TAKING OFF - UNDERSTANDING THE SUSTAINABLE AVIATION BIOFUEL POTENTIAL IN SUB-SAHARAN AFRICA: A SYSTEM ANALYSIS INVESTIGATION INTO THE CURRENT AND FUTURE POTENTIAL FOR SUSTAINABLE BIOFUEL FEEDSTOCK PRODUCTION IN THE SUB-SAHARAN AFRICA REGION

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ABSTRACT

To achieve the goal of limiting global warming to 1.5°C, rapid decarbonisation of all economic sectors is required, including aviation. Airlines looking to reduce their carbon footprints could create a substantial demand-pull for biomass-based fuels, perceived to be ‘low carbon’, which may come with significant sustainability risks. This study provides an assessment of the current and future production potential for sustainable biofuel production in sub-Saharan Africa, in an effort to understand the region’s potential contribution to a global market for sustainable aviation fuels. This requires a systems analysis approach to estimating the availability of biomass for producing biofuel in general and aviation biofuel in particular. FAO/IIASA’s ‘Agro-ecological zones’ models using the latest available spatial environmental data and feedstock requirement information, additionally integrating strict sustainability criteria based on the Roundtable for Sustainable Biomaterials allow us to identify technical biofuel production potentials based on optimisation of “remain” land that is not needed for current or future food production or biodiversity conservation and does not hold significant carbon stocks. Results indicate that following strict sustainability criteria the sub-continent can produce a significant amount of biofuels from energy crops. However, by 2050, yields are expected to decline for some energy crops, due to a combination of adverse impacts of climate change on agricultural productivity and reduced land availability.

1. CONTEXT AND STUDY AIM

The Paris Agreement (UN, 2015) at COP21 in 2015 brought the global community together in its commitment to limit global warming to a 2°C temperature increase, with the ambition to achieve a limit of 1.5°C. To achieve this goal, rapid decarbonisation of all economic sectors is required, including those not covered by the Paris Agreement. Aviation is a case in point. Currently, the aviation sector contributes between 2% and 2.5% of global CO2 emissions (IPCC, 1999; IPCC, 2007; Lee et al., 2009). Adding non-CO2 emissions approximately doubles the sector’s contribution to global warming (Lee et al., 2009). While these figures may appear relatively low today, the fast growth in air traffic and the related increase in jet fuel consumption suggest that by 2050 global aviation could account for over 22% of all anthropogenic CO2 emissions (Cames et al., 2015).

To mitigate the growing impact on climate, the United Nations (UN) body governing international aviation, the International Civil Aviation Organization (ICAO) has adopted two aspirational goals for the sector – a 2% annual fuel efficiency improvement through 2050, and carbon-neutral growth from 2020 onwards (known as the CNG2020 goal). However, the technical and operational advances available today will not be able to keep pace with the fast growth in air traffic (ICAO, 2016). The sector is therefore placing much hope on a combination of alternative fuels and market-based measures (such as carbon offsets) to mitigate its growing emissions and close the sector's CO2 gap (Figure 1).

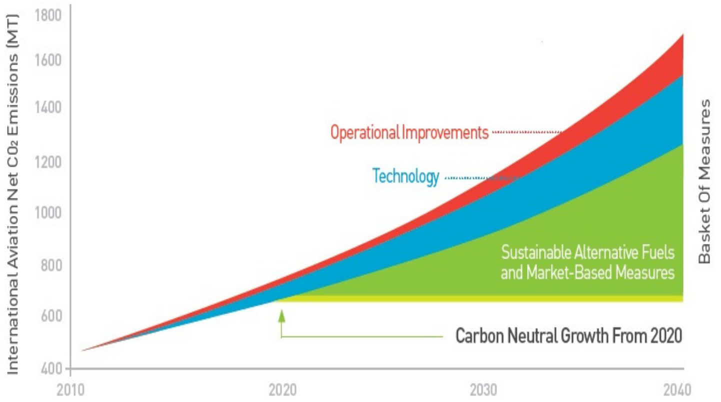

Figure 1: Contributions of measures for reducing the net CO2 emissions of international aviation (ICAO, 2016)

