedstocks complying with GHG criterion 1 for a collection radius of 100 km. Oil palm and jatropha are the defining feedstocks in this case (see Figure 4.9). Bright spots of cumulative biofuel potentials based on vegetable oil of more than 2000 TJ occur in several locations in tropical SSA, notably in Congo DR and the Gulf of Guiana region. In these regions (green colour) the vegetable oil potential, mainly derived from oil palm cultivation, could supply biofuel plants with a capacity of more than 100 million litres[31]. Several other locations with main supplies from jatropha plantations could provide vegetable oil to biofuel plants of capacities between 31 million litres (about 1000 TJ) and 55 million litres (about 1800 TJ).

31 1 million liters (ML) biodiesel is equivalent to 32.6 TJ.

Figure 4.18. Cumulative feedstock potential of oil producing crops on rain-fed REMAIN land of 2010 in a circle of a) 50 km and b) 100 km around a location

a) Collection radius 50km

b) Collection radius 100 km



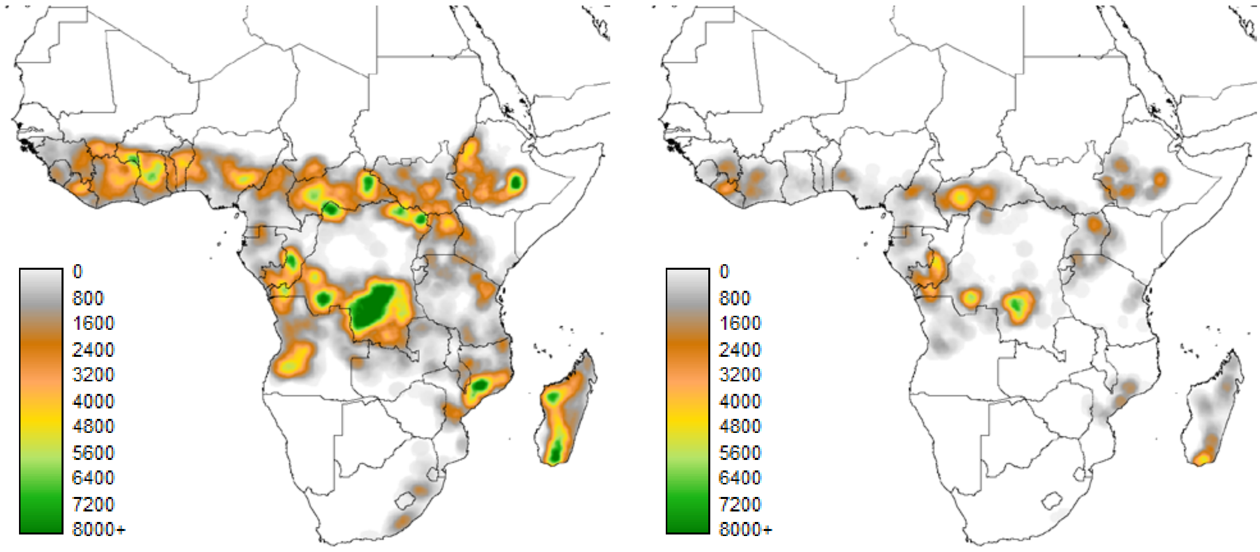
Note: The map shows for each pixel the estimated cumulative vegetable oil based biofuel potential (in TJ of biofuel equivalent) using all feedstocks subject to GHG Criterion 1 from prime, good and moderately suitable rain-fed REMAIN land in a circle of 100 km. One million litres of vegetable oil based biofuels is equivalent to 32.6 TJ (LHV).

Figure 4.19 highlights cumulative biofuel potentials concerning the sugar, starch and ligno-cellulosic biomass based conversion pathways for the production of biofuels. Assuming only feedstocks for current proven industrial scale technologies (i.e. without considering miscanthus), almost only sugarcane can meet the GHG 1 criterion for cultivation on rain-fed REMAIN land. There are four hot spots for rain-fed sugarcane based biofuel production from REMAIN land emerging in Central Africa (Southern Congo DR, Congo Republic, Central African Republic). These regions could support large biofuel industries with an annual production capacity of more than 300 million litres annually (green spots in Figure 4.19b). The southern tip of Madagascar is another region with a potential for large-scale fuel production from sugarcane.

Construction of industries with an annual biofuel capacity of up to 150 million litres, represented by the brown to yellow spots shown in the map in Figure 4.19b, could be explored in Ethiopia, Uganda, Mozambique, Cote d'Ivoire and Liberia. Considering both miscanthus and sugarcane as feedstocks for biofuel production, significantly larger regions appear as potential production hotspots (Figure 4.19a).

Figure 4.19. Cumulative biofuel feedstock potential from REMAIN land in a circle of 100 km, 2010

a) Collection radius 50km *b) Collection radius 100 km*



Note: The map shows for each pixel the estimated cumulative potential production (in TJ biofuel equivalent) using all crop biomass of (a) sugarcane and miscanthus, and (b) sugarcane only, from prime, good and moderately suitable rain-fed REMAIN land subject to GHG Criterion 1 within a circle of 100 km. One million litres sugar/starch based biofuel is equivalent to 21.6 TJ (LHV).

4.6 Sensitivity and uncertainties

Results produced in quantitative simulation studies are always subject to specific assumptions, sensitivities and uncertainties in data and parameters. In this section some factors are briefly discussed, which can have a considerable impact on the numerical results, or which we know exist but are practically impossible to include in a continental scale study. Finally, we discuss some possible limitations of the data and the applied methodology.

4.6.1 Co-product allocation

The processing of feedstocks and conversion to biofuels often produces significant amounts of useful co-products. GHG emissions caused by the production of feedstock crops, including the carbon losses due to land use changes, should thus be allocated among the jointly produced products derived from the crop, i.e. the biofuel and the various co-products.

This study applies economic allocation among co-products to partition GHG emissions from dLUC and from crop cultivation among co-products. The rationale for economic allocation is that environmental burdens of a multifunctional process should be allocated in proportion to their market value, because product demand is the main driving force for the production system and product value shares can reveal the relative importance of co-products.

The type and volume of jointly produced co-products largely depends on the feedstock used and the specific biofuel conversion pathway. Products to consider include residues from the harvest of feedstocks (straw, husks, shells, stems) and co-products generated during industrial processing of the feedstock into biofuel, including protein-rich animal feed (e.g. protein cakes from crushing oilseeds, DDGS[32] from starch based ethanol production) and various other materials of potential use in industrial processes (e.g. glycerine).

32 'Distiller dry grains with solubles' (DDGS) is the residual slurry of insoluble fiber, protein and liquid following the fermentation and separation of ethanol by distillation.

The economic viability of feedstock production and the biofuel chain depends to a large extent on the ability of the industry to derive value from the biofuels as well as from the co-products that are generated during the processing and conversion. The benefit of agro-producers (farmers) depends on the farm-gate crop price they receive, which in turn depends on the economic uses that can be made of the crop. By producing multiple and complementary products, companies can take advantage of the differences in biomass components and intermediates in order to maximize the value, energy content, and environmental benefits derived from a particular feedstock. Also, as they can be allocated a part of the GHG burden, co-products play an important role in the sustainability evaluation of particular biofuel production pathways.

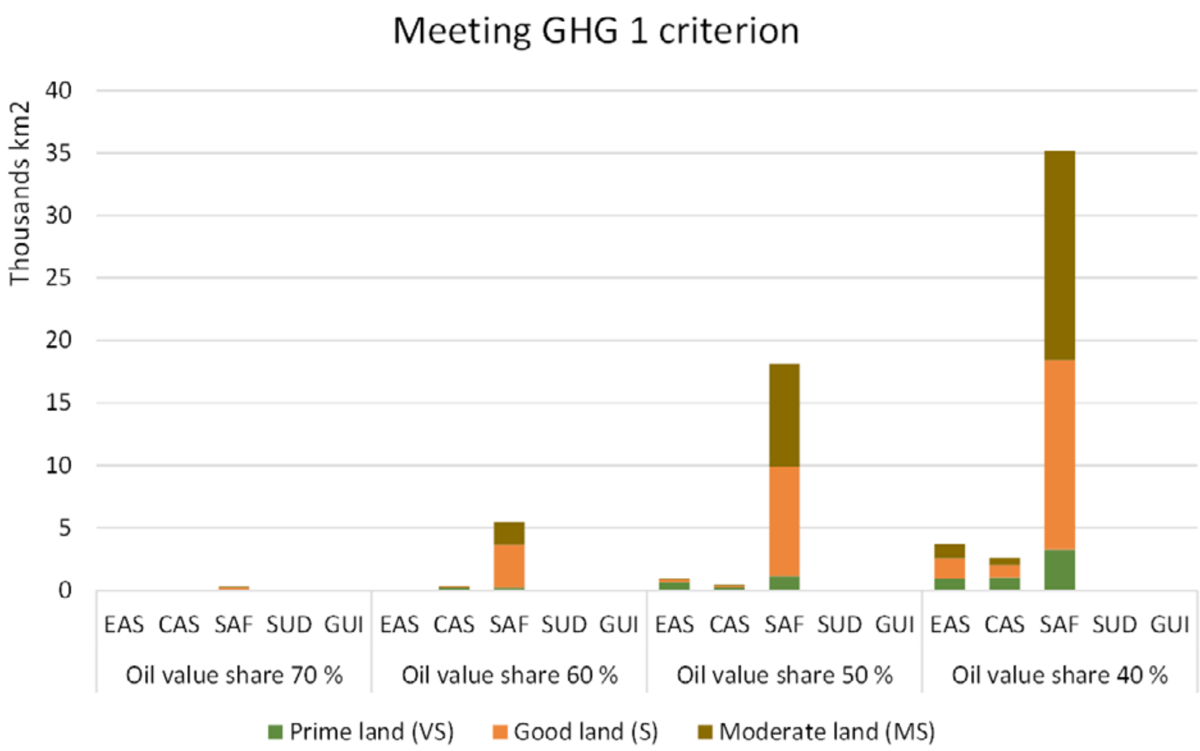
For example, the favourable sustainability rating of sugarcane results from a combination of sugarcane being a highly productive plant of which a large part can be used for ethanol production. Sugarcane stalks are crushed to produce a sucrose solution than can be fermented into ethanol. The crushed stalks, termed 'bagasse', are burned to produce heat used for the fermentation process and sometimes electricity. This enables the industry to operate without significant fossil fuel inputs, thereby achieving a high overall greenhouse gas saving of 80%–90% in comparison to fossil fuel use. Biofuel supply chain life cycle GHG emissions are sensitive to the type of process energy used, whether from renewable energy sources or using fossil fuels. This study assumes 'best practice' management documented in the literature, which leads to low life cycle carbon emissions (Table 3.4), falling mostly in the range of 20-35 gCO2eq/MJ. For example, palm oil pressing produces large amounts of palm oil mill effluent, a liquid waste that requires treatment (as it is acidic and contains residual oil) and releases large amounts of methane. Best practices assume the installation of closed anaerobic pond systems and the recovery of the methane for cogeneration of heat and power (Kurnia et al., 2016).

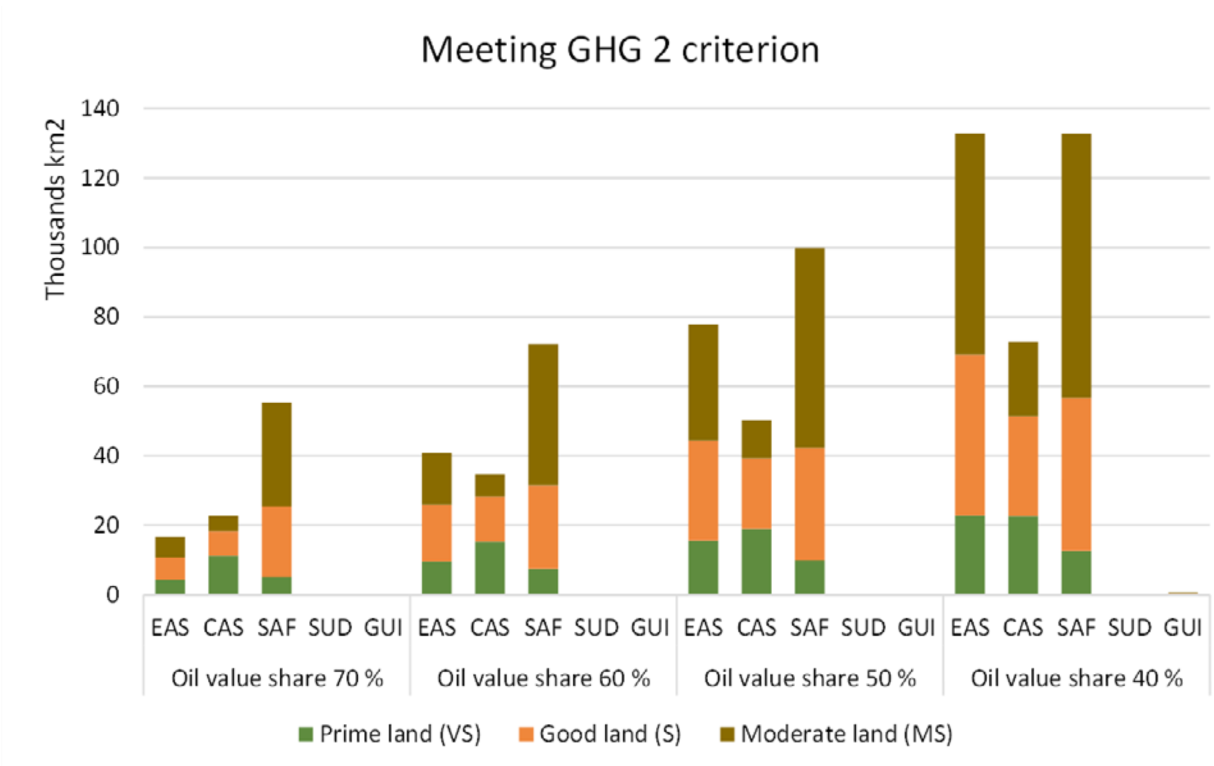
Further, we apply value shares of co-products to allocate a fair share of GHGs from direct land use changes to biofuels (see 3.5.2.4), which depends on prices and technical conversion factors that are plant specific. To highlight the importance of the chosen value shares attributed to the oil and hence to the biofuel, we present below the results of a sensitivity analysis undertaken for Solaris tobacco.

As a reference value, in the current study we allocate 70 % of the GHG burden from direct land use changes to the biofuels derived from Solaris tobacco. The other 30% of GHG emissions are attributed to the other co-products (e.g. press cake for livestock feed). Figure 4.20 highlights the impact of using different allocation shares for the biofuel component, from 70% to 40%. Obviously, the lower the share of the GHG emissions allocated to the biofuel component, the easier it is for the biofuel chain to meet a GHG criterion. Our analysis shows that allocation shares of 60 % and below are required for biofuels from Solaris tobacco to meet the strict GHG 1 criterion on any significant amount of REMAIN land.

Figure 4.20 highlights the importance of the chosen GHG emissions criterion in the evaluation and its sensitivity regarding assumptions related to co-products.

Figure 4.20. Suitability of REMAIN land for Solaris tobacco production using different value shares for allocating the GHG burden from direct land use change to the vegetable oil component, in 2010





EAS Eastern Africa; CAS Central Africa; SAF Southern Africa, SUD Sudano-Sahelian Africa; GUI Gulf of Guinea

From 920 thousand km2 REMAIN land in SSA with prime, good and moderate quality for the production of Solaris tobacco (Annex III-10), some 340 thousand km2 can meet the GHG 2 criterion when using an oil value share of 40%. These extents will gradually decrease to 95 thousand km2 with increasing the GHG allocation share from 40% to 70%. Eligible REMAIN land extents for Solaris tobacco cultivation further decrease when meeting the GHG 1 criterion is required, ranging from 41.5 thousand km2 for a 40% oil value share to 0.3 thousand km2 for a 70% oil value share.

4.6.2 Additional sustainability considerations

Beyond the sustainability evaluations and application of detailed exclusion layers used to protect the environment, biodiversity and future food security in this continental-scale study, there are additional sustainability aspects to be considered that relate to the management of biofuel feedstock production at the local scale.

Biodiversity implications of selected biofuel feedstocks

The impacts of biofuel feedstock production on biodiversity depend on feedstock specific characteristics together with typical field management practices such as scale of operation, degree of mono-cropping, tillage methods, fertilization intensity, use of agro-chemicals to combat pest and diseases, use of GMOs, invasive characteristics of feedstocks, etc. Generally, conversion of natural ecosystems (shrub land and grasslands) for agricultural use tends to induce losses of biodiversity. Land conversion for mono-cropping without compensation by means of 'habitat islands' and 'migration corridors' may have far-reaching negative impacts on ecosystem survival around the converted land. Furthermore, conversion of shrub land and grassland may lead to: (i) over-exploiting (mining) nutrients and organic matter; (ii) inducing nutrient losses due to soil erosion; and (iii) compacting top-soil layers due to use of heavy machines. Together these impacts from inadequate management practices may render converted sites unsuitable for any agricultural use in the long term, while promoting invasion of a few hardy weed types that often are highly flammable.

