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Report

SUSTAINABLE AVIATION BIOFUELS FOR SOUTH AMERICA

A systems analysis investigation into opportunities for sustainable biofuel feedstock production to 2050

Günther Fischer, James Reeler, Sylvia Tramberend, Harrij van Velthuizen

December 2024

World Wide Fund for Nature – South Africa

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Acronyms

ATAG	Air Transport Action Group
CMIP5	Coupled Model Intercomparison Project Phase 5
CORSIA	Carbon Offsetting and Reduction System for International Aviation
dLUC	Direct land use changes
DM	Dry matter
EJ	Exajoules (equals 1000 PJ)
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Databases
GAEZ	Global Agro-Ecological Zoning Model
GAUL	Global Administrative Unit Layers
GBF	Global Biodiversity Framework
GCM	General circulation model
GHG	Greenhouse gas
GLWD	Global Wetland Database
GMIA	Global Map of Irrigated Areas
GMO	Genetically modified organism
GPCC	Global Precipitation Climatology Centre
HWSD	Harmonized World Soil Database
ICAO	International Civil Aviation Organization
IIASA	International Institute for Applied Systems Analysis
IPCC	International Panel on Climate Change
KBA	Key Biodiversity Areas
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LUT	Land Utilization Type
MB	Macauba palm with *Brachiaria* grass intercropping
Mt	Million tons
OEM	Original equipment manufacturer
PJ	Petajoules
ppm	Parts per million
PTL	Power to liquids
RCP	Representative Concentration Pathway
REMAIN	Remaining land once environmental and food sustainability criteria were addressed
RPR	Residue to Produce Ratio
RSB	Roundtable on Sustainable Biomaterials
ths	thousand
TJ	Terajoules
TLU	Tropical Livestock Unit
SAF	Sustainable Aviation Fuels
SDG	Sustainable Development Goal
SOC	Soil organic carbon
SSP	Shared Socio-economic Pathway
WDPA	World Database of Protected Areas
WWF	World Wide Fund for Nature

Summary

As a significant global emitter of greenhouse gases (GHG), the aviation industry is expected to continue to grow. The International Civil Aviation Organization (ICAO) aims to achieve net-zero carbon emissions by 2050, with carbon-neutral growth from 2020 through offsetting and alternative fuels. Increased demand for aviation biofuels could have significant impacts on agricultural systems, ecosystems, biodiversity, and critical land and water resources. South America has abundant fertile land resources and is a major global agricultural producer and exporter. However, the region faces sustainability challenges such as tropical deforestation, biodiversity loss, and land degradation. An assessment of South America's potential supply of biofuel feedstocks is critical to ensuring that the aviation industry's mitigation pathways are sustainable.

The research approach considers a broad range of sustainability criteria aligned with the Roundtable of Sustainable Biomaterials (RSB). This large-scale assessment considers food security, nature conservation, soil and water regimes and at least GHG emission savings compared to fossil fuels over a 20-year accounting period. Using the Global Agro-ecological Zones methodologies, we assess the potential supply of 16 biofuel feedstocks up to the 2050s, including those already widely grown (e.g., sugarcane, oil palm), at demonstration scale (e.g., miscanthus, jatropha), and in early stages of development (macauba palm, energy cane). To explore options for multifunctional agriculture, we analyze the intercropping of macauba palm with *Brachiaria* grass and carinata and camelina grown as winter cover crops. Intercropping has fewer restrictions on land use. Dual production of feed and vegetable oil requires less land to be set aside to meet RSB food security criteria.

The selection of feedstocks allows for a range of scenarios for sustainable biofuel production. Depending on policy, technological development, economics and socio-cultural preferences, certain biofuels could be preferred over others. In some areas, several biofuel feedstocks could meet the RSB