While alternative fuels or "Sustainable aviation fuels (SAF)," as they are more commonly referred to within the aviation sector, are no longer synonymous with biofuels because of recent ground-breaking innovation in alternative liquid fuel technology, the expectation is that in the short to medium term, much of these fuels will be bio-based. The magnitude of the potential demand for SAF is a cause for concern. ICAO has proposed a volumetric target for biofuel used in international aviation of 285 million tons per annum, which is approximately 50% of the projected total fuel demand of international aviation in 2050 (ICAO, 2017). Domestic aviation is also likely to become an important source of demand for bio jet fuel, with an increasing number of countries considering blending mandates for such fuel. By comparison, the total current biofuel output globally is in the range of 130 million tons per annum (IEA, 2019). The controversy around biofuels has been growing with the levels of production. The new sector will potentially add demand that is more than double the current levels of production, which raises serious sustainability risks for the biomass used to produce SAF.

Biomass is a limited resource and the sustainability of its large-scale supply depends on the resources available for its production. Sustainability must be considered in the broader context of demand for food and water, the need to safeguard natural environments and protected areas, and the competing biomass demand for power generation and transport fuels in other sectors (road and shipping). The vast land resources in sub-Saharan Africa (SSA) have placed the region among one of the major expansion areas for the production of biofuel feedstocks. To ground these aspirations in real-world-conditions, the development of biomass for energy needs to take due account of SSA's agricultural and socio-economic development.

The aim of this study was to provide a realistic assessment of the current and future biofuel production potential of countries in SSA that will not compete with production of food, feed and other industrial crops, nor the need to preserve critical biodiversity and ecosystem services. The assessment covered both energy crops and agricultural residues; however since significant upscaling of energy crops production represents higher sustainability risks, the focus in this paper is on the former.

Understanding the sustainable biofuel production potential of the region addresses a secondary aim of the study, which is gaining a sense of the possible role the sub-continent could play in the emerging global market for SAF, the opportunity this potential new export market represents and what conditions need to be present to maximise the benefits while minimising the risks.

2. APPROACH, METHODS AND DATA

2.1 Systems Analysis for Studying the Agriculture-Energy-Environment Nexus

The transition to a low-carbon economy by using biomass as one of the energy sources will intensify the linkages between the agriculture and energy sectors. As food, feed and energy markets are increasingly integrated, challenges and opportunities will arise. Moreover, the agricultural production system is embedded in a dynamic socio-economic, environmental and cultural setting. Understanding these key linkages is imperative for an evaluation of possible consequences and indirect effects of policies that govern the agriculture and energy markets.

Increasing biofuel feedstock production in SSA, while at the same time meeting growing food demand and following strict sustainability principles, faces a high degree of complexity. Integrated systems analysis that adequately considers the spatial and inter-temporal linkages of the whole system, while analysing its individual components, provides a suitable analytical framework to address complex systems. In this instance the ‘system’ under analysis is the agriculture-energy-environment nexus, while food and biofuel feedstock production are its individual, but interdependent, components. The aim is to estimate biofuel potentials that are compatible with long-term food security and environmental integrity.

Following the systems analysis approach, the modelling framework employed in this study consists of six main elements (Figure 2):

1. A storyline and quantified macro-drivers of development. For this purpose, we chose the widely used Shared Socio-economic Pathways (SSPs)[1], which include projections of demographic changes, economic growth and the related changes in diets and agricultural production needed to support them in each country globally. The SSP narratives also include assumptions on important elements of the international setting, such as trade liberalisation, technological progress and the priorities of land-use regulation. In this study, we modelled the outcomes of SSP1 – ‘Sustainability’ and ‘SSP2 – ‘Middle of the road’.
2. A Greenhouse Gas (GHG) concentration pathway (measured in CO2 equivalents). This is associated with the chosen development scenario, which is used to define applicable future climate scenarios. Here we relied on the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs) that are widely used to model the possible climate effects of different CO2 concentrations[2]. In this study, we considered RCP 2.6 (compatible with a warming limit of 1.5°C) and RCP 6.0 (medium warming).