Beyond land conversion, feedstock cultivation practices can have various environmental implications. When grown commercially, some feedstocks are cultivated on a large scale in monocultures with intensive fertilizer applications and the use of biocides to control weeds or combat pest and diseases. GMOs may require less input per unit output but may have a devastating effect on biodiversity. The use of GMO feedstocks may genetically 'contaminate' landraces and potentially reduce the genetic adaptive capacity, for example the ability to endure specific ecological and biophysical stresses. Another example of the indirect effects of GMOs is illustrated by a soybean variety that is tolerant to herbicides, allowing the farmer to apply high doses of agro-chemicals to eradicate weeds that compete for nutrients, water, and light and to eliminate possible hosts for pests or diseases. However, this practice may also eliminate the micro and meso-level ecosystems of natural flora and fauna.

The application of organic farming methods for the production of feedstocks is considered to be of little economic promise due to lower productivity and the necessary smaller scale of production. All the feedstocks considered in this study are assumed to be grown under minimum tillage systems and best practice principles such as returning crop residues and nutrients to the field.

From the above it can be concluded that biodiversity effects of feedstock cultivation are crop specific and are closely linked to the type and intensity of management applied. Some points to remember include the following issues:

- Monocultures require the inclusion of 'habitat islands' and/or 'migration corridors' to safeguard biodiversity (example oil palm).
- Biotechnology involves risks and uncertainties regarding effects on agro-diversity. The excessive use of specific herbicides can severely impact biodiversity (example soybean). Until now, biotechnology and/or

development of GMOs involve only a few crops, mainly soybean, maize, triticale, Solaris tobacco, cotton, sweet sorghum and sugarcane. Rather limited biotechnology developments apply to jatropha (not domesticated), cassava, camelina and miscanthus.

- Annual biofuel feedstocks require regular field activities, substantial fertilization and use of agro-chemicals for controlling pests and diseases. All of these activities cause environmental impacts for soil and water bodies, which in turn may affect biodiversity.

- Toxicity of the biofuel feedstocks may impact safe handling of the produce (jatropha[33]) or its toxicity is affecting other competing crops and plants (camelina[34]) and thus pose the risk of reducing biodiversity.

- Some of the assessed feedstocks are classified as potentially invasive species with the potential to affect biodiversity well beyond the cultivated fields.

Invasive species

Non-native species that grow and reproduce rapidly may threaten agricultural systems and disrupt ecosystems. Invasive Species Regulations are increasingly introduced into national laws. For example, South Africa introduced an 'Invasive Species Regulations' act in 2014.

Jatropha (Jatropha curcas) is classified as an aggressively invasive species. Its introduction is actually banned in several countries including South Africa. Jatropha adapts easily to different environments including marginal areas, it is propagated through nuts and suckers. It can form dense stands which limit the regeneration of native plants.

Oil palm (Elaeis guineensis) has been widely introduced pan-tropically, and has seen a surge in plantation establishment due to the increased interest in biofuels. There are, however, some reports of it escaping cultivation and naturalizing, and it has been noted as invasive in a few islands in Micronesia, with unconfirmed reports of invasiveness in Bahia, Brazil, possible threatening remnant native coastal Atlantic forest. However, there are no firm records of it having significant negative environmental effects directly, other than those caused by clearing land for new plantations. Thus, while not a major invasive species, it may be prudent to survey any spread near to sensitive ecological sites.

Camelina (Camelina sativa) is classified as a high risk invasive species. It has the ability to survive in a diverse range of habitats. It is considered an agricultural weed, environmental weed, and a naturalized weed (GCW, 2007) in addition to an economic weed (API, 2008). However, Camelina sativa is primarily a minor weed in flax and not often a problem in other crops. Camelina is hermaphroditic and propagates through tiny seeds.

Miscanthus (Miscanthus x giganteus), the variety considered in this study, a hybrid of Miscanthus sinensis and Miscanthus sacchaiflorus is not listed as being invasive. Miscanthus sinensis however is classified as high risk invasive species in the global invasive species database. It reproduces primarily through rhizomes, but it also produces seeds which are mainly dispersed by wind (USDA Forest Service, 2006). A full risk assessment for potential invasiveness in the sub-Saharan African ecosystems still needs to be carried out before the crop can be introduced to the region.

33 Jatropha's seeds are toxic to humans and animals.
34 Camelina is an allelopathic crop affecting other crops and plants.

4.6.3 Limitations

This study uses best available data for identifying suitable areas for biofuel feedstock production in excess of land required for food production and for environmental conservation and safeguarding of key biodiversity areas. Land excluded for food production considers projected future food requirements. Forests are generally excluded. A limitation of the analysis may be due to areas not included in the 'environment exclusion map'. Although 40% or 9.8 million km2 have been set-aside for the environment across sub-Saharan Africa (see Table 4.3), including 30% of current grass- and shrub land (2.8 million km2), this study may nevertheless have missed some areas of importance for biodiversity and environmental conservation that have not yet been properly recorded in global databases.

For example, in Madagascar some 80% of grass- and shrub land are not included in any of the data sources used in this study for defining exclusion areas of high value for the environment. At the same time Madagascar is renowned for its high biodiversity and high degree of endemism (Ganzhorn et al., 2001). This discrepancy may indicate data gaps in recording or legally protecting some ecologically important and sensitive areas. Another region of concern for potentially limited data available to safeguard environmental values may be Central Africa. As much as three fourth of grass- and shrub land in this region have been classified as REMAIN land, a higher share than the average of 59 % for the entire Sub-Saharan region. In Congo DR, REMAIN land amounts to 79% (0.5 million km2) of total grass/shrub land. This is well below the standards in other countries and regions.

The scenario approach used in this study to estimate future food demand and related cropland use relies on two (out of five) shared socio-economic development pathways created in the context of the IPCC AR5 assessment process. While the two chosen development scenarios were jointly elaborated and are widely used by an international research community, they cannot cover all conceivable and possible trajectories of future food demand and associated cropland requirements.

Finally, a limitation worth noting is the lack of continental scale reliable spatial data on the occurrence and severity of degraded land. Biofuel feedstock production on degraded land could significantly increase the possibility, especially of annual crops, to meet the required GHG emissions saving criteria, which are often prohibitive due to the soil and vegetation carbon losses that would be encountered in the conversion of REMAIN land. Under conditions of land degradation before conversion of REMAIN land, the cultivation of biofuel feedstocks may actually increase the amount of carbon stored in soils, which would allow annual crops to meet the GHG 1 criterion. Positive effects on biodiversity have been noted in degraded or marginal areas where new perennial mixed species have been introduced to restore ecosystem functioning and increase biodiversity (Tilman et al., 2006). Lacking adequate spatial information on land degradation, this factor could not be taken into account in the assessment of biofuel feedstock potentials. Appropriate cultivation measures of e.g. jatropha or miscanthus could enhance the quality of degraded soil and the vegetation structure, and therefore habitat quality could be enhanced. However, a major gap and obstacle in this regards is the lack of an agreed definition, classification or quantification of "degraded" lands (and similar terminology) and further research and analysis involving LCAs of all relevant options is required (Webb and Coates, 2012).

5 CONCLUSIONS

This study presents an assessment of sub-Saharan Africa's (SSA) biofuel production potentials in accordance with defined sustainability criteria. The guiding assumptions for setting sustainability criteria are the principles of the Roundtable on Sustainable Biomaterials (RSB). Once food security and environmental sustainability criteria have been accounted for, the balance of remaining land has been explored for its suitability and capacity to produce a variety of biofuel feedstocks.

Large investments are urgently required in sub-Saharan Africa's (SSA) economies to foster GDP growth, boost employment opportunities, generate income and reduce malnutrition and hunger, which is currently again on the rise in SSA. A widely discussed option is to channel investments to the agricultural sector, employing currently about 70 percent of the SSA labour force. Sustainable production of highly demanded biofuels for the global aviation industry is seen as one possible option for tapping into SSA's underutilized agricultural land potential.

The overall results of the study regarding the availability and productivity of land reserves in SSA indicate the existence of some 5.5 million km2 grassland and shrub land (termed as REMAIN land), in excess of land that is needed to achieve food security, land that is legally protected or land that should be set aside for nature conservation and environmental protection, including forest land, key biodiversity areas and wetlands. About 1.9 million km2 or 32% of this REMAIN land, an area larger than Tanzania, Kenya and Uganda together, has been assessed as agro-ecologically very suitable or suitable for the production of some annual or perennial biofuel feedstocks. However, exploitation of these land resources, requiring land conversion from natural shrub land and grasslands to cropland followed by intensive feedstock cultivation practices, will result in substantial initial carbon debts due to the removal of the existing vegetation and the partial loss of soil carbon.

Following the strict sustainability greenhouse gas saving criteria set by the Roundtable on Sustainable Biomaterials (RSB) – requiring at minimum a 60% GHG emissions saving relative to the fossil fuel comparator when using a 20-year accounting period – implies that almost exclusively perennial biofuel feedstocks, requiring less frequent and less intensive cultivation of soils, can meet those criteria when conversion of natural grassland or shrub land is involved.

As a consequence, only land that meets the specific ecological growth requirements of perennials can be considered, which restricts the choice of suitable rain-fed areas to mainly the sub-humid and humid climate zones. Considering all 11 biofuel feedstocks evaluated in this study and selection of the best feedstock in energy terms when multiple feedstock production is agronomically viable, 0.8 million km2 are very suitable or suitable for biofuel feedstock production.

In terms of production systems, eligible feedstocks are restricted to miscanthus and jatropha, both currently not yet produced at economic scales in SSA, and traditional large-scale plantation crops such as oil palm and sugarcane. Miscanthus, a promising biomass feedstock in SSA conditions, relies on not fully developed second-generation conversion technologies, which may be problematic for the introduction in SSA countries. In the case of jatropha, this feedstock had only limited success in many locations, the main problems being irregular and sometimes low yields, invasiveness characteristics and the fact that jatropha seeds are poisonous for livestock and humans. The perennial nature of miscanthus and jatropha may limit the acceptance of farmers to switch from the flexibility of cultivating annual crops to the longer time horizon required for the cultivation of perennials.

In addition, the estimated biofuel potentials of the available REMAIN land in 2010 will likely be significantly reduced in the future, in the order of 20% depending on scenario, due to land conversion for food production needed in response to future demographic changes and improved diets due to the expected economic development process and income growth in SSA countries between 2010 to 2050. The land suitability and yield impacts of climate change will further reduce potential biofuel production by about 10-15%, especially when the potential is based only on perennial crops as a consequence of imposing a strict GHG criterion for soil carbon recuperation.

As our results show, annual feedstocks cannot or only barely meet RSB criteria regarding minimum greenhouse gas savings due to direct land use change implications of REMAIN land. This may severely hamper options to involve small scale production by local farmers and to integrate biofuel feedstocks in food, feed and fodder crop rotations. Moreover, such rotations would be beneficial for maintaining soil productivity.

Below we summarize specific conclusions that have emerged from different simulation experiments and analysis of the results:

The food – energy –environment nexus of agricultural production

Increasing biofuel feedstock production in sub-Saharan Africa, while at the same time meeting food demand targets and strictly following sustainability principles, faces a high degree of complexity. Approaches of systems analysis, nexus research and integrated solutions are best suited to address complex development pathways. A core principle of systems analysis is awareness of the full system in the analysis of its individual (sub-) components. Complex systems such as studied here require a systems perspective to attain the desired sustainability goals and avoid unintended consequences. Systems analysis approaches are well suited to address the complex interlinkages of the spatial and temporal dimensions of the agriculture-energy-environment system.

Availability and quality of REMAIN land

Total REMAIN land extents in SSA are estimated in this study to be in the order of 5.5 million km2 or about 23% of SSA total land area. REMAIN land in 2010 comprises of 2.8 million km2 classified as shrub land and 2.7 million km2 grassland. Largest shares of REMAIN land in a region's total land are found in the Southern Africa region (about 30%, but mostly arid and semi-arid land) and the smallest share in the Sudano-Sahelian region (17%). Countries with large percentages of REMAIN land include Madagascar (50%), South Africa (40%) and Kenya (40%).

By 2050, due to additional cropland required to meet the food demand of growing populations, current REMAIN land extents will be substantially reduced. Percentage reductions vary, depending on scenario, for SSA as a whole between 6%-9%. Largest relative reductions of REMAIN land occur in the Gulf of Guinea region (by 19-28%) and the smallest reductions are projected in the Sudano-Sahelian (by 1%-5%) and Southern Africa regions (by 2%-4%).

Based on the suitability of the eleven crops assessed in this study, about 1.9 million km2 of REMAIN land or 35% are of prime or good quality for cultivation of one or more biofuel feedstock crops. The crops best adapted to ecological conditions of available REMAIN land in SSA are sweet sorghum (very suitable and suitable in about 1.6 million km2) and soybean (almost 1.4 million km2). Rain-fed perennial crops (oil palm, jatropha, miscanthus) and long cycle annual crops (sugarcane and cassava) are mainly suitable for cultivation in sub-humid and humid environments of Central Africa. Least adapted to prevailing conditions of SSA REMAIN land are triticale, with only 34,000 km2 of prime or good quality REMAIN land, and camelina with only 38,000 km2. These crops require cooler temperatures which in SSA are confined to highland areas and some parts of South Africa.

It is important to note that prime and good quality REMAIN land (some 1.9 million km2) poses little or no constraints to crop cultivation and is quality-wise comparable with current cropland (almost 2.4 million km2).

Compliance with GHG emissions saving criteria

Although significant amounts of REMAIN land are of prime and good quality for the production of the explored crops, the compliance with GHG criteria significantly restricts the biofuel potentials. Notably, almost none of the annual feedstock crops can meet the strict GHG criterion required by the RSB (i.e., the GHG 1 criterion).

At the lower end, when applying the GHG 1 criterion and considering only prime and good land, some 838 thousand km2, out of total 5,504 thousand km2 REMAIN land, qualify for the cultivation of biofuel feedstocks, which could produce 7.1 thousand PJ of biofuels (LHV equivalent). The majority of the prime and good REMAIN land extents in the biofuel 'umbrella' are stemming from miscanthus (52% of the GHG 1 compliant potential), followed by oil palm (18%) and sugarcane (13%). When considering only sugar/starch producing feedstocks, the potential production would be slightly lower (5.2 thousand PJ) and substantially lower, namely 4.1 thousand PJ, when only considering oil producing feedstocks.

When applying the somewhat less strict GHG 2 emissions saving criterion and considering all eleven feedstocks, the estimated potential increases to 13.3 thousand PJ (biofuel equivalent), nearly twice the potential under GHG 1. In addition to the feedstocks qualifying under GHG 1, a number of annual crops can meet the GHG 2 criterion. As a result, the composition of the selected best performing feedstocks becomes more differentiated. The most important feedstocks on prime and good REMAIN land include sweet sorghum (47% of the GHG 2 compliant potential), followed by miscanthus (19%), sugarcane (14%) and oil palm (9%).

Future productivity of biofuel feedstocks on REMAIN land

Over time the extents and quality of REMAIN land available in 2010 will be declining due to growing food demand and progressing climate change which affects crop suitability and attainable yields. Additional cropland use for food production is likely to expand into REMAIN land with the most suitable biophysical conditions (climate, terrain, soil) for agriculture. Thus, available REMAIN land does not only become less in the development process toward 2050 but also loses selectively the agronomically better suited parts. Between 2010 and 2050, overall extents of REMAIN land decrease by between 320 thousand km2 (scenario SC 1 Sustainability) and 491 thousand km2 (scenario SC 2 Middle of the Road). However, note that only a fraction of overall REMAIN land is of prime and good land quality for the production of biofuel feedstocks and even less is compliant with GHG criteria.

By 2050, under constraints of the GHG 1 criterion, the estimated future biofuel potential on prime and good land amounts to about 3.0-4.0 thousand PJ compared to a potential estimated for current REMAIN land and current climate conditions of about 7.1 thousand PJ. Depending on scenario, land allocation for the cultivation of such future biofuel volumes amounts to a range of 423-533 thousand km2 (compared to 838 thousand km2 in 2010). Perennial feedstocks will suffer substantial production losses under changed climate and altered REMAIN land availability, which renders GHG 1 compliant biofuel potentials quite vulnerable to future climate variability and change. Depending on scenario, the overall biofuel production potential (from prime, good and moderate REMAIN land) is reduced by 28%-35% compared to 2010.