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[1] For a complete overview of the SSPs, see https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

[2] For more information on the Representative Concentration Pathways, see for example: sedac.ipcc-data.org/ddc/_ar5_scenario_process/RCPs.html

3. The Global Agro-Ecological Zones method (GAEZ). This methodology 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. These impacts have been aggregated and incorporated into the World Food System model.
5. The global general equilibrium World Food System (WFS) model. It is informed by the development storyline, scenario-specific quantified drivers (population and economic growth) and estimated climate change yield impacts, and was used to evaluate global food system scenarios. This model 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 these activities[3].
6. Results of the WFS simulations. These were 'downscaled' and distributed across the area under investigation, in this case SSA.

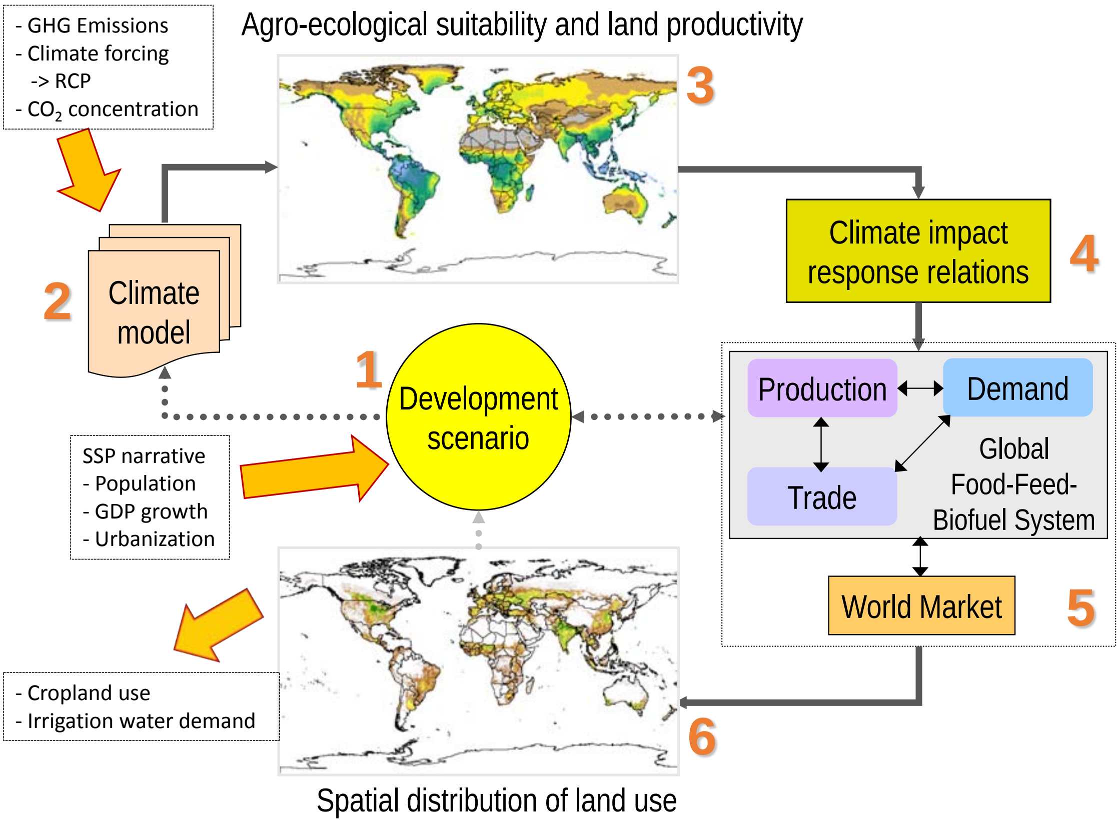

Figure 2: Ecological-economic modelling framework for future projections applied in this study

2.2 Incorporating Sustainability Principles

The prerequisite for biofuel production in SSA or elsewhere should be conformity to the highest sustainability standard. This study applies the sustainability standard for biomaterials, including biofuels, developed by the Roundtable on Sustainable Biomaterials (RSB) (RSB, 2016), which is regarded as best-in-class (WWF, 2013)[4]. Some of the RSB's 12 principles and related criteria are applicable to and can only be assessed at the project

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[3] For more information on the World Food System model, see: iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/WFS.en.html

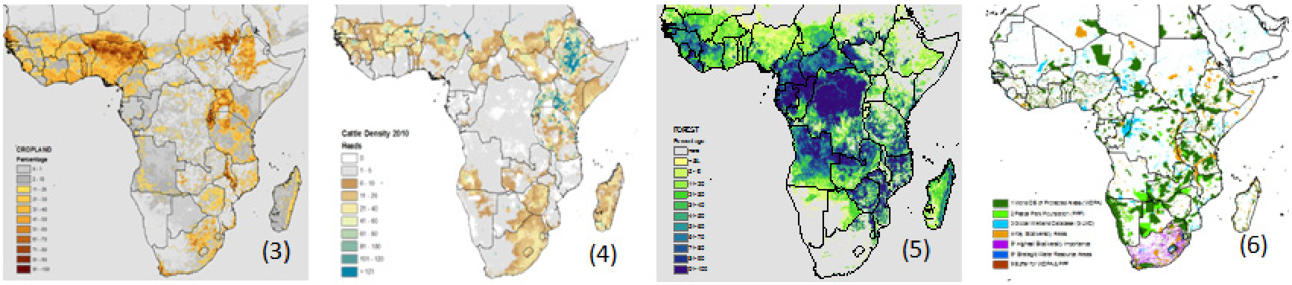
[4] For more information on the RSB, see www.rsb.org

level, while its environmental principles can be applied at a broad geographic scale and used as constraints for potential biofuel feedstock production in SSA.

Below we summarize those principles and describe their interpretation in our study approach:

- Principle 3 on GHG criteria: Any biofuels produced in SSA must deliver a minimum of 60% GHG emission savings compared to fossil fuels.
- Principle 6 on Food security: Cropland needed for current and future food, feed and industrial crop (other than biofuel feedstock) production has been reserved upfront (Figure 3), as have grassland/savannah required for feeding ruminant livestock (Figure 4). No biofuel feedstock production is allowed in these areas.
- Principle 7 on Conservation: No deforestation for biofuel feedstock production is allowed (Figure 5). Protected areas, key biodiversity areas and other areas providing important ecosystems services as classified by a number of conservation databases are also designated as no-go zones for biofuel feedstock production (Figure 6). In addition, where biofuel feedstock production is allowed, it follows the principles of conservation agriculture.
- Principle 8 on Soil conservation: Soils of high organic matter content where land conversion would cause a high carbon debt, as well as all steep terrain have also been excluded from biofuel feedstock production.
- Principle 9 on Water management: Biofuel feedstock production is rain-fed only[5].

Principles 6, 7 and 8 have been operationalised by creating the spatial layers shown in Figures 3 – 6 and designating them as “no-go” areas for biofuel feedstock production.



Figures 3-6: Exclusion layers - Cropland (3), Grazing land (4), Forest (5) and Environment (6)

These exclusion layers were deducted from total land in the region, which resulted in the quantification of land that could be considered for biofuel feedstock production once food and environmental sustainability criteria have been taken into account, termed ‘REMAIN’ land. We have compiled a layer of REMAIN land for the base year 2010, which has been dynamically updated to 2050 applying selected socio-economic development and climate change scenarios. In a second step, the identified ‘REMAIN’ land was assessed for its agro-ecological suitability for potential production of biofuel feedstocks listed in Table 1.

We refer to Fischer et al. (2019) for details on the applied methods and data.

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[5] This might be an over-conservative assumption in some basins in the region, however due to limited data availability for the delineation of water-scarce areas, we chose to err on the side of caution.

Table 1: Feedstock crops assessed for potential contribution to biofuel production

First-generation biofuel production chains	First-generation biofuel production chains	Second-generation biofuel production chains
BIODIESEL	BIOETHANOL	LIGNOCELLULOSIC ETHANOL
• Solaris tobacco • Jatropha • Oil palm • Soybean • Camelina	• Sugarcane • Maize (grain and stover) • Sweet sorghum • Cassava • Triticale	• Miscanthus • Crop residues

Of the feedstocks included in the analysis, all have been farmed in the region to different extents, except miscanthus. Solaris has not been farmed commercially but is very similar to conventional tobacco and has concluded successful trials in South Africa and Malawi.