When applying the GHG 2 criterion, which allows more flexibility to adapt to local conditions due to a wider base for crop selection than GHG 1, the resulting changes in biofuel potential between 2010 and 2050 are less severe. The simulated reductions are between -10% to -21% depending on the scenario considered. By 2050 some 9.0 thousand PJ to 11.4 thousand PJ from prime and good REMAIN land can be produced, compared to 13.3 thousand PJ in 2010. For the annual feedstock crops impacts due to climate change are more variable and in some cases result in gains. Notably for Solaris tobacco the projected future climate conditions have a strong positive effect on productivity on REMAIN land.

From a regional viewpoint, the Central Africa region has the best conditions for perennial feedstocks and has the highest share in production potentials on prime and good REMAIN land of 32% (under GHG 2) and some 47% (under GHG 1) of the respective SSA totals.

Allowing annual crops to participate in feedstock selection, as is possible under the GHG 2 criterion, gives more flexibility in the use of resources and is resulting in better adaptation options in response to climate change.

Spatial concentration of feedstock production potentials

For biofuel production to be viable, a minimum cumulative concentration of biomass raw materials must be available around a biofuel production plant. In this context, achievable cumulative energy production potentials were calculated for each grid-cell assuming a collection radius of 50 km, 100 km and 200 km.

Considering cumulative feedstock potentials (in TJ of biofuel) from REMAIN land for vegetable oil producing feedstocks complying with the GHG 1 criterion, oil palm and jatropha emerge as the defining feedstocks. Bright spots of cumulative biofuel potentials of over 3000 TJ occur in several locations in tropical SSA, notably in the Democratic Republic of Congo and the Gulf of Guinea region. In these areas, vegetable oil mainly coming from oil palm, could support biofuel plants with capacities of more than 87 million litres[35]. In other locations, also in Central Africa and the Gulf of Guinea region, with substantial supply potentials from jatropha plantations, vegetable oil could be supplied for plants with capacities between 29 million litres (about 1000 TJ) and 52 million litres (about 1800 TJ). Other regions such as Eastern Africa, the Sudano–Sahelian region and Southern Africa, with the exception of Madagascar and central Mozambique, lack areas with substantial cumulative oil producing feedstock production potentials compliant with GHG 1.

A similar spatial pattern emerges when considering sugar/starch based biofuel feedstock production. Apart from the Central Africa region, sizeable concentrations are found in Eastern Africa (Ethiopia, Mozambique and Madagascar) and to a lesser extent in the Gulf of Guinea region. These concentration areas partly overlap with oil based production concentrations. The dominant feedstock is, by far, miscanthus requiring second generation biofuel production technologies. When excluding miscanthus, sugarcane is the most important feedstock for sugar/starch based fuel production. Concentration areas (when excluding miscanthus) are almost exclusively found in Central Africa and in some pockets of the Eastern Africa region. For both biofuel conversion pathways the most extended concentration areas for potential feedstock production exist in the southeast part of the Democratic Republic of Congo.

Crop residues from food production

Substantial amounts of crop residues are produced from current cropland in SAA. An estimated 235 million tons stalks and straw (in dry weight) were generated in 2009-11 from growing cereals on about 940 thousand km2. More than one third of this potential is from maize production (37%), followed by sorghum (24%), millet (17%), and rice (14%). Major oil crops and cotton generate another 41 million tons (in dry weight) of crop residues from growing on about 180 thousand km2. Sugarcane harvesting (on 13 thousand km2) produces some 4.3 million tons (in dry weight) biomass from tops and leaves, which is currently mostly burnt at harvest, and 7.5 million tons (dry weight) as bagasse.

Allowing 2 tons of crop residues per hectare to remain on the field as cover to reduce soil loss risks and to maintain soil fertility, results for 2010 in a usable crop residue potential of 75.7 million tons from cereals, 11.8 million tons from oil crops and 9.6 million tons from sugarcane (in dry weight). Therefore, cereal crop residues would add around 7% to the GHG 1 compliant potentials from REMAIN land, and around 9% if all crop residues were used for second-generation biofuel production. Relative crop residue contributions vary by region, with a potentially high contribution in Southern Africa (25%) and the lowest contribution in the Central African region (1%).

Unlike REMAIN land, which will be decreasing towards the 2050's, cultivated land and associated crop residues will be increasing. Hence by 2050, in several SSA countries residues from food production may exceed the future GHG 1 compliant potentials from REMAIN land.

35 We assume usage for Kerosene Jet Fuel A-1 (Kerosene) with an energy content per volume of 34.6 MJ / liter based on a lower heating value (heat of combustion) of 42.8 MJ / kg and an energy density at 15 degree Celsius of 0.808 g / liter.

Employment generation

Increased biofuel production is considered a great opportunity for job creation in rural areas, especially in less developed regions with a large share of the population employed in the agricultural sector and with the comparative advantage of a relatively cheap, abundant labour force. The number and kind of jobs created in the agriculture sector will depend on crop type and applied management scheme. A crucial factor for labour intensity is whether the harvest is manual or mechanical using harvest machines. Full mechanization of feedstock cultivation can reduce labour inputs substantially and therefore is a critical consideration with regard to employment generation.

For most annual biofuel feedstocks (maize, soybean, sweet sorghum, triticale, camelina), where mechanization can provide large efficiency improvements and production cost advantages, farm activities are assumed to be fully mechanized. The exception is Solaris tobacco where seeds are usually harvested using manual labour. Some perennial crops (oil palm, jatropha, cassava) involve substantial labour inputs especially for manual harvesting. Miscanthus is assumed to be fully mechanized including field preparation/planting (once per rotation period of 15 to 20 years) and annual harvesting.

When applying labour requirement factors from the available literature to the estimated biofuel potential of rain-fed REMAIN land in 2010, we estimate that feedstock cultivation based on prime and good REMAIN land could generate up to 20 million jobs in agriculture based on potentials compliant with the GHG 1 criterion; mainly jatropha, but also oil palm and sugarcane would provide these jobs. When the higher potential under the GHG 2 criterion is used, then about 21.6 million person-years are required for cultivating the respective feedstock potential.

When crop selection considers energy production also on land of moderate suitability then miscanthus, having a somewhat lower agronomic suitability on much of the available REMAIN land but giving a higher fuel energy yield than jatropha, replaces jatropha in many locations and labour requirements decrease due to mechanization of miscanthus production to 11.3 to 15.3 million jobs, with sugarcane and oil palm dominating the labour demand. These estimates indicate that job creation for biofuel feedstock production is quite uncertain and highly dependent on the chosen mix of feedstock crops, which in turn depends on agronomic, economic and GHG selection criteria used.

In addition, if sugarcane in the feedstock mix were harvested manually (instead of assumed mechanical harvesting) the labour input for prime and good land would increase to 25.8 million to 29.8 million jobs and for crop selection based on prime, good and moderate land to a range of 21.1 to 34.1 million jobs for feedstock potentials subject to GHG 1 and GHG 2, respectively. Note, the poor working conditions of the sugarcane cutters are widely acknowledged but can provide an important source of income for workers lacking formal education or qualification.

Potential contribution of sustainable bio jet from REMAIN land in SSA to global aviation biofuel requirements

The ultimate goal of this analysis was to contrast sustainable biofuel potentials with future aviation biofuel demand projections. As mentioned in Section 1, ICAO suggests that possibly all jet fuel could be biomass-based by 2040/2050. However, the recently proposed volumetric targets proposed only a 50% share of alternative fuel in total fuel demand of international aviation[36], which for currently available fuel demand projections translates to some 285 million tons per annum. For the sake of the argument, we compare this demand figure with the potential for sustainable biofuels estimated in this study to provide an indication of what proportion of global sustainable aviation fuels could be produced from RSB-compliant crops on REMAIN land and from crop residues in sub-Saharan Africa.

Prime and good quality REMAIN land of SSA, complying with the GHG 1 criterion, amounts to some 84 million hectares and could potentially produce - under current climate conditions - an equivalent of 7,064 PJ, corresponding to 165 million tons of biojet fuel[37]. By comparison, international aviation consumed about 142 million tons fossil jet

36 ICAO (2017): Proposed ICAO Vision on in Aviation Alternative Fuels, CAAF/2-WP/13
37 Assuming a typical energy content of jet fuel (kerosene) of 42.8 MJ/kg.

fuel in 2010. The potential when including moderately suitable REMAIN land for the production of the assessed energy crops adds another 8,450 PJ (197 million tons jet fuel) to the overall technical potential. However, the economic attractiveness of farming on moderately suitable land is uncertain. Profitability under moderate suitability could be achieved in case of high product prices but requires more detailed analysis. Miscanthus is the main crop that contributes to this potential, followed by oil palm and sugar cane.

More importantly, looking into the future, the potential for energy crop production on very suitable and suitable land is significantly reduced, to some 3,000 to 4,000 PJ or 70-93 million tons by 2050, depending on the intensity of the CO_2 fertilisation effect, with only little difference between the SC1 and SC2 scenarios. This represents a halving of the potential compared to current conditions. As discussed, the decrease is due to reductions in the availability of REMAIN land as well as the significant adverse impacts of climate change on agricultural productivity, in particular of perennial tropical feedstocks. Again, including moderately suitable land increases future technical potential by another 7,200 PJ or another 168 million tons jet fuel per annum. Table 5.1 summarizes future (2050) technical potential from energy crops in sub-Saharan Africa and contrasts the estimates with a currently available projection of demand, as pursued by ICAO.

Table 5.1. Technical potential for biojet from energy crops in sub-Saharan Africa relative to projected global demand for alternative aviation fuels

Alternative jet fuel demand by global international aviation in 2050	285 million tons
SSA technical potential by 2050[1] from VS and S land	70-93 million tons
SSA technical potential by 2050 from VS, S and MS land	237-261 million tons
% of global international aviation demand that could be met by biofuels from SSA	25% – 90%

1 Technical potential by 2050 are based on results presented in Table 4.12. The range is due to scenario and consideration of the CO_2 fertilization effect.

In summary, our assessment suggests that the region with the highest potential for expansion of crop-based feedstock production can at best contribute between 25% – 90% of future alternative aviation fuel demand in the form of RSB-compliant biojet, if alternative fuels are targeted at 50% of the total jet fuel demand from international aviation. It is important to note that this amount represents the technical potential and the realizable economic potential will be a proportion of the former. Furthermore, this is under the assumption that all energy crops on suitable REMAIN land in sub-Saharan Africa are used to produce biofuels for aviation and none are directed towards other uses (e.g., land transportation) which is unlikely to be the case.

Beyond land conversion, feedstock cultivation practices can involve various environmental risks and implications. When grown commercially, some feedstocks are cultivated on a large scale in monocultures with intensive fertilizer applications and the use of biocides to control weeds or combat pest and diseases. Monocultures require the inclusion of ‘habitat islands’ and/or ‘migration corridors’ to safeguard biodiversity. Biotechnology involves risks and uncertainties regarding effects on agro-diversity. Annual biofuel feedstocks require regular field activities, substantial fertilization and use of agro-chemicals for controlling pests and diseases. All of these activities cause environmental impacts for soil and water bodies, which in turn may affect biodiversity. Also, some of the assessed feedstocks are classified as potentially invasive species with the potential to affect biodiversity well beyond the cultivated fields.

Finally, it is worth noting that miscanthus, the crop that has the highest potential across the region, is not traditionally grown in sub-Saharan Africa and might indeed pose the risk of invasiveness in many regional ecosystems. Should that be the case, the SSA potential would be further substantially reduced.

Nevertheless, in addition to the potential from dedicated biofuel crops, crop residues from cultivation of food and non-food crops (food, feed and industrial) can contribute about another 7-9% to the potential in 2010. Also, note that the supply of crop residues will increase in the future, as food production needs to grow significantly.

Three general conclusions can be drawn from the results of this study:

1. There is a meaningful potential for RSB compliant biojet fuel that can be produced in sub-Saharan Africa, and hence there is no reason to lower the sustainability bar to include unsustainable alternative fuels in the portfolio of fuel supply options to airlines.

2. Almost exclusively perennial biofuel feedstocks, requiring less frequent and less intensive cultivation of soils, can meet the RSB criteria when conversion of natural grass- or shrub land is involved. The acceptance of farmers to invest in the cultivation of perennial crops depends on the long-term viability of the biofuel feedstock industry as it reduces the farmer's flexibility in the use of resources compared to annual crops.

3. While the potential for sustainable aviation fuels from land-based energy crops in SSA can be considered meaningful, it is not going to be sufficient to meet projected global demand for alternative aviation fuels. This means that the development and commercialisation of alternative sustainable aviation fuels production routes must be stepped up to complement those that depend on land-based crops.

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ANNEX I. BIOFUEL FEEDSTOCKS ANALYSED FOR THE PURPOSE OF THIS STUDY

The GAEZ v4 crop suitability assessment includes specifications for a large number of food, feed and fibre crops, including several potential biofuel feedstocks. For the purpose of this study, specifically three additional crops of interest for biofuel feedstock production have been integrated into the GAEZ land utilization types database, namely Solaris energy tobacco and camelina for the production of vegetable oil based biofuels, and triticale as a feedstock for the conventional sugar/starch based conversion pathway. Annex I summarizes some basic information for the three new feedstock crops in GAEZ v4, followed by a brief characterization of the other eight feedstock crops assessed in this study.

ANNEX I-1. SOLARIS TOBACCO

Solaris is a new variety tobacco plant specifically developed for oil seed production. Solaris production has been certified since 2012 by 2BSvs (Biomasse, Biocarburants, Schéma volontaire pour la durabilité) being compliant to the biomass biofuel, sustainability voluntary scheme. Since 2015, Solaris has also been certified by the Roundtable on Sustainable Biomass (RSB). Exclusive rights to exploit and develop the industrial patent for energy tobacco is held by Sunchem Holding. Sunchem is developing and testing industrially viable agronomic processes and production chains.

Depending on climatic conditions, Solaris can be harvested sequentially two to three times a year. The cross-bred variety contains no nicotine, has excessive seed and limited leaf production compared to traditional tobacco. Solaris grows under a range of climatic conditions, is cultivated as traditional tobacco requiring similar inputs of fertilizer, water, and crop protection measures.

Feedstock	Produce	Intermediate product	End product	Potential uses
Solaris	Seed	Vegetable oil	Vegetable oil	Food/other
			Bio-diesel/jet fuel	Transport/aviation
		Oil cake	Feed	Livestock
	Residue	Biomass	Feed	Livestock
			Biomass	Combustion/pulp production
			2nd generation bio-ethanol	Transport/aviation
			Organic matter	Returned to field

Crop productivity

Sunchem research data from seven research sites in Africa, Europe and Brazil indicates ranges of rain-fed and irrigated Solaris tobacco seed yields under conditions of two and three annual harvests (see Table A.I-1). The reported Solaris maximum seed yields achieved in trials are respectively 3.8 tons/ha in Malawi (rain-fed; two harvests) and 6.8 tons/ha in South Africa (irrigated; three harvests). Solaris seed yields in Italy, from two harvests and irrigated cultivation, ranged between 3.6 tons/ha to 5 tons/ha.

Table A.I-1. Solaris crop calendars and seed yield ranges

Location of field research (SUNCHEM)	Water supply system	Growth cycle (days)	Growth cycle (beg/end)	Temp. range during field phase (oC)	Avg. rainfall during field phase (mm)	Planting density (plants/ha)	Number of harvests	Seed yield ranges (ton/ha)
South Africa - Lim-popo- Marble hall 24°58′S 29°18′E, 920 m	Drip irrigation	195	end Sep- beg April	20-25	450	36,000	3	5.0-6.8
Malawi - Lilongwe 13°59′S 33°47′E, 1050 m	Mainly rain-fed	135	end Nov-mid April	20-23	750	35,000	2	3.6-3.8
Malawi - Mzuzu 11°27′S 33°35′E, 1254 m	Mainly rain-fed	120	end Nov-mid April	18-21	920	35,000	2	3.6
Italy - Avezzano 42°02′28″N 13°26′23″E, 695 m	Perfusion (sprinkler)	145	mid May-beg Oct	15-21	270	32,000	2	3.6-5.0
Italy - Sant'eusanio del sangro 42°10′N 14°20′E, 200 m	Perfusion (sprinkler)	145	mid May- beg Oct	16-23	210	32,000	2	3.6-5.0
Bulgaria - Haskovo 41°56′N 25°34′E, 196 m	Perfusion (sprinkler)	145	mid May- beg Oct	16-23	200	32,000	2	2.7-4.0
Brazil - Santa Cruz do Sul 29°42′50″S 52°25′43″W, 73 m	Drip irrigation	180	end Nov-end May	16-23	775	35,000	3	5.0-5.6

Source: Personal communication Francesco Di Lucia, agronomist Sunchem Holding Ltd.