3. RESULTS

The first step in the assessment was to delineate and quantify the tracts of land potentially available for sustainable biofuel feedstock production. A balance of 5.5 million km^2 (23% of total land) can be classified as 'REMAIN LAND' once environmental and food sustainability criteria have been addressed and very low-productivity sparsely vegetated and bare land has been excluded (Table 2).

Table 2: Availability of current "REMAIN land" in milion km^2

Total land extent of sub-Saharan Africa (2010)	**24.27**
Exclusion layer FOOD	-2.35
Exclusion layer FOREST	-6.90
Exclusion layer ENVIRONMENT + GRAZING	-3.89
Exclusion SPARSELY VEGETATED and BARE LAND	-5.62
"REMAIN LAND"	**5.5**

In Figure 7, the map on the left shows the distribution and density of REMAIN land across SSA in 2010 as percentage of land in each 5 arcmin grid cell. The map on the right shows the estimated number of annual growing period days under current climatic conditions. Combined together, the maps indicate that a high density of REMAIN land usually coincides with limiting agro-climatic conditions. Hence only a relatively small fraction of REMAIN land can support economically viable biofuel feedstock production because of differences in prevailing agro-climatic, soil and terrain conditions. These areas are classified as very suitable (VS) (prime) or suitable (S) (good) for specific energy crop production, achieving 80–100% (VS) and 60–80% (S) of the potential maximum rain-fed yield, assuming advanced input/management regimes. Moderately suitable (MS) land (40–60% of maximum yield) is usually not economically viable for commercial production, but may become so with high commodity demand and resulting high raw material prices. Marginally suitable areas (less than 40% of headline yields) have not been considered as viable for commercial crop production.

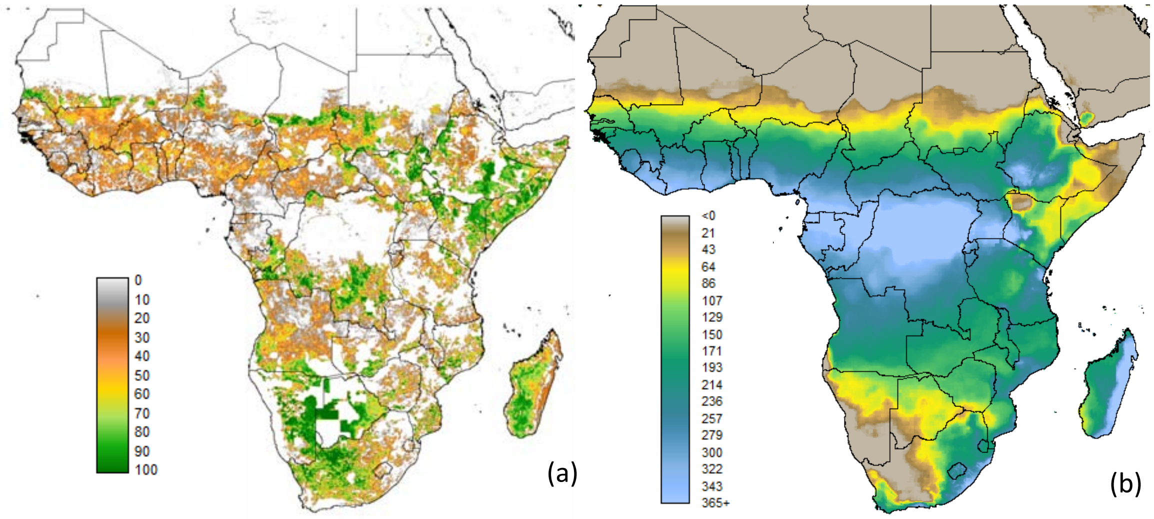

Figure 7: Intensity and spatial distribution of REMAIN land (%) (a) and number of annual growing period days (b), in 2010

The extent of suitable REMAIN land for biofuel feedstock cultivation depends on the particular feedstock that is cultivated. Between only 1% (triticale) and 29% (sweet sorghum) of SSA's REMAIN land is of prime or good quality for the cultivation of different feedstock crops. Crucially, not all REMAIN land that is at least moderately suitable for the cultivation of energy crops will support the production of biofuels that are compliant with the minimum 60% GHG savings criterion, mainly owing to emissions from direct land-use change.

Figure 8 highlights the reduction in land availability as sustainability constraints are added. Of the total 1 910 000 km^2 of REMAIN land that is of prime and good quality for the production of at least one of the feedstocks considered in this study, only about 838 000 km^2 (almost 84 million hectares) of REMAIN land would produce energy crops that could be used to produce biofuels that comply with the GHG savings criterion. This is 44% of all REMAIN land of prime and good quality, about 15% of total REMAIN land, or 3% of the total land area in the SSA region.

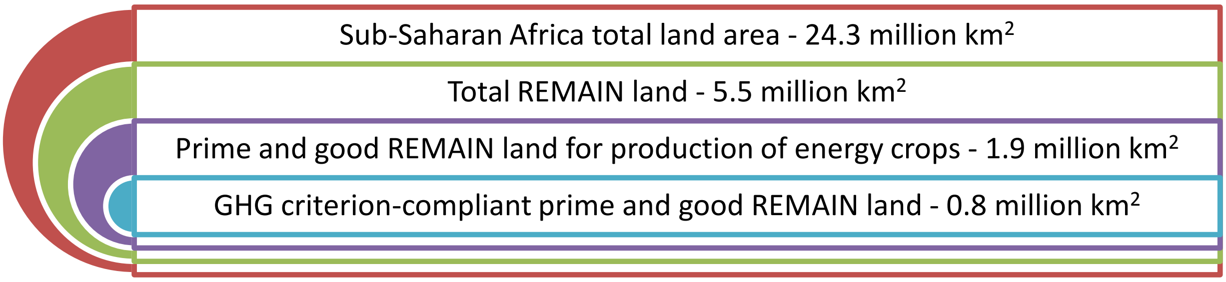

Figure 8: Changes in viable biofuel feedstock production area following additions of sustainability criteria

Similarly, the total achievable energy yield on prime and good quality land is 18 650 PJ, but less than half of that (7 064 PJ) would be compliant with the required minimum 60% reduction in GHG emissions. If moderately suitable areas are also considered, the extent of land that meets the 60% GHG savings criterion almost doubles to 1 570 000 km^2, as does the compliant energy yield. If 'REMAIN' land in SSA was optimised for energy yield, then the distribution of crops per sub-region would be as shown in Table 3. The technical potential of RSB-compliant biofuels in SSA comprises mostly of perennial crops.

Miscanthus emerges as the most promising feedstock by far, contributing about 50% of the total potential if only prime and good quality land is considered, and 75% if moderately suitable land is included.

Table 3: Technical potential for RSB-compliant biofuel on REMAIN land, under current conditions (PJ)

Regions	Eastern Africa	Central Africa	Southern Africa	Sudano-Sahelian Africa	Gulf of Guinea	TOTAL
Potential from prime and good quality land						
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	1 217
Solaris	0	0	1	0	0	1
TOTAL VS+S	**1 564**	**3 342**	**617**	**353**	**1 188**	**7 064**
Potential from prime, good quality and moderately suitable land						
Sugarcane	301	898	0	27	167	1 394
Miscanthus	2 644	4 923	1 293	1 058	1 990	11 908
Oil palm	47	1 293	0	0	437	2 023
Jatropha	11	126	3	30	2	184
Solaris tobacco	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

Because of land conversions required for additional food production and the expanding built environment, by 2050 the total REMAIN land will be reduced by between 320 000 km^2 (6%) and 501 000 km^2 (10%), depending on the future scenario considered. In addition, some of the better quality REMAIN land will be diverted for food production and the impact of climate change will causes some tracts of land currently classified as ‘prime’ and ‘good quality’ for the production of energy crops to become only moderately suitable in the future. These factors combined lead to a significant reduction in future potentials, in most countries in SSA (with some notable exceptions). If only prime and good quality land is considered, the projected reduction compared to the current production potential is more than 40%. If moderately suitable areas are also included, the reduction is less pronounced – about 28%, with negligible differences between the two future scenarios. Table 4 presents a summary for SSA, comparing current and future technical potentials for biofuel production for the two scenarios explored in this study, per feedstock crop[6].