Environmental requirements of Solaris tobacco

Solaris energy tobacco belongs to the Solanaceae, has a C3-II photosynthesis pathway and is adapted to grow under sub-tropical and moderately warm tropical environments requiring ample solar radiation. Solaris tobacco is sensitive to the physical and chemical properties of the soil. The best soils are those with sandy loam and loamy textures, have medium to high natural fertility, are well drained and properly aerated. Solaris tobacco does not tolerate waterlogging because it causes deprivation of oxygen in the soil, which is essential for the development of a fibrous root system. The optimum soil pH for Solaris ranges from 5.0 – 6.5. Solaris energy tobacco is very sensitive to salinity and sodicity.

To maintain turgidity and expansion of its leaf area, Solaris tobacco needs considerable amounts of water. Rain-fed production requires 1000 mm rainfall, well spread over a period of six to nine months. Relative humidity should be below 75% and moderately warm temperatures (between 20oC and 25oC) are preferred. Solaris does not tolerate early or late frost.

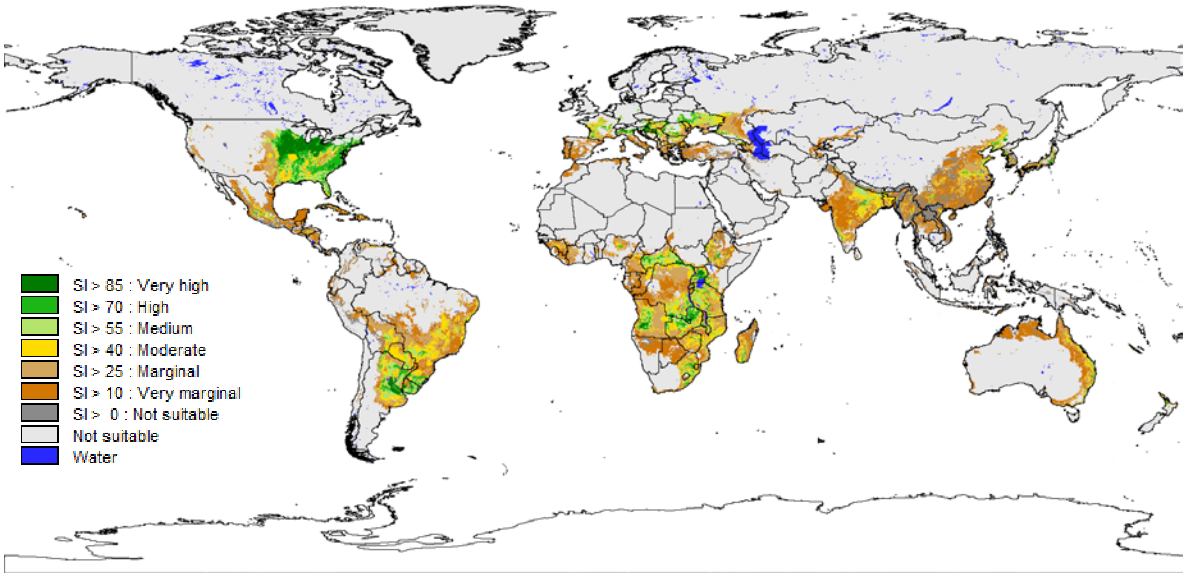
Solaris production entails a seedbed/nursery stage from emergence to a plant height of 10-15 cm (about 40 days), followed by a field stage with two harvests (120 days) or three harvests (165 days). Harvest is targeted at 15% browning of seeds. Under rain-fed conditions, mainly two-harvest systems are used. Under drip or perfusion irrigation systems, also three harvests can be achieved. In order to break soil borne pest and disease cycles (e.g., nematodes) a three-year rotation with grasses or cereal crops is recommended. Fertilizer requirements are moderately high.

Agro-ecological zones model input

For the assessment of suitability and productivity of Solaris tobacco, high (non-limiting) inputs and advanced management are assumed, based on: (i) Sunchem bred high seed/oil yielding varieties; (ii) adequate applications of nutrients and chemical pest, disease and weed control; and (iii) mechanization with medium/low labour intensity. Rain-fed and irrigated conditions were assessed.

Five different growth cycles were considered, namely: Solaris 120 days (two harvests); Solaris 135 days (two harvests); Solaris 150 days (two harvests); Solaris 180 days (three harvests) and Solaris 195 days (three harvests). Eco-physiological requirements[38] and tolerances of Solaris tobacco are contained in the GAEZ land utilization types (LUT) database that was updated and extended for this study.

Figure A.I-1. Suitability of rain-fed Solaris tobacco



Note: The map shows for all land the assessed agro-ecological suitability index (SI) of rain-fed Solaris tobacco: SI=1.0*VS+0.777*S+0.555*MS+0.3*mS+.167*vmS, where VS (very suitable), S (suitable), MS (moderately suitable), mS (marginally suitable) and vmS (very marginally suitable) represent extents of different suitability classes within a 5 arc-minute grid cell.

38 Climate and feedstock related parameters used include: Thermal climate requirements; temperature growing period and temperature profile requirements; temperature sums requirements; air humidity requirements; photosynthesis response to radiation and temperature; phenological requirements; photoperiodicity properties; growth cycle from emergence to transplanting from transplanting to full maturity/harvest; durations of main crop development stages; crop water coefficients; yield response to water deficit; harvest indexes; maximum leaf area index; plant height at maturity; agro-climatic constraints (pest diseases, weeds, workability and sensitivity to frost, and soil born constraints and control of main pest. Edaphic parameters include: Soil profile attribute requirements/tolerances (Organic carbon, pH, cation exchange capacity (CEC) of soil and of clay fraction, base saturation (BS), total exchangeable bases (TEB), CaCO3, gypsum, salinity, sodicity); specific soil texture requirements; soil drainage requirements; soil phase tolerances; rooting depth; terrain/slope requirements, and waterlogging/ flooding tolerances.

Agro-ecological suitability of rain-fed Solaris tobacco

Figure A.I-1 shows that Solaris tobacco potentially grows well in eastern USA; northern Argentina, Uruguay and southern Brazil; southern Europe; parts of South and East Asia, and in the Southern Africa region, the Eastern Africa region and some drier parts of the Central Africa region. The map shows a suitability index of rain-fed Solaris tobacco per 5 arc-minute grid cell. Regional summaries of suitable areas and attainable yields for the baseline period (1981-2010) are presented in Table A.I-2, respectively for prime land (very suitable), good land (suitable) and moderate land (moderately suitable).

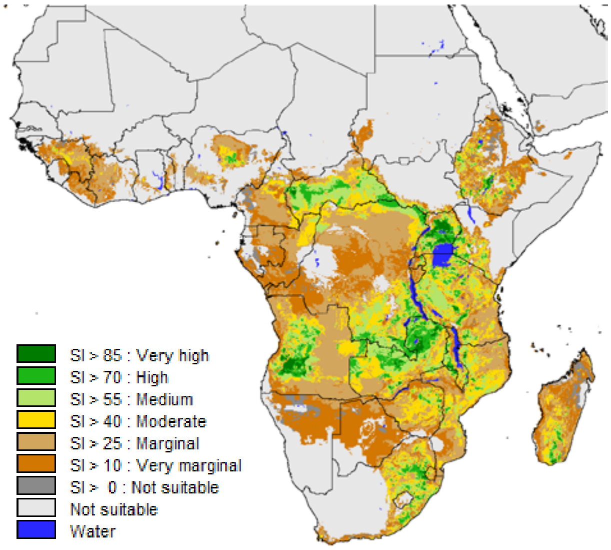
Table A.I-2. Suitable extents and maximum seed yields of rain-fed Solaris tobacco in current global cropland

	Historical climate, period 1981-2010				
REGION	Cropland extents (1000 km²)	Land quality classes - Solaris (1000 km²)			Maximum yield (tons/ha)
		Prime land	Good land	Moderate land	
Northern America	2066.8	351.1	480.4	123.8	5.0
Europe and Northern Asia	2896.0	44.5	232.4	311.4	3.7
Central America and Caribbean	407.9	15.5	30.8	56.3	5.6
South America	1455.0	84.7	216.9	454.7	5.3
Oceania	484.0	3.5	16.8	35.7	5.5
sub-Saharan Africa	2354.4	94.0	313.4	290.1	5.6
Northern Africa and West Asia	902.0	0.6	6.2	26.8	4.3
Southern and Eastern Asia	4891.5	35.6	236.8	765.1	5.8
World Total	15457.6	629.5	1533.8	2063.8	5.8

In SSA, Solaris tobacco can be grown well outside the humid and hot zones of sub-Saharan Africa. Agro-ecological best areas are found in Uganda, Tanzania, Malawi, Zambia, Angola, South Africa, parts of Ethiopia and Kenya, and the Central African Republic. Figure A.I-2a shows suitability for rain-fed Solaris tobacco cultivation in SSA and Figure A.I-2b indicates average attainable grid-cell output (tons dry seed/ha) by 5 arc-minute grid cell. Finally, Table A.I-3 lists suitable extents and maximum class yields for rain-fed Solaris tobacco assessed for cropland areas in 2010.

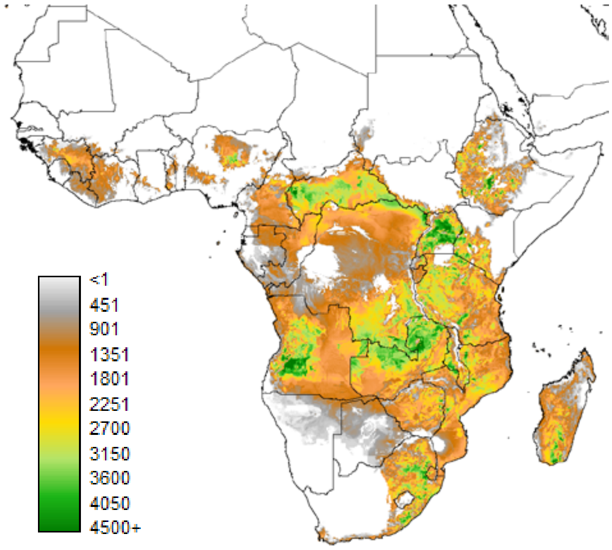
Figure A.I-2. Suitability and attainable output of rain-fed Solaris tobacco in SSA

a) Suitability index, by class



Note: The map shows the assessed agro-ecological suitability index (SI) of rain-fed Solaris tobacco: SI=1.0*VS+0.777*S+0.555*MS+0.3*mS+.167*vmS

b) Average attainable output (tons dry seed/ha)



Note: The map shows average attainable grid-cell output (tons dry seed/ha) for rain-fed Solaris tobacco.

Table A.I-3. Suitable extents and maximum seed yields of rain-fed Solaris tobacco in SSA cropland

	Historical climate, period 1981-2010				
REGION	Cropland extents (1000 km²)	Land quality classes - Solaris (1000 km²)			Maximum yield (tons/ha)
		Prime land	Good land	Moderate land	
Eastern Africa	531.5	66.0	163.0	108.1	5.6
Central Africa	234.8	5.8	30.5	42.9	5.1
Southern Africa	318.4	21.4	100.7	97.6	5.6
Sudano-Sahelian Africa	590.4	0.2	3.2	2.4	5.0
Gulf of Guinea region	678.1	0.7	16.0	39.0	4.8
SSA Total	2353.2	94.0	313.4	290.1	5.6

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ANNEX I-1. SOLARIS TOBACCO

Camelina sativa is a member of the Crusiferae (Brassicaceae) family, which includes mustards, rapes and canola. Camelina originates from north and central Europe. It has been traditionally cultivated as an oilseed crop to produce vegetable oil and animal feed. More recently, camelina is being recognized for its high quality vegetable oil, rich in omega-3 fatty acids, and for being a potential feedstock source for bio jet fuel.

Camelina is a short duration crop of 85-100 days and grows well in temperate climates from where it originates. In temperate zones, camelina is mainly grown as spring or as winter crop with a hibernation period in winter. In temperate conditions some camelina types appear also suitable to be grown as second crop in late summer and autumn before the occurrence of early frosts (Dobre et. al., 2014). In subtropical areas camelina is grown through the winter, without hibernation but with considerably longer growth cycles (Berti et al., 2011). Finally, camelina has successfully been introduced in tropical highland environments (ORDA, 2014).

Feedstock	Produce	Intermediate product	End product	Potential uses
Camelina	Seed	Vegetable oil	Vegetable oil	Food/other
			Bio-diesel/jet fuel	Transport/aviation
		Oil cake (meal)	Feed	Livestock
	Residue	Biomass	Feed	Livestock
			Organic matter	Returned to field

Crop productivity

Reported rain-fed seed yields of short cycle camelina types (winter, spring, autumn and tropical highland types) vary between 500 kg/ha and 1000 kg/ha. Under irrigated conditions seed yields achieved for these types are up to 1300 kg/ha. In areas with oceanic Mediterranean climates camelina types with long growth cycles of 180-210 days are grown through the cool winter period. For these types rain-fed seed yields of about 2 tons per hectare have been reported (Berti et al., 2011).

Environmental requirements of camelina

Camelina has a C3-I photosynthesis pathway and is adapted to grow in temperate, subtropical and tropical highland environments with cool and moderately cool temperatures. Camelina seed germinates at low temperatures and seedlings are frost tolerant. It responds well under drought stress conditions and outperforms other oil crops in low rainfall areas (i.e., 400 - 500 mm annually). In contrast, less good performance is recorded under wet conditions and on poorly drained soils. Camelina adapts relatively easily to different environmental conditions. It performs on a wide range of soils, e.g., it tolerates a soil pH range as wide as 5.5 to 8.2; optimum pH values are 6.2 to 7.5. Best suited soils are deep, well drained, silt loams that do not crust and are void of salinity problems.

Although camelina is reported to be successfully grown on marginal land, it responds well to modest amounts of fertilizer (nitrogen-sulfur-phosphorous) provided good soil moisture availability prevails. Rotations with wheat, barley, peas and lentils are recommended. Rotations with canola, mustard, etc. increase the risk of carry-over of insect and disease problems that are common with these crops. Due to insect and disease problems camelina should ideally be grown only every four years in the same field. Due to the fact that camelina does not produce high amounts of root biomass and residues, growing camelina may lead to increased rates of soil erosion.

Agro-ecological zones model input

For the assessment of suitability and productivity of camelina, high (non-limiting) inputs and advanced management are assumed, based on: (i) high seed/oil yielding varieties; (ii) adequate applications of nutrients and chemical pest, disease and weed control; (iii) full mechanization with medium/low labour intensity; and (iv) rain-fed conditions only.

Twelve different camelina LUT/growth cycle combinations are considered in different environments and different growth cycle combinations namely:

(i) Temperate winter types with hibernation period represented by four different pre- and post-dormancy growth cycles combinations: 25-75 days, 30-90 days, 35-105 days and 40-120 days;

(ii) temperate spring types with growth cycles of 75 and 90 days;

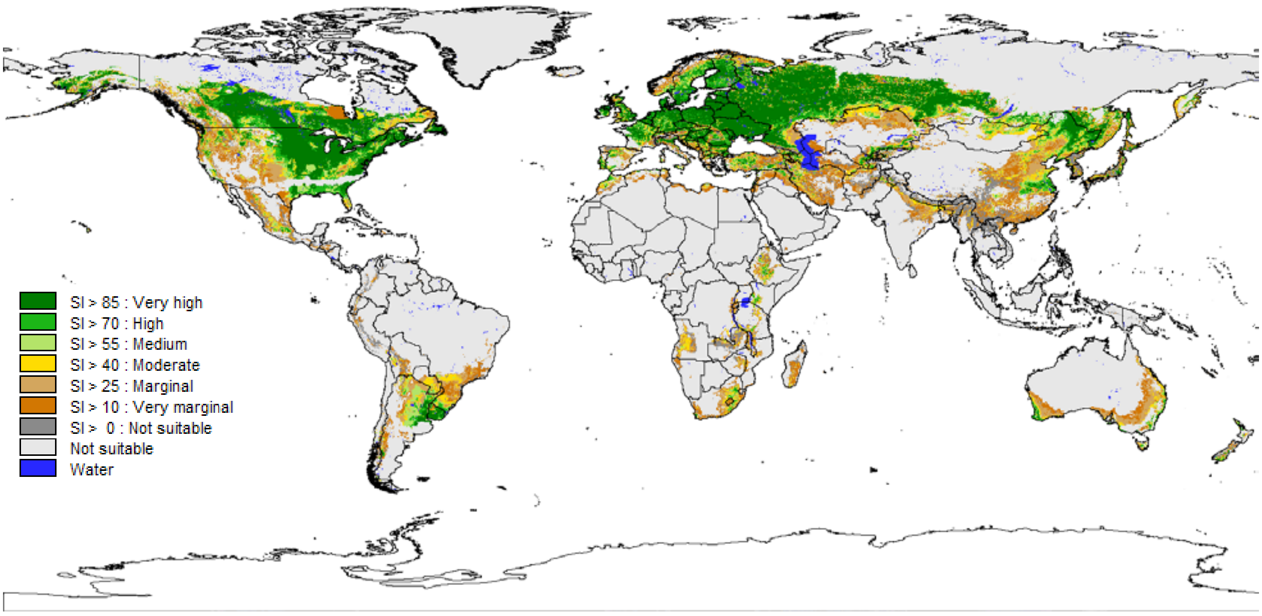
(iii) temperate autumn types grown as second crop in late summer and autumn before winter break with growth cycles of 90 and 105 days;

(iv) subtropical types grown through winter with long growth cycles of respectively 180 and 210 days, and

(v) tropical highland types grown in rainy season with growth cycles of 105 and 120 days respectively.

Eco-physiological requirements and tolerances of camelina are contained in the GAEZ land utilization types (LUT) database that was updated and extended for this study.

Figure A.I-3. Suitability of rain-fed camelina



Note: The map shows for all land the assessed agro-ecological suitability index (SI) of rain-fed camelina: SI=1.0*VS+0.777*S+0.555*MS+0.3*mS+.167*vmS, where VS (very suitable), S (suitable), MS (moderately suitable), mS (marginally suitable) and vmS (very marginally suitable) represent extents of different suitability classes within a 5 arc-minute grid cell.

Agro-ecological suitability of rain-fed camelina

As shown in Figure A.I-3 below, under baseline (1981-2010) climate, rain-fed camelina would potentially grow well in temperate climate zones in North America, Europe and Asia. In sub-Saharan Africa camelina's potential distribution is limited to highland areas of East and Southern Africa. The map shows a suitability index of rain-fed Solaris tobacco per 5 arc-minute grid cell. Regional summaries of suitable areas and attainable yields for the baseline period (1981-2010) are presented in Table A.I-4, respectively for prime land (very suitable), good land (suitable) and moderate land (moderately suitable).

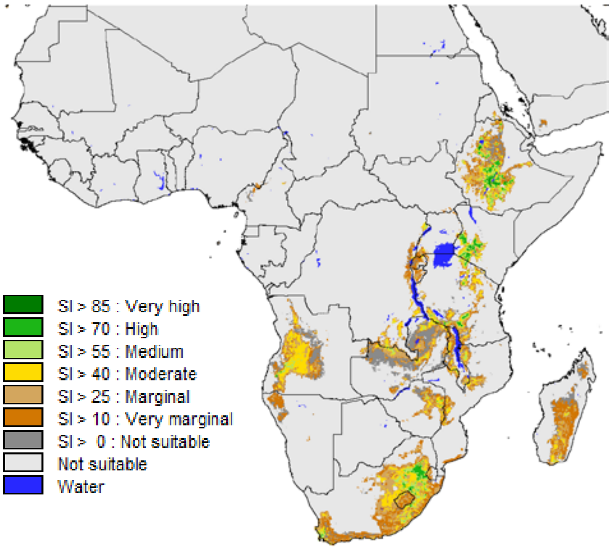
Table A.I-4. Suitable extents and maximum seed yields of rain-fed camelina in current global cropland

	Historical climate, period 1981-2010				
REGION	Cropland extents (1000 km²)	Land quality classes - Camelina (1000 km²)			Maximum yield (tons/ha)
		Prime land	Good land	Moderate land	
Northern America	2066.8	1298.4	332.5	141.1	2.3
Europe and Northern Asia	2896.0	1885.0	493.0	143.9	2.5
Central America and Caribbean	407.9	6.7	19.9	20.6	1.4
South America	1455.0	66.7	166.0	205.0	2.2
Oceania	484.0	30.5	33.4	63.8	2.0
sub-Saharan Africa	2354.4	31.2	120.5	116.4	1.7
Northern Africa and West Asia	902.0	182.1	148.6	84.1	2.5
Southern and Eastern Asia	4891.5	264.4	415.1	542.6	2.4
World Total	15457.6	3765.0	1729.0	1317.7	2.5

In sub-Saharan Africa camelina's potential distribution is limited to highland areas of Eastern Africa (Ethiopia, Kenya and Tanzania) and to South Africa. Figure A.I-4a shows suitability for rain-fed camelina cultivation in SSA and Figure A.I-4b indicates average attainable grid-cell output (tons dry seed/ha) by 5 arc-minute grid cell. Finally, Table A.I-5 lists suitable extents and maximum class yields for rain-fed camelina assessed for cropland areas in 2010.

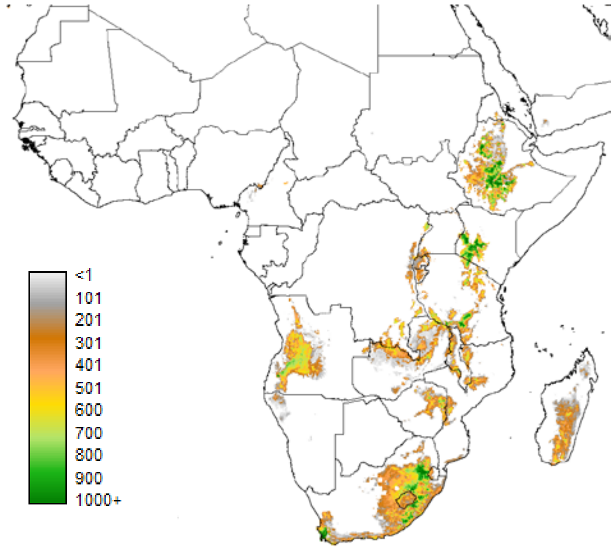
Figure A.I-4. Suitability and attainable output of rain-fed camelina in SSA

a) Suitability



Note: The map shows the assessed agro-ecological suitability index (SI) of rain-fed camelina: SI=1.0*VS+0.777*S+0.555*MS+0.3*mS +.167*vmS

b) Average attainable output (tons dry seed/ha)



Note: The map shows average attainable grid-cell output (tons dry seed/ha) for rain-fed camelina.

Table A.I-5. Suitable extents and maximum seed yields of rain-fed camelina in current SSA cropland

REGION	Historical climate, period 1981-2010				
	Cropland extents (1000 km²)	Land quality classes - Camelina (1000 km²)			Maximum yield (tons/ha)
		Prime land	Good land	Moderate land	
Eastern Africa	531.5	21.1	81.0	54.6	1.4
Central Africa	234.8	0.04	2.1	11.1	1.2
Southern Africa	318.4	10.0	36.9	49.8	1.7
Sudano-Sahelian Africa	590.4	0.1	0.4	0.4	1.2
Gulf of Guinea region	678.1	0.0	0.0	0.6	0.7
SSA Total	2353.2	31.2	120.5	116.4.0	1.7

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ANNEX I-3. TRITICALE

Triticale is a cross-bred hybrid of wheat (Triticum) and rye (Secale). It is mainly used as livestock feed for ruminants and monogastric animals in the form of forage and grain. Early triticale varieties were marred by variable yields and composition, low energy densities and low palatability. However, current varieties are high yielding and possess stable desirable nutritional characteristics for use in poultry, swine and ruminant diets.

Triticale has no direct competition with food grain; it is suitable as livestock feed and for bio-ethanol production. Research indicates that triticale has a marginally better conversion to bio-ethanol compared to wheat. One ton of triticale grain produces 372 litres of ethanol, while in the case of wheat 365 litres ethanol can be produced (Meale and McAllister, 2015).

Feedstock	Produce	Intermediate product	End product	Potential uses
Triticale	Seed	Grain	Bakery products/Feed	Food/Livestock
		Starch/sugar	Bio-ethanol/jet fuel	Transport/aviation
		DDGS	Feed	Livestock
	Residue	Biomass	Feed	Livestock
			Biomass	Co-firing
			2nd generation bio-ethanol	Transport/aviation
			Organic matter	Returned to field

Crop productivity

Triticale combines the high yield potential of wheat with the biotic and abiotic stress tolerances of rye, making it more suitable for the production in marginal areas. Despite having certain advantages over wheat, global triticale production is still very low. Apart from susceptibility to specific diseases, triticale is somewhat later maturing than wheat. Triticale has a lower protein concentration and gluten strength than wheat making bread-making quality relatively poor. (Randhava et al. 2015). Nevertheless, research on triticale is conducted worldwide and holds great promise as a commercial crop for industrial use.

Agronomic research in the UK found that yields of triticale were similar or slightly higher than for wheat. The higher yield of triticale came from a higher biomass throughout the season and more grains per ear. In 2010-2014 (FAO production statistics) main triticale producers were Poland (1,215 thousand ha), Belarus (460 thousand ha), Germany (393 thousand ha) and France (393 thousand ha). Highest country-wide average yields for that period were recorded in temperate Europe, namely in Belgium (7.1 tons/ha), Germany (6.1 tons/ha), Switzerland (5.9 tons/ha) and Netherlands (5.7 tons/ha).

Environmental requirements of triticale

Triticale has a C3-I photosynthesis pathway and is adapted to grow in temperate, moderately cool subtropical and tropical highland environments. Triticale is highly adaptable to soil conditions; it can be grown on a wide range of soils. It grows well on soils with sandy loam to heavy clay textures. Somewhat heavier textured soils - between silt loam, clay loam and clay with blocky structure - are best. Tolerable pH values range from 5.2 to 8.5; optimum conditions are pH 6.0-8.0. Triticale is similar to wheat moderately tolerant to saline conditions and vulnerable to waterlogging and poor drainage, but more tolerant to Zn deficiencies as compared to wheat and barley. Triticale requires at least 250 mm rainfall during its growing period when grown for fodder; for grain production, at least 350 mm of well distributed rainfall over the growing period is required. In low rainfall areas, soil water conservation techniques are in use to obtain satisfactory yields. Triticale has a superior drought resistance compared to oat, wheat and barley, while rainfall in excess of 1000 mm is less suitable due to causing wetness related diseases.

Agro-ecological zones model input

For the assessment of suitability and productivity of triticale, assumed high levels input and advanced management based on: (i) high grain yielding varieties; (ii) adequate applications of nutrients and chemical pest, disease and weed control; (iii) full mechanization with medium/low labour intensity; and (iv) rain-fed conditions only.

For the AEZ assessment in this study, ten different triticale LUT/growth cycle combinations are considered in different environments, namely:

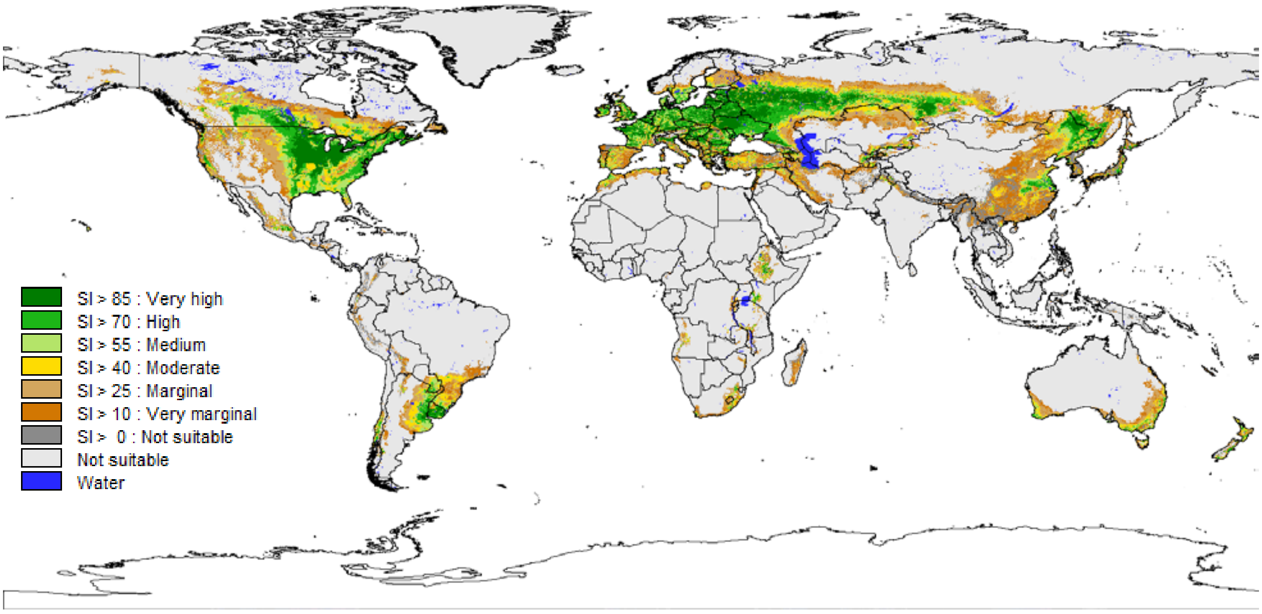
(i) Temperate winter types with a distinct hibernation period are represented by three different pre- and post-dormancy growth cycles combinations: 35-105 days, 40-120 days, and 45-135 days;

(ii) temperate/subtropical spring types with three different growth cycles of 105, 120 and 135 days;

(iii) subtropical/tropical highland types grown with growth cycles of 135, 150, 180 and 210 days respectively.

Eco-physiological requirements and tolerances of camelina are contained in the GAEZ land utilization types (LUT) database that was updated and extended for this study.

Figure A.I-5. Suitability of rain-fed triticale



Note: The map shows for all land the assessed agro-ecological suitability index (SI) of rain-fed triticale: SI=1.0*VS+0.777*S+0.555*MS+0.3*mS+.167*vmS, where VS (very suitable), S (suitable), MS (moderately suitable), mS (marginally suitable) and vmS (very marginally suitable) represent extents of different suitability classes within a 5 arc-minute grid cell.

Agro-ecological suitability of rain-fed triticale

Globally, rain-fed triticale potentially grows well, under baseline (1981-2010) climate conditions, in temperate climate zones of North America, Europe and Asia (Figure A.I-5). The map shows average attainable outputs (tons/ha) of rain-fed triticale by 5 arc-minute grid cell. Regional results for baseline period (1981-2010) are presented in Table A.I-6, respectively for prime land (very suitable), good land (suitable) and moderate land (moderately suitable).

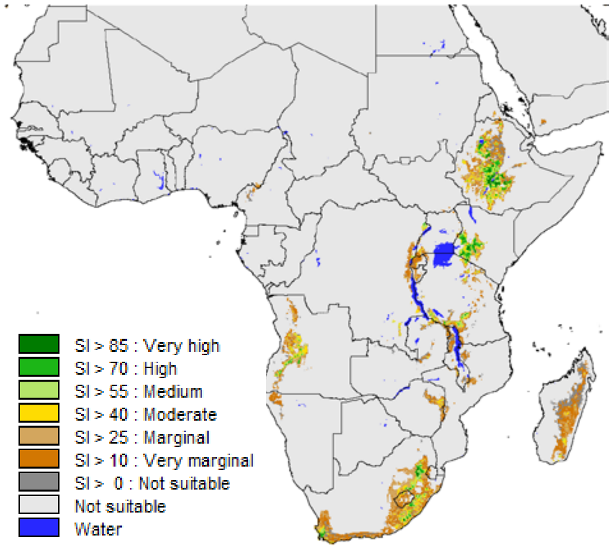
Table A.I-6. Suitable extents and maximum seed yields of rain-fed triticale in current global cropland

	Historical climate, period 1981-2010				
REGION	Cropland extents (1000 km²)	Land quality classes - Triticale (1000 km²)			Maximum yield (tons/ha)
		Prime land	Good land	Moderate land	
Northern America	2066.8	713.5	702.0	331.5	6.8
Europe and Northern Asia	2896.0	1056.5	1097.2	408.1	7.2
Central America and Caribbean	407.9	8.4	13.0	10.5	7.8
South America	1455.0	37.3	155.7	246.5	8.3
Oceania	484.0	18.9	65.8	79.9	8.4
sub-Saharan Africa	2354.4	36.5	84.7	58.4	8.4
Northern Africa and West Asia	902.0	53.7	193.1	186.7	7.1
Southern and Eastern Asia	4891.5	92.5	335.3	613.2	7.2
World Total	15457.6	2017.2	2646.8	1934.9	8.4

In sub-Saharan Africa the potential distribution of triticale is quite limited, mainly to highland areas of Eastern Africa (Ethiopia, Kenya and Tanzania) and to South Africa. Figure A.I-6a shows suitability for rain-fed triticale cultivation in SSA and Figure A.I-6b indicates average attainable grid-cell output (tons dry seed/ha) by 5 arc-minute grid cell. Finally, Table A.I-7 lists suitable extents and maximum class yields for rain-fed triticale assessed for cropland areas in 2010.