The crop most dramatically affected by the combination of the above factors is sugarcane, with its energy yield expected to decline by about 70–80%. Miscanthus and oil palm are also expected to see a significant reduction in their energy yields, more so on prime and good quality land than on moderately suitable land. On the other hand, the yields of some crops are likely to improve due to climate change, such as sorghum, jatropha and Solaris tobacco. This is as a consequence of the specific pattern of projected climate change combined with the CO_2 fertilisation effect.

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[6] If a crop is not included in Table 6 it means it does not have a significant potential under the conditions studied.

Table 4: Current and future production potential of RSB-compliant biofuel on REMAIN land, per feedstock

		Current potential	**Future potential (2050) "Sustainability"**		**Future potential (2050) "Middle of the road"**	
		PJ	PJ	% change	PJ	% change
Prime and good quality land	Sorghum	0	18	1 800	38	3 800
	Sugarcane	907	222	-76	150	-83
	Miscanthus	3 645	1 890	-48	1 963	-46
	Oil palm	1 294	801	-38	920	-29
	Jatropha	17	1 001	5 788	906	5 229
	Solaris tobacco	1	30	3 000	28	2 700
	TOTAL VS+S	**7 064**	**3 962**	**-44**	**4 003**	**-43**
Prime, good quality and moderate land	Sorghum	0	37	3 700	71	7 100
	Sugarcane	1 394	422	-70	306	-78
	Miscanthus	11 908	8 934	-25	8 848	-26
	Oil palm	2 023	1 545	-24	1 754	-13
	Jatropha	184	204	11	150	-18
	Solaris tobacco	1	28	2 700	30	2 900
	TOTAL VS+S+MS	**15 510**	**11 171**	**-28**	**11 159**	**-28**

Source: Own calculations

In summary, the future biofuels production potential will likely be significantly reduced as a result of land conversion for food production, changes in land suitability and the impacts of climate change on crop yields. If only prime and good quality land are considered for feedstock production, the reduction will be over 40%, and if moderately suitable land is included, it will be almost 30%.

4. SENSITIVITY AND LIMITATIONS

Results produced in quantitative simulation studies are subject to specific assumptions, sensitivities and uncertainties in data and parameters. The sensitivity analysis shows that the size of the sustainable biofuel potential is highly dependent on the allocation of the GHG burden to the biofuel portion of multi-purpose crops. In this study, we use the "economic allocation" method, which attributes shares of GHG burden based on relative prices of co-products and use long-term averages of prices for the various co-products (WRI, 2011). However, with fluctuations in price, the GHG allocation across all co-products of a multi-product plant could change. Therefore, the picture at any given point in time could be different compared to estimates based on long-term average prices.

This study used best-available data to identify suitable areas for biofuel feedstock production on land that is not required for food production, environmental conservation or safeguarding key biodiversity areas, however it may nevertheless have missed some areas of importance for biodiversity and environmental conservation that have not yet been properly recorded in global and regional databases.

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 for annual crops, to meet the required 60% GHG emission savings criterion, which is often prohibitive owing to the soil and vegetation carbon losses that would be encountered in the conversion of REMAIN land. Under conditions of land degradation before conversion to REMAIN land, the cultivation of biofuel feedstocks may actually increase the amount of carbon stored in soils, but we were unable to quantify this in our study. An internationally agreed definition of “degraded land” is a pre-requisite for inclusion of such areas in land cover datasets.

5. CONCLUSIONS AND RECOMMENDATIONS

The ultimate goal of this analysis was to compare sustainable biofuel production potential with future aviation biofuel demand projections to understand the role that SSA could play in such a global green fuels market. Although the ICAO proposed target for alternative jet fuel has not yet been approved, Table 5 compares the envisioned demand figure with the potential for sustainable biofuels estimated in this study.