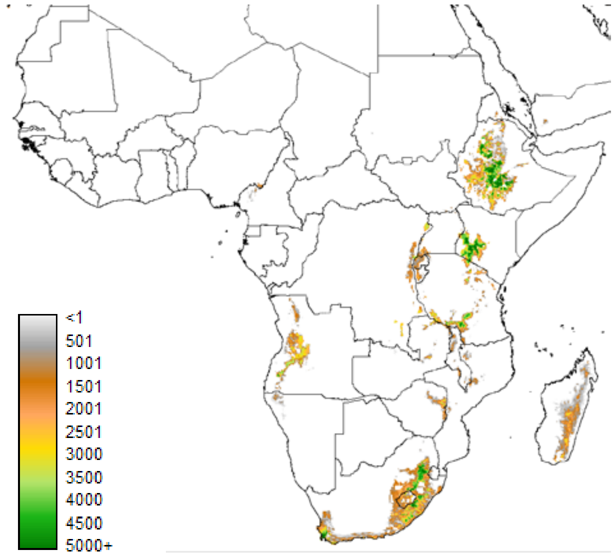
Table A.I-6. Suitable extents and maximum seed yields of rain-fed triticale in current global cropland

a) Suitability index



Note: The map shows the assessed agro-ecological suitability index (SI) of rain-fed triticale: SI=1.0*VS+0.777*S+0.555*MS+0.3*mS+.167*vmS

b) Average attainable output (tons dry seed/ha)



Note: The map shows average attainable grid-cell output (tons dry grain/ha) for rain-fed triticale.

Table A.I-6. Suitable extents and maximum seed yields of rain-fed triticale in current global cropland

	Historical climate, period 1981-2010				
REGION	Cropland extents (1000 km²)	Land quality classes - Triticale (1000 km²)			Maximum yield (tons/ha)
		Prime land	Good land	Moderate land	
Eastern Africa	531.5	31.9	64.9	36.7	8.3
Central Africa	234.8	0.03	3.4	4.2	6.7
Southern Africa	318.4	4.6	16.2	16.3	8.4
Sudano-Sahelian Africa	590.4	0.01	0.1	0.7	6.7
Gulf of Guinea region	678.1	0.0	0.1	0.5	3.9
SSA Total	2353.2	36.5	84.7	58.4	8.4

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ANNEX I-4. DESCRIPTIONS OF OTHER FEEDSTOCK CROPS ASSESSED IN THIS STUDY

General descriptions for miscanthus, sugarcane, maize, cassava, oil palm, soybean, jatropha and sweet sorghum are provided below.

Miscanthus

Miscanthus sinensis originates from East Asia and includes a number of ornamental varieties. Miscanthus has high yield potential for cellulose fibre production. Its extensive underground rhizome system is a storage organ for nutrients and forms shoots every year. From the second season onwards miscanthus grows to a height of 2.5–3.5 m. Miscanthus is productive for over 15 years (up to 25 years), which compensates for the relative high cost of planting material. Bio-energy feedstocks for second-generation technology chains produce relatively high energy yields with modest use of agro-chemicals and low tillage intensities. Miscanthus can be grown on a wide range of soils from sandy to clay soils also on peat soils. Miscanthus does not tolerate prolonged dry periods or periods with stagnant water. Miscanthus biophysical requirements are similar to those for maize.

Giant miscanthus, Miscanthus x giganteus, a hybrid of miscanthus sinensis and miscanthus sacchaiflorus.is an important non-invasive species with similar ecological requirements and productivity compared to Miscanthus sinensis. This giant miscanthus has been selected to represent miscanthus in the present assessment.

Sugarcane

Sugar cane (Saccharum officinarum) is grown most effective in sub-humid and humid tropical lowland and warm subtropics. It does particularly well in semi-arid zones under irrigation. A short, dry, and moderately cool period at the end of its cultivation cycle significantly increases sugar content at harvest. Good commercial yields vary between 110 and 150 tons of fresh cane per hectare. Ecological requirements of sugar cane include warm, sunny conditions and adequate soil moisture supply during most of its cultivation cycle. Sugar cane prefers deep, well drained, well structured, and aerated loamy to clayey fertile soils.

Maize

Maize (Zea mays) grows well in areas with high temperatures and short day-lengths (tropical varieties) as well as in moderately cool temperatures and longer day-lengths (subtropical/temperate varieties). Good commercial yields vary between 8 and 10 t/ha.

Ecological requirements of maize are matched by a range of thermal conditions from hot to moderately cool. High maize yields require sunny conditions and adequate soil moisture supply during most of its cultivation cycle. Maize is susceptible to salinity, sodicity, excess calcium carbonate and gypsum, and has low tolerance to waterlogging and high groundwater tables. It prefers moderately deep to deep, well drained, well structured, and aerated loamy to clayey fertile soils. Ideal soil pH range is 5.8–7.8.

Cassava

Cassava (Manihot esculenta) is adapted to perform best in tropical lowland conditions. It produces yields across a range of moisture regimes from semi-arid to per-humid (i.e., 500–5000 mm annual rainfall). Cassava is a short-term perennial grown as an annual crop, yield (tuber/starch) is located in the roots with the yield formation period coinciding with much, or all, of its life span. Good commercial yields of fresh roots vary between 35 to more than 50 tons per hectare

Ecological requirements of cassava are modest in terms of soil fertility and moisture supply. Cassava can be grown on soils with low fertility. On very fertile soils the vegetative growth of cassava is very luxurious at the expense of the roots. Cassava is very sensitive to salinity, prefers moderately deep soils that are at least moderately well drained. Cassava is sensitive to waterlogging and no flooding should occur.

An aggressive strain of a virus called Cassava Mosaic Disease (CMD) has decimated harvests throughout Africa, with disastrous food security consequences.. The International Institute of Tropical Agriculture (IITA) in Nigeria, through its cassava breeding and selection program, has produced a series of disease-free varieties. These varieties were multiplied in nurseries of national research institutions, local governments, and civil society, and eventually produced adequate amounts of planting material for massive re-introduction in Central Africa.

Oil palm

Oil palm (Elaeis guineensis) is adapted to perform best under conditions of warm temperatures and more than 1300 annual sunshine hours. Oil palm performs best in humid tropical conditions. Oil Palm is a perennial the yield formation period coincides almost with its entire life span. Good commercial yields vary between 5 and 7 tons of oil per hectare.

Ecological requirements of oil palm include warm, sunny conditions high air humidity and generous soil moisture supply. Oil palm is very sensitive to salinity, does not tolerate poorly drained soils with ironstone gravel, sandy coastal soils, or deep peat soils. Potassium is the main nutrient required and nitrogen is needed for rapid growth of young palms. Available phosphorous and exchangeable potassium should be high. However, palm oil is very sensitive to excess calcium carbonate and gypsum. Oil palm prefers deep, permeable, well structured, and clay to clay-loam soils.

Soybean

Soybean (Glycine max) is adapted to perform under warm to moderately cool conditions. Soybean's wide climatic adaptability spectrum makes it possible for it to be grown across a range of thermal regimes, ranging from tropical to subtropical and temperate zones with warm summers, and across moisture regimes ranging from semi-arid to humid.

Breeding has developed a large number of soybean cultivars that are well adapted to specific local conditions, e.g., varying growth cycle lengths and improved resistance to diseases associated with prolonged humid conditions. Also the harvest index (share of seed in total biomass production) has been substantially enhanced. Good commercial soybean yields vary between 3.5 and 4.5 tons of grain per hectare. At present, GM soybeans yields are reported to exceed 5 tons per hectare. These yields are achieved in large scale enterprises in Brazil and Argentina.

Ecological requirements of soybean include moderately warm and warm temperatures for photosynthesis and growth and adequate soil moisture supply during the entire cultivation cycle. (During part of its growth cycle it tolerates moderately cool temperatures). Soybean can be grown on a wide variety of soils. However, high soybean yields require high levels of fertilization and use of agro-chemicals to deal with competition of weeds and combat pest and diseases. Soybean is susceptible to salinity, sodicity, excess calcium carbonate and gypsum, and has low tolerance to waterlogging. Soybean prefers deep, well drained, well structured, loamy to clayey fertile soils.

Jatropha

Jatropha (Jatropha curcas) is native to Central America and has become naturalized in many tropical and subtropical areas, including Africa. Originating in the Caribbean, jatropha was spread as a valuable hedge plant to Africa and Asia. As with many members of the family Euphorbiaceae, jatropha contains compounds that are highly toxic.

Jatropha, also referred to as Physic nut, adapted to perform best under conditions of warm temperatures. It has moderate response to higher light intensities and relatively moderate rates of photosynthesis. Jatropha is a perennial its yield formation period is covering the greater part of its life span. Recorded seed yields vary widely between 0.5 and 12 tons per hectare and show high variability in seed weight and oil content. Rotation lengths in plantations are approximately 20 years with maximum yields obtained after four to six years. After that, yields may be reduced due mainly to pest and disease problems.

Jatropha is reported as being a hardy, drought tolerant plant, and highly water use efficient. In fact, short dry periods induce flowering and benefits yields. Jatropha prefers deep well aerated sandy loam soils, it does not tolerate flooding and waterlogged conditions. Although it has low nutrient requirements, grows well on marginal soils, and tolerates saline conditions, jatropha responds well to organic matter and chemical fertilizer. Jatropha does not tolerate vertic soil conditions associated with montmorillonite clay types.

Generally, jatropha is tolerant or resistant to pests and diseases, however under humid conditions serious problems with fungi, viruses, and insect attacks are recorded. Collar rot occurs in juvenile stages and during periods with waterlogging. Other problems are leaf spots and root rot, while pruning might trigger fungal and bacterial infection. All pest and diseases are claimed to be controllable, although with high use agro-chemicals.

In humid climatic zones, jatropha tends to produce flowers in sequence. Harvesting of jatropha nuts, while preserving new flowers, is best achieved manually. For mechanical harvesting it is difficult to target mature nuts only and it thereby may reduce achievable yields.

Sweet Sorghum

Sweet sorghum (Sorghum bicolor (L.) Moench) has a high sugar content in stalks and leaves. It is a crop with wide adaptation range from temperate to sub-tropical and tropical areas; it grows rapidly and produces substantial biomass as well. Maximum yields are achieved at average temperatures during the growth cycle of at least 25°C. Photosynthesis is best at day-time temperatures higher than 30°C. During planting time the sorghum seed needs soil temperatures above 15°C. Sweet sorghum stalks can yield 15 to 20 per cent fermentable sugar suitable for distilling to bioethanol. Good ethanol yields achieved in the US range between 3750 and 7500 liter per hectare.

Sorghum usually grows poorly on sandy soils, except where a heavy textured subsoil is present. Sorghum is more tolerant of alkaline salts than other grain crops and can therefore be successfully cultivated on soils with a wide pH range. Sorghum can better tolerate short periods of waterlogging compared to maize. Soils with a clay percentage of between 10 and 30% are optimal for sorghum production.

Sweet sorghum diseases are best controlled by rotating fields with non-grass crops. The same diseases that affect grain sorghum also attack sweet sorghum.

One important production challenge is that, upon harvest, sugars rapidly degrade. The need to immediately squeeze the juice out creates logistical challenges in harvesting and transporting stalks for sugar extraction and conversion. This reduces flexibility and can increase transportation costs.

ANNEX II. EXTENTS OF REMAIN LAND IN SSA, BY COUNTRY, IN 2010

This study applies the Global Administrative Unit Layers (GAUL) distributed by the Food and Agricultural Organization of the United Nations. Once a year an update of the hierarchic spatial data layers is released including the country level, first level administrative units (e.g. province), and second level administrative units (e.g. districts). Original polygons of the year 2014 version were converted to a 30 arc-second grid database (about 1x1 km) for data aggregation and reporting. Table A.II-1 below summarizes the regions and countries and the total physical area calculated from the 30 arc-second GIS layer. Table A.II-2 presents estimated extents of REMAIN land in SSA, by country, in 2010.

Table A.II-1. Regions and Countries of sub-Saharan Africa

Major Region	Country	Area [1000 km²]	Major Region	Country	Area [1000 km²]
Eastern Africa	Burundi	27	Sudano-Sahelian Africa	Burkina Faso	275
	Ethiopia	1137		Chad	1272
	Kenya	586		Djibouti	22
	Madagascar	592		Eritrea	121
	Rwanda	26		Gambia	11
	Tanzania UR	946		Mali	1258
	Uganda	243		Mauritania	1043
Central Africa	Angola	1254		Niger	1189
	Cameroon	468		Senegal	197
	Central African Rep.	624		Somalia	637
	Congo, Dem. Rep.	2345		South Sudan	634
	Congo, Rep.	343		Abyei	10
	Equatorial Guinea	27		Sudan (former)	1853
	Gabon	266	Gulf of Guinea	Benin	116
Southern Africa	Botswana	581		Cote d'Ivoire	324
	Lesotho	31		Ghana	240
	Malawi	119		Guinea	245
	Mozambique	791		Guinea-Bissau	31
	Namibia	827		Liberia	97
	South Africa	1223		Nigeria	915
	Swaziland	17		Sierra Leone	73
	Zambia	756		Togo	57
	Zimbabwe	393	Rest	Rest of SSA	27

Table A.II-2. Extents of REMAIN land in sub-Saharan Africa, in 2010

square kilometers	Total land	REMAIN shrub-land	REMAIN grassland	REMAIN total
Eastern Africa	3,556,322	409,767	631,636	1,041,403
Burundi	27,058	1,658	2,143	3,801
Ethiopia	1,136,761	124,149	204,891	329,040
Kenya	586,179	101,384	132,897	234,282
Madagascar	591,580	62,774	232,989	295,763
Rwanda	25,564	326	282	608
Tanzania UR	945,977	104,406	47,251	151,657
Uganda	243,204	15,068	11,184	26,253
Central Africa	5,327,534	820,684	330,762	1,151,446
Angola	1,254,423	168,620	159,855	328,476
Cameroon	468,421	39,437	23,678	63,115
Central African Rep.	623,705	59,946	74,096	134,042
Congo, Dem. Rep.	2,345,013	493,843	35,514	529,357
Congo, Rep.	342,955	46,300	23,614	69,914
Equatorial Guinea	27,149	1,317	1,236	2,553
Gabon	265,868	11,221	12,769	23,990
Southern Africa	4,737,172	668,861	761,844	1,430,706
Botswana	580,636	31,846	177,394	209,240
Lesotho	30,521	431	5,255	5,686
Malawi	119,418	6,953	6,451	13,404
Mozambique	791,236	141,581	44,287	185,868
Namibia	827,334	11,028	300,814	311,841
South Africa	1,222,587	355,044	138,220	493,264
Swaziland	17,335	1,061	748	1,810
Zambia	755,530	91,372	43,726	135,097
Zimbabwe	392,574	29,547	44,949	74,496
Sudano-Sahelian Afr.	8,521,454	663,200	830,101	1,493,301
Abyei	9,980	126	25	151
Burkina Faso	274,871	36,983	37,403	74,386
Chad	1,271,730	60,483	157,778	218,260
Djibouti	21,807	15	633	648
Eritrea	121,430	12,527	9,005	21,532
Gambia	11,286	443	250	693
Mali	1,257,738	57,845	121,909	179,753
Mauritania	1,043,068	5,271	91,384	96,654
Niger	1,188,528	646	106,752	107,398
Senegal	197,281	20,431	11,349	31,780
Somalia	636,890	231,182	63,473	294,655
South Sudan	633,983	136,203	77,470	213,672
Sudan	1,852,862	101,046	152,672	253,718
Gulf of Guinea	2,096,840	250,634	135,494	386,128

square kilometers	Total land	REMAIN shrub-land	REMAIN grassland	REMAIN total
Benin	115,946	24,614	4,118	28,732
Cote d'Ivoire	323,795	44,636	25,023	69,659
Ghana	240,401	46,942	15,412	62,354
Guinea	244,524	9,143	29,155	38,297
Guinea-Bissau	30,861	2,212	1,481	3,694
Liberia	96,734	8,337	10,875	19,212
Nigeria	914,681	100,455	41,506	141,961
Sierra Leone	72,759	4,307	6,948	11,255
Togo	57,142	9,990	976	10,966
Rest of SSA	26,655	186	1,100	1,286
SSA Total	24,265,976	2,813,332	2,690,937	5,504,270

ANNEX III. SUITABILITY AND POTENTIAL PRODUCTION OF BIOFUEL FEEDSTOCKS ON REMAIN LAND, BY REGION, IN 2010

Annex III presents for each of the eleven biofuel feedstocks, the extents of REMAIN land (km2) assessed as very suitable (prime land), suitable (good land) or moderately suitable (moderate land) for rain-fed production (in dry weight), in total without considering GHG criteria, and extents compliant with the GHG 1 and GHG 2 criteria.

For comparison the table below shows total extents of REMAIN land by region.

square kilometers	Total REMAIN
Eastern Africa	1,041,403
Central Africa	1,151,446
Southern Africa	1,430,706
Sudano-Sahelian A.	1,493,301
Gulf of Guinea	386,128
SSAF	5,502,984

ANNEX III-1. SUGARCANE

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed sugarcane production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	VS+S share in REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	42,248	4 %	30,712	42,030	219
Central Africa	173,251	15 %	56,065	129,154	44,097
Southern Africa	5,341	0 %	1,858	3,594	1,746
Sudano-Sahelian Africa	5,764	0 %	3,394	5,587	178
Gulf of Guinea	18,962	5 %	14,385	18,962	0
SSA	245,569	4 %	106,415	199,330	46,239

b) Moderate land (MS)

square kilometers	Total MS	MS share in REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	59,369	6 %	50,142	59,007	362
Central Africa	331,332	29 %	136,609	258,605	72,727
Southern Africa	24,013	2 %	10,601	17,229	6,784
Sudano-Sahelian Africa	9,964	1 %	2,541	9,833	131
Gulf of Guinea	72,241	19 %	38,468	72,172	70
SSA	496,929	9 %	238,363	416,853	80,075

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed sugarcane and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons sugar	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	38,382	19 %	27,510	38,180	202
Central Africa	144,057	70 %	45,254	106,243	37,814
Southern Africa	4,061	2 %	1,440	2,766	1,295
Sudano-Sahelian Africa	4,557	2 %	2,692	4,421	136
Gulf of Guinea	15,634	8 %	11,841	15,634	0
SSA	206,694	100 %	88,738	167,248	39,446

b) Moderate land (MS)

1000 tons sugar	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	34,044	12 %	28,695	33,842	202
Central Africa	188,655	67 %	77,105	147,229	41,426
Southern Africa	14,199	5 %	6,311	10,246	3,953
Sudano-Sahelian Africa	5,592	2 %	1,501	5,526	67
Gulf of Guinea	40,406	14 %	21,878	40,368	38
SSA	282,900	100 %	135,491	237,214	45,686

ANNEX III-2. MAIZE

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed maize production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	285,406	27 %	0	140,618	144,788
Central Africa	143,972	13 %	0	40,405	103,567
Southern Africa	203,423	14 %	0	92,213	111,211
Sudano-Sahelian Africa	349,038	23 %	0	124,822	224,215
Gulf of Guinea	134,471	35 %	0	11,517	122,954
SSA	1,116,310	20 %	0	409,575	706,735

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	136,627	13 %	0	42,393	94,234
Central Africa	325,970	28 %	0	54,551	271,419
Southern Africa	135,822	9 %	0	59,948	75,874
Sudano-Sahelian Africa	136,065	9 %	0	20,221	115,844
Gulf of Guinea	65,974	17 %	0	918	65,056
SSA	800,461	15 %	0	178,029	622,432

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed maize and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons grain	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	219,714	26 %	0	114,954	104,760
Central Africa	100,980	12 %	0	30,920	70,060
Southern Africa	157,078	19 %	0	73,522	83,556
Sudano-Sahelian Africa	257,053	31 %	0	102,592	154,461
Gulf of Guinea	96,727	12 %	0	9,703	87,024
SSA	831,554	100 %	0	331,693	499,861

b) Moderate land (MS)

1000 tons grain	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	65,449	17 %	0	21,468	43,981
Central Africa	156,693	40 %	0	26,067	130,626
Southern Africa	67,599	17 %	0	31,637	35,962
Sudano-Sahelian Africa	63,839	16 %	0	9,917	53,922
Gulf of Guinea	33,328	9 %	0	447	32,881
SSA	386,910	100 %	0	89,535	297,375

ANNEX III-3. CASSAVA

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed cassava production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	181,386	17 %	0	47,878	133,507
Central Africa	513,972	45 %	0	27,631	486,341
Southern Africa	153,550	11 %	0	32,758	120,791
Sudano-Sahelian Africa	84,574	6 %	0	57	84,517
Gulf of Guinea	154,815	40 %	0	98	154,718
SSA	1,088,298	20 %	0	108,422	979,876

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	156,168	15 %	0	34,775	121,393
Central Africa	355,305	31 %	0	18,562	336,743
Southern Africa	105,931	7 %	0	25,920	80,011
Sudano-Sahelian Africa	89,542	6 %	0	90	89,452
Gulf of Guinea	94,662	25 %	0	70	94,593
SSA	801,619	15 %	0	79,418	722,201

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed cassava and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons grain	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	136,876	17 %	0	36,134	100,742
Central Africa	405,961	50 %	0	20,252	385,709
Southern Africa	105,619	13 %	0	21,024	84,594
Sudano-Sahelian Africa	58,962	7 %	0	47	58,915
Gulf of Guinea	111,306	14 %	0	72	111,235
SSA	818,726	100 %	0	77,529	741,196

b) Moderate land (MS)

1000 tons grain	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	76,765	19 %	0	16,857	59,908
Central Africa	187,843	46 %	0	8,865	178,978
Southern Africa	49,841	12 %	0	12,185	37,656
Sudano-Sahelian Africa	42,199	10 %	0	45	42,154
Gulf of Guinea	52,479	13 %	0	38	52,440
SSA	409,131	100 %	0	37,991	371,140

ANNEX III-4. SWEET SORGHUM

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed sweet sorghum production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	339,183	33 %	0	224,332	114,851
Central Africa	420,378	37 %	0	67,524	352,853
Southern Africa	256,722	18 %	0	139,399	117,323
Sudano-Sahelian Africa	389,540	26 %	0	228,404	161,136
Gulf of Guinea	182,970	47 %	0	39,646	143,324
SSA	1,588,795	29 %	0	699,304	889,490

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	141,753	14 %	0	78,670	63,083
Central Africa	442,176	38 %	0	72,650	369,525
Southern Africa	203,391	14 %	0	144,318	59,073
Sudano-Sahelian Africa	227,663	15 %	0	95,863	131,800
Gulf of Guinea	72,567	19 %	0	4,839	67,728
SSA	1,087,557	20 %	0	396,339	691,218

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed sweet sorghum and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons stem	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	460,060	23 %	0	313,118	146,942
Central Africa	500,011	25 %	0	89,063	410,948
Southern Africa	332,443	17 %	0	181,706	150,738
Sudano-Sahelian Africa	484,173	24 %	0	295,496	188,677
Gulf of Guinea	232,331	12 %	0	53,811	178,520
SSA	2,009,021	100 %	0	933,194	1,075,827

b) Moderate land (MS)

1000 tons stem	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	122,358	13 %	0	69,648	52,710
Central Africa	374,973	41 %	0	61,439	313,534
Southern Africa	167,933	18 %	0	117,876	50,057
Sudano-Sahelian Africa	179,812	20 %	0	73,136	106,676
Gulf of Guinea	64,405	7 %	0	3,880	60,525
SSA	909,488	100 %	0	325,978	583,510

ANNEX III-5. TRITICALE

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed triticale production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	20,056	2 %	0	37	20,018
Central Africa	6,809	1 %	0	187	6,622
Southern Africa	7,299	1 %	0	1,600	5,699
Sudano-Sahelian Africa	0	0 %	0	0	0
Gulf of Guinea	5	0 %	0	0	5
SSA	34,168	1 %	0	1,824	32,344

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	17,978	2 %	0	33	17,944
Central Africa	11,532	1 %	0	51	11,481
Southern Africa	8,501	1 %	0	666	7,834
Sudano-Sahelian Africa	21	0 %	0	0	21
Gulf of Guinea	31	0 %	0	0	31
SSA	38,062	1 %	0	750	37,312

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed triticale and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons grain	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	8,548	61 %	0	16	8,532
Central Africa	2,236	16 %	0	88	2,148
Southern Africa	3,208	23 %	0	816	2,392
Sudano-Sahelian Africa	0	0 %	0	0	0
Gulf of Guinea	2	0 %	0	0	2
SSA	13,992	100 %	0	919	13,073

b) Moderate land (MS)

1000 tons grain	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	4,942	47 %	0	11	4,931
Central Africa	3,260	31 %	0	18	3,241
Southern Africa	2,378	22 %	0	231	2,147
Sudano-Sahelian Africa	5	0 %	0	0	5
Gulf of Guinea	7	0 %	0	0	7
SSA	10,592	100 %	0	261	10,331

ANNEX III-6. MISCANTHUS

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed miscanthus production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	110,639	11 %	110,639	110,639	0
Central Africa	147,376	13 %	145,945	147,376	0
Southern Africa	48,811	3 %	48,811	48,811	0
Sudano-Sahelian Africa	26,834	2 %	26,834	26,834	0
Gulf of Guinea	55,286	14 %	55,286	55,286	0
SSA	388,951	7 %	387,520	388,951	0

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	170,245	16 %	170,244	170,245	0
Central Africa	560,818	49 %	559,500	560,818	0
Southern Africa	80,607	6 %	80,607	80,607	0
Sudano-Sahelian Africa	85,735	6 %	85,735	85,735	0
Gulf of Guinea	184,605	48 %	184,605	184,605	0
SSA	1,082,021	20 %	1,080,702	1,082,021	0

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed miscanthus and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

*10000 ton agb**	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	22,089	30 %	22,089	22,089	0
Central Africa	27,301	37 %	27,034	27,301	0
Southern Africa	9,311	13 %	9,311	9,311	0
Sudano-Sahelian Africa	5,001	7 %	5,001	5,001	0
Gulf of Guinea	10,132	14 %	10,132	10,132	0
SSA	73,834	100 %	73,568	73,834	0

b) Moderate land (MS)

*10000 ton agb**	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	23,997	16 %	23,997	23,997	0
Central Africa	78,403	51 %	78,209	78,403	0
Southern Africa	11,063	7 %	11,063	11,063	0
Sudano-Sahelian Africa	12,211	8 %	12,211	12,211	0
Gulf of Guinea	27,495	18 %	27,495	27,495	0
SSA	153,171	100 %	152,976	153,171	0

agb above ground biomass (matter)

ANNEX III-7. SOYBEAN

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed soybean production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	293,661	28 %	0	32,998	260,663
Central Africa	364,256	32 %	0	14,650	349,606
Southern Africa	226,975	16 %	0	58,190	168,785
Sudano-Sahelian Africa	329,639	22 %	0	1,014	328,625
Gulf of Guinea	156,748	41 %	0	0	156,748
SSA	1,371,281	25 %	0	106,852	1,264,429

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	124,076	12 %	0	11,704	112,372
Central Africa	495,629	43 %	0	27,970	467,659
Southern Africa	146,679	10 %	0	53,942	92,737
Sudano-Sahelian Africa	127,065	9 %	0	65	127,000
Gulf of Guinea	97,550	25 %	0	0	97,550
SSA	991,007	18 %	0	93,681	897,326

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed soybean and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons beans	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	103,078	23 %	0	12,362	90,716
Central Africa	114,607	25 %	0	4,959	109,648
Southern Africa	77,859	17 %	0	20,499	57,360
Sudano-Sahelian Africa	106,523	23 %	0	372	106,151
Gulf of Guinea	51,850	11 %	0	0	51,850
SSA	453,918	100 %	0	38,192	415,726

b) Moderate land (MS)

1000 tons beans	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	28,958	13 %	0	2,904	26,054
Central Africa	115,571	50 %	0	6,001	109,569
Southern Africa	33,547	15 %	0	12,882	20,665
Sudano-Sahelian Africa	29,069	13 %	0	15	29,054
Gulf of Guinea	23,734	10 %	0	0	23,734
SSA	230,881	100 %	0	21,802	209,078

ANNEX III-8. OIL PALM

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed oil palm production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	2,153	0 %	2,153	2,153	0
Central Africa	59,699	5 %	59,699	59,699	0
Southern Africa	0	0 %	0	0	0
Sudano-Sahelian Africa	0	0 %	0	0	0
Gulf of Guinea	18,340	5 %	18,340	18,340	0
SSA	80,194	1 %	80,194	80,194	0

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	1,739	0 %	1,739	1,739	0
Central Africa	117,834	10 %	117,834	117,834	0
Southern Africa	28	0 %	28	28	0
Sudano-Sahelian Africa	111	0 %	111	111	0
Gulf of Guinea	21,329	6 %	21,329	21,329	0
SSA	141,043	3 %	141,043	141,043	0

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed oil palm and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons oil	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	1,213	3 %	1,213	1,213	0
Central Africa	28,436	74 %	28,436	28,436	0
Southern Africa	0	0 %	0	0	0
Sudano-Sahelian Africa	0	0 %	0	0	0
Gulf of Guinea	8,858	23 %	8,858	8,858	0
SSA	38,508	100 %	38,508	38,508	0

b) Moderate land (MS)

1000 tons oil	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	595	1 %	595	595	0
Central Africa	38,889	83 %	38,889	38,889	0
Southern Africa	9	0 %	9	9	0
Sudano-Sahelian Africa	31	0 %	31	31	0
Gulf of Guinea	7,185	15 %	7,185	7,185	0
SSA	46,710	100 %	46,710	46,710	0

ANNEX III-9. JATROPHA

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed jatropha production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	157,770	15 %	156,454	157,509	262
Central Africa	488,372	42 %	438,247	477,130	11,241
Southern Africa	67,672	5 %	63,327	67,063	609
Sudano-Sahelian Africa	46,298	3 %	46,232	46,298	0
Gulf of Guinea	153,039	40 %	153,039	153,039	0
SSA	913,155	17 %	857,303	901,042	12,113

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	119,496	11 %	119,073	119,446	50
Central Africa	340,875	30 %	307,506	334,436	6,438
Southern Africa	47,824	3 %	44,158	47,465	359
Sudano-Sahelian Africa	72,239	5 %	72,239	72,239	0
Gulf of Guinea	90,011	23 %	90,011	90,011	0
SSA	670,456	12 %	632,998	663,609	6,847

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed jatropha and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons seed	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	44,599	19 %	44,213	44,523	76
Central Africa	123,434	52 %	110,902	120,634	2,800
Southern Africa	18,951	8 %	17,756	18,778	173
Sudano-Sahelian Africa	12,482	5 %	12,463	12,482	0
Gulf of Guinea	39,470	17 %	39,470	39,470	0
SSA	238,937	100 %	224,805	235,887	3,050

b) Moderate land (MS)

1000 tons seed	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	21,754	18 %	21,677	21,745	9
Central Africa	60,962	50 %	54,934	59,757	1,205
Southern Africa	8,464	7 %	7,821	8,401	63
Sudano-Sahelian Africa	12,818	11 %	12,818	12,818	0
Gulf of Guinea	17,605	14 %	17,605	17,605	0
SSA	121,604	100 %	114,857	120,328	1,276

ANNEX III-10. SOLARIS TOBACCO

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed Solaris tobacco production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	106,328	10 %	0	10,677	95,651
Central Africa	161,251	14 %	0	18,307	142,943
Southern Africa	91,824	6 %	215	25,357	66,467
Sudano-Sahelian Africa	4,784	0 %	0	0	4,784
Gulf of Guinea	44	0 %	0	22	22
SSA	366,652	7 %	215	54,363	312,289

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	132,006	13 %	0	6,096	125,910
Central Africa	255,862	22 %	0	4,365	251,497
Southern Africa	148,348	10 %	94	30,028	118,320
Sudano-Sahelian Africa	8,430	1 %	0	0	8,430
Gulf of Guinea	5	0 %	0	3	3
SSA	553,712	10 %	94	40,492	513,220

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed Solaris tobacco and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons seed	Total VS+S	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	37,318	30 %	0	3,899	33,419
Central Africa	54,905	44 %	0	7,053	47,852
Southern Africa	29,133	24 %	66	8,186	20,947
Sudano-Sahelian Africa	1,498	1 %	0	0	1,498
Gulf of Guinea	17	0 %	0	9	9
SSA	123,638	100 %	66	19,146	104,492

b) Moderate land (MS)

1000 tons seed	Total MS	Share in SSA	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	30,805	24 %	0	1,458	29,346
Central Africa	60,576	47 %	0	986	59,590
Southern Africa	34,254	26 %	23	6,882	27,372
Sudano-Sahelian Africa	1,932	1 %	0	0	1,932
Gulf of Guinea	1	0 %	0	1	1
SSA	129,643	100 %	23	9,328	120,316

ANNEX III-11. CAMELINA

Suitability of REMAIN land

Suitability of REMAIN land for rain-fed camelina production and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

square kilometers	Total VS+S	Share of VS+S in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	23,939	2 %	0	0	23,939
Central Africa	1,529	0 %	0	0	1,529
Southern Africa	12,673	1 %	0	0	12,673
Sudano-Sahelian Africa	12	0 %	0	0	12
Gulf of Guinea	0	0 %	0	0	0
SSA	38,153	1 %	0	0	38,153

b) Moderate land (MS)

square kilometers	Total MS	Share of MS in Total REMAIN land	Compliance with GHG criteria		
			GHG 1	GHG 2	not met
Eastern Africa	45,050	4 %	0	0	45,050
Central Africa	50,372	4 %	0	0	50,372
Southern Africa	59,210	4 %	0	0	59,210
Sudano-Sahelian Africa	53	0 %	0	0	53
Gulf of Guinea	13	0 %	0	0	13
SSA	154,697	3 %	0	0	154,697

Potential production on REMAIN land

Potential production on REMAIN land of rain-fed camelina and its compliance with different GHG criteria for biofuel production pathways, in 2010

a) Prime and good land (VS+S)

1000 tons seed	**Total VS+S**	**Share in SSA**	**Compliance with GHG criteria**		
			GHG 1	GHG 2	not met
Eastern Africa	2,071	63 %	0	0	2,071
Central Africa	126	4 %	0	0	126
Southern Africa	1,071	33 %	0	0	1,071
Sudano-Sahelian Africa	1	0 %	0	0	1
Gulf of Guinea	0	0 %	0	0	0
SSA	3,269	100 %	0	0	3,269

b) Moderate land (MS)

1000 tons seed	**Total MS**	**Share in SSA**	**Compliance with GHG criteria**		
			GHG 1	GHG 2	not met
Eastern Africa	2,722	30 %	0	0	2,722
Central Africa	3,105	34 %	0	0	3,105
Southern Africa	3,372	37 %	0	0	3,372
Sudano-Sahelian Africa	3	0 %	0	0	3
Gulf of Guinea	1	0 %	0	0	1
SSA	9,203	100 %	0	0	9,203

ANNEX IV. UNDERSTANDING THE DIFFERENCES IN GHG EMISSION CRITERIA

In this study two alternative GHG criteria have been tested and imposed to ensure satisfactory greenhouse gas emission savings of the selected feedstock types, including the consideration of carbon losses due to land conversion from REMAIN land (i.e. grass or shrub land) to the cultivation of crops.