Table 5: Technical potential for RSB-compliant aviation biofuel 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 mt**
SSA technical potential by 2050 from VS and S land	93 mt
SSA technical potential by 2050 from VS, S and MS land	260 mt
% of global international aviation demand that could be met by SSA	30–90%

* VS = very suitable; S = suitable; MS = moderately suitable

In summary, our assessment suggests that SSA can at best contribute between 30% and 90% of future SAF demand in the form of RSB-compliant aviation biofuel, 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*, with the attainable *economic potential* a proportion of this. Furthermore, this is under the assumption that all energy crops on suitable REMAIN land in SSA are used to produce biofuels for international aviation and none are directed towards other uses.

Where the conversion of virgin land is involved, it is mostly perennial biofuel feedstocks, requiring less frequent and less intensive cultivation of soils that can meet the RSB criteria. The willingness of farmers to invest in the cultivation of perennial energy crops depends on the will of the aviation industry and its fuel suppliers to engage in long-term off-take agreements to help them mitigate risks related to the production of perennial crops. While annual energy crops are rarely able to repay their carbon debts (if incurred), they still have a role to play on degraded land (for example, restoration of degraded mining land). In addition, they could replace other industrial crops that are in decline, for example replacing traditional smoking tobacco with Solaris tobacco. Intercropping or rotation cropping could also help annual crops achieve compliance with the GHG savings criterion.

Finally, the meaningful potential for RSB-compliant aviation biofuel in the region may be substantially increased if the necessary investments are made to improve the quality of currently degraded land. Even so, the potential for fuels from land-based energy crops is not going to be sufficient to meet projected global demand for SAF. Thus, the development and commercialisation of alternative SAF production routes, such as synthetic fuels based on solid and gaseous waste or green hydrogen and carbon from direct air capture must be stepped up to complement those that depend on land-based crops and agricultural residues.

7. REFERENCES

Cames, M, Graichen, J, Siemons, A & Cook, V, 2015. Emission Reduction Targets for International Aviation and Shipping, in: Policies, DGFI (ed.) IP/A/ENVI/2015-11, Brussels: European Parliament.

FAO. FAO/IIASA/ISRIC/ISS-CAS/JRC (2012) Harmonized World Soil Database (version 1.21), Rome, Italy and Laxenburg, Austria: FAO and IIASA.

Fischer, G, Tramberend, S, van Velthuizen, H, Bole-Rentel, T & Reeler, J, 2019. Sustainable Aviation Biofuel Feedstock Potential in sub-Saharan Africa. World Wide Fund for Nature. Available at: http://pure.iiasa.ac.at/id/eprint/15626/

Ganzhorn, JU, Lowry, PP, Schatz, GE & Sommer, S, 2001. The biodiversity of Madagascar: One of the world's hottest hotspots on its way out, *Oryx*, 35:346-348.

ICAO, 2016. ICAO Envrionmental Report (2016) Montreal: International Civil Aviation Organisation

ICAO, 2017. Proposed ICAO Vision on Aviation Alternative Fuels, CAAF/2-WP/13. Available at: icao.int/Meetings/CAAF2/Documents/CAAF.2.WP.013.4.en.pdf

IPCC, 2007. Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds)], Cambridge: Cambridge University Press. Available at: ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm.

IPCC, 2013. Summary for Policymakers, in: Climate Change 2013: The physical science basis: Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF , Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (eds)], Cambridge: Cambridge University Press, Available at: doi: 10.1017/CBO9781107415324.

Kimball, B, Kobayashi, K & Bindi, M, 2002. Responses of agricultural crops to free-air CO^2 enrichment, *Advances in Agronomy*, 77:293-368.

Lee, DS, Fahey, DW, Forster, PM, Newton, PJ, Wit, RC, Lim, LL, Owen, B & Sausen, R, 2009. Aviation and global climate change in the 21st century, *Atmospheric Environment*, 43:3520-3537.

RSB. RSB Principles & Criteria for the Sustainable Production of Biomass, Biofuels and Biomaterials, 2016. RSB Standard, Version 3.0, Roundtable on Sustainable Biomaterial.

UN, 2015. The Paris Agreement, Available at: unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

World Resources Institute and World Business Council for Sustainable Development, 2011. Greenhouse Gas Protocol, Product Life Cycle Accounting and Reporting Standard.

WWF, 2013. Searching for Sustainability: Comparative analysis of certification schemes for biomass used for the production of biofuels, Düsseldorf: World Wide Fund for Nature.