The cumulative GHG balance (per MJ) of a fuel chain in year t can be written as

$$dGHG(t) = t * (eCO2_{fossil} - eCO2_{LCA}) - T_0 * dCO2_{LUC}$$

where

t	time [years]
T_0	length of the accounting period [years]
$dCO2_{LUC}$	annualized CO2equ emission due to direct land use change [gCO2eq/MJ]
$eCO2_{LCA}$	lifecycle emissions of biofuel pathway (excluding land use change) [gCO2eq/MJ]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [gCO2eq/MJ]

The resulting average GHG saving rate s_GHG (t) achieved after t years is:

$$s_{GHG}(t) = [t * (eCO2_{fossil} - eCO2_{LCA}) - T_0 * dCO2_{LUC}] / (t * eCO2_{fossil})$$

or

$$s_{GHG}(t) = 1 - \left[\frac{eCO2_{LCA}}{eCO2_{fossil}}\right] - \left[\frac{dCO2_{LUC}}{eCO2_{fossil}}\right] * \frac{T_0}{t}$$

From equation (3) it can be easily seen that for long periods in the limit, i.e. for $t\rightarrow\infty$, the GHG saving rate only depends on the results of the lifecycle emissions of a biofuel pathway (excluding land use change), namely

$$\lim_{t\rightarrow\infty} s_{GHG}(t) = 1 - \left[\frac{eCO2_{LCA}}{eCO2_{fossil}}\right]$$

The first GHG criterion used in the study requires annualized emissions per MJ from biofuel production, including annualized changes in soil and vegetation carbon stocks, to achieve at least a minimum relative GHG saving smin. The RSB standard sets the minimum threshold smin at 60% savings compared to the use of fossil fuels. We apply as fossil comparator in this study a value of 94 gCO2eq/MJ. The first GHG criterion is tested according to equ. (5):

$$eCO2_{LCA} + dCO2_{LUC} \leq (1 - s_{min}) * eCO2_{fossil}$$

where

s_{min} minimum GHG saving rate expressed as share of comparator [dimensionless]

When defining relative lifecycle emissions s_{LCA} and relative land carbon losses c_{LUC} as

$$s_{LCA} = 1 - [\frac{eCO2_{LCA}}{eCO2_{fossil}}] \quad \text{and} \quad c_{LUC} = [\frac{dCO2_{LUC}}{eCO2_{fossil}}]$$

the average GHG saving rate s_{GHG} (t) introduced in equation (3) can be written as

$$s_{GHG}\ (t) = s_{LCA} - c_{LUC} * (\frac{T_0}{t})$$

To satisfy the GHG criterion 1, the necessary condition for t=T0 regarding the minimum saving threshold translates into

$$s_{GHG}\ (T_0) \geq s_{min}$$

which is

$$s_{LCA} - c_{LUC} \geq s_{min}$$

or

$$c_{LUC} \leq s_{LCA} - s_{min}$$

Condition (11) means that annualized carbon losses due to land use change cannot exceed the difference between lifecycle savings and the minimum required saving.

Due to the carbon losses resulting from land conversion, meeting GHG criterion 1 puts rather severe restrictions on the possible conversion of grassland/shrub land and applicable soil management options for cultivation of annual crops for biofuel feedstock production.

To provide a broader understanding of GHG emission impacts, we also evaluated a second, somewhat less strict, GHG emission criterion demanding two conditions. First, the lifecycle emissions of the biofuel production (excluding land use change) must achieve a minimum emission saving s_{min} compared to the lifecycle emissions of the fossil comparator. Second, it requires that the carbon debt encountered due to land use change has a payback time of less than half the accounting period, i.e. within 10 years when using an accounting period of 20 years. The GHG 2 criterion can be described by equations (12) and (13):

$$eCO2_{LCA} \leq (1 - s_{min}) * eCO2_{fossil}$$

and

$$T_0 * dCO2_{LUC} \leq \frac{T_0}{2} * (eCO2_{fossil} - eCO2_{LCA})$$

Using the variables introduced above, the conditions (12) and (13) can also be written as

$$s_{LCA} \geq s_{min}$$

and

$$c_{LUC} \leq \frac{1}{2} s_{LCA}$$

When comparing two different biofuel chains characterized by lifecycle saving coefficients s^1_{LCA} and s^2_{LCA} and by respective annualized dLUC carbon loss factors c^1_{LUC} and c^2_{LUC}, the resulting difference in average GHG saving rates $\Delta s_{GHG}(t)$ in year t can be calculated using equation (8):

$$\Delta s_{GHG}(t) = \Delta s_{LCA} - \Delta c_{LUC} * \left(\frac{T_0}{t}\right)$$

where Δs_{LCA} and Δc_{LUC} denote the differences in the respective coefficients. Condition (16) underlines the importance of achieving best possible lifecycle results and shows that the importance of differences in dLUC related carbon losses diminishes with time of use.

An example of GHG criteria impacts for selection of annual crops

In this calculation example we illustrate the impact of applying the different GHG emission saving criteria by portraying a representative case of Solaris tobacco.

We assess land conversion in the tropical montane zone from grassland to cultivation of Solaris tobacco under a land management of no tillage and high organic input (without input of manure) of a mineral soil with an average organic carbon content in the topsoil layer (0-30cm depth) of 40 ton C ha^{-1}. In comparison, IPPC lists for mineral soils in this climatic zone a range of default soil carbon stocks of 34 - 88 ton C ha^{-1}.

Under these conditions and applying the reference soil carbon stock change factors for the assumed management, an estimated annualized soil carbon loss over the accounting period of 20 years results of dCs = 40*(1.0-0.64*1.16*1.08)/20 = 0.396 ton C ha^{-1}. For the grassland cover in this example a biomass carbon stock C_b = 4.5 ton C ha^{-1} before conversion is assumed. Since the land is converted to annual cropping, all grass biomass is lost and therefore the annualized lost biomass is $dC_b = C_b/20 = 0.225$ ton C ha^{-1}. The annualized CO2equ emissions due to direct land use change $dCO2_{LUC}$ [$gCO2_{eq}$/MJ] are then calculated according to

$$dCO2_{LUC} = \rho * (dC_S + dC_B) * (\frac{44}{12}) * 1e^6 / Y_{fuel}$$

where

dC_B annualized change in biomass carbon stocks due to land use change [ton C/ha]

dC_S annualized change in carbon stocks of mineral soil due to land use change [ton C/ha]

ρ share of land use change emissions allocated to biofuel feedstock [dimensionless]

Y_{fuel} annual fuel yield of projected land use [MJ/ha]

For the calculation of the Solaris fuel yield Yfuel we use in this example a crop yield of YSol = 5 ton ha-1 and a conversion technology producing 370 litres of fuel per ton with an energy content of 12095 MJ per ton of Solaris tobacco seeds. Thus, Yfuel = 12095*YSol. For the attribution of dLUC emissions to Solaris oil we use 70% and therefore ρ = 0.7.

Using coefficients and parameter values as given above, we can now express the annualized CO2equ emissions due to direct land use change as a function of soil carbon stock and Solaris crop yield:

$$dCO2_{LUC} = 0.7 * (\frac{C_s}{20} * (1.0 - 0.64 * 1.16 * 1.08) + \frac{4.5}{20}) * (\frac{44}{12}) * 1e^6 / (12095 * Y_{Sol})$$

Which can be simplified to

$$dCO2_{LUC} = (C_S * 2.1031 + 47.747) / Y_{Sol}$$

To continue the evaluation in this example, we use lifecycle emissions for Solaris fuel production of $eCO2_{LCA} = 23$ $gCO2_{eq}$/MJ and the fossil comparator $eCO2_{fossil} = 94$ $gCO2_{eq}$/MJ and we calculate the relative lifecycle emissions s_{LCA} and relative land carbon losses c_{LUC} used in equation (8) as: GHG 1 criterion: Application of the GHG 1 criterion this

$$s_{LCA} = 1 - [\frac{eCO2_{LCA}}{eCO2_{fossil}}] = 0.7553$$

Which can be simplified to

$$c_{LUC} = \frac{dCO2_{LUC}}{eCO2_{fossil}} = (C_S * 0.02237 + 0.50795) / Y_{Sol}$$

implies meeting condition (11), namely $c_{LUC} \leq s_{LCA} - s_{min}$. With a minimum GHG savings requirement of 60%, s_{min} = 0.6, this becomes:

$$(C_S * 0.02237 + 0.50795)/Y_{Sol} \leq 0.7553 - 0.60$$

or

$$C_S \leq 6.9414 * Y_{Sol} - 22.7034$$

For a good Solaris seed yield of Y_{Sol} = 5 ton ha^{-1} in this example, meeting the GHG 1 criterion would require $C_s \leq 12.0$ ton C ha^{-1} which is much lower than the actual soil carbon stock of 40 ton C ha^{-1}. Hence, Solaris tobacco cannot meet the GHG 1 criterion in this location.

GHG 2 criterion: Under the GHG 2 criterion the conditions (14) and (15) must be met, namely

$s_{LCA} \geq s_{min}$ and $c_{LUC} \leq \frac{1}{2} s_{LCA}$. With s_{LCA} = 0.7553 the first condition is met by Solaris based fuel. The second condition implies:

$$(C_S * 0.02237 + 0.50795)/Y_{Sol} \leq 0.37765$$

or

$$C_S \leq 16.880 * Y_{Sol} - 22.7034$$

Using again a Solaris seed yield of Y_{Sol} = 5 ton ha^{-1} implies that the GHG 2 criterion can be met on soils with a carbon stock of $C_s \leq 61.7$ ton C ha^{-1}. In our example the Solaris based fuel can meet the GHG 2 criterion.Finally, let us look at the average GHG savings rate that can be achieved with the Solaris based fuel under the conditions assumed in this example. Using equation (8) we have after t years an average saving of

$$s_{GHG}(t) = s_{LCA} - c_{LUC} * \left(\frac{T_0}{t}\right)$$

which is

$$s_{GHG}(t) = 0.7553 - (C_S * 0.02237 + 0.50795)/Y_{Sol} * \left(\frac{20}{t}\right)$$

and for the values used in this example

$$s_{GHG}(t) = 0.7553 - (40 * 0.02237 + 0.50795)/5 * \left(\frac{20}{t}\right)$$

or

$$s_{GHG}(t) = 0.7553 - 5.6115/t$$

This means that after 10 years due to paying back the soil carbon debt a GHG saving of 19% is reached, after 20 years the saving becomes 47% (compared to required 60% under GHG 1) relative to fossil fuel use, after 30 years it will be 57% percent, and assuming that the scheme would run for 50 years the achievable savings would be 64%.

Conclusions

The above comparison of the two GHG criteria used in the study leads to a few key points on their differences and some conclusions concerning their relevance for feedstock production on REMAIN land:

- For $c_{LUC} \geq 0$ the condition (10) defining GHG criterion 1 is always more limiting than the combination of conditions (14) and (15) used for GHG 2.
- In the limit, when the new land use is assumed to persist, GHG savings for both criteria solely depend on the ratio of lifecycle greenhouse emissions relative to the fossil comparator.
- In the worst case under GHG 2, i.e. when the carbon payback period for land cover change is exactly half of the accounting period T_o, the average greenhouse gas saving achieved over the accounting period T_o is half of s_{LCA}.
- Tightening the conditions on permissible lifecycle emissions and resulting savings rates s_{LCA} in combination with an acceptable payback period for dLUC carbon losses would provide focused and best possible incentives for savings in the longer term as this would apply also to situations where no or very minor soil/vegetation carbon losses occur.
- Results of the study highlight the importance of GHG criteria specification in the calculation of feedstock potentials.
- Use of the GHG 1 criterion has a large effect on the applicability of annual crops for feedstock production on REMAIN land as only a small fraction of total extents can meet this criterion. Perennial crops can generally meet the strict GHG 1 criterion due to carbon stored in the vegetation and better protection of soil carbon. As a consequence of applying the GHG 1 criterion, only land can be considered that meets the specific ecological growth requirements of perennials, which restricts the choice of suitable rain-fed areas to mainly the moist sub-humid and humid climate zones and REMAIN resources in the dry sub-humid and semi-arid zones are excluded from rain-fed feedstock production.
- As shown in the calculation example, in locations where perennials cannot be grown without irrigation and annual crops are not able to meet the GHG 1 criterion, crops admitted under the GHG 2 criterion could still produce large quantities of biofuel feedstocks and achieve substantial greenhouse gas savings.
- Limiting feedstock production to perennials may severely hamper options to involve small scale production by local farmers and to integrate biofuel feedstocks in food, feed and fodder crop rotations. Moreover, such rotations would be beneficial for maintaining soil productivity.

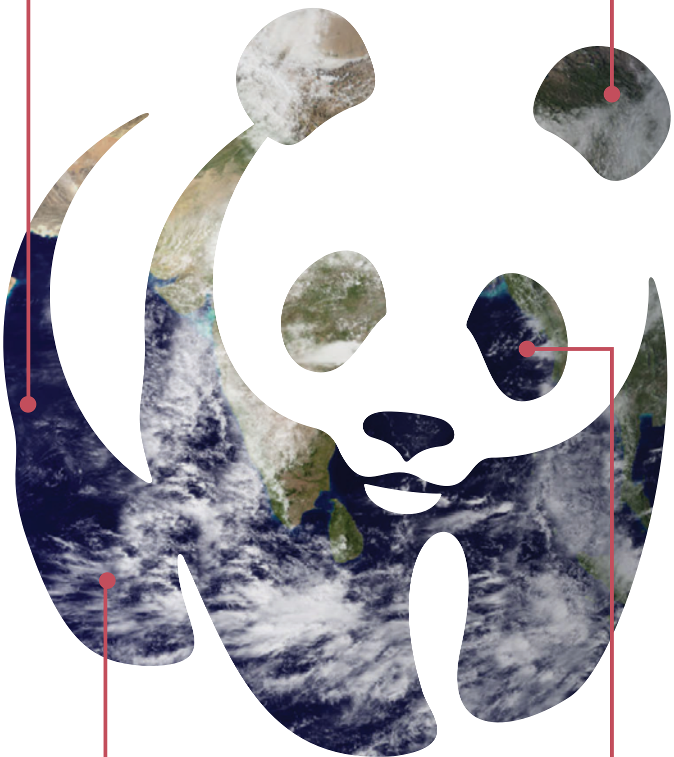
Understanding the sustainable aviation biofuel potential in sub-Saharan Africa

50%

Minimum reduction in net aviation CO_2 emissions needed by 2050, relative to 2005 levels

30%

Proportion of global demand for alternative aviation fuels that could be produced in sub-Saharan Africa



150 000

Number of commercial flights already fuelled with a blend of alternative fuel

54%

Portion of land in sub-Saharan Africa needed to produce food and protect critical ecosystems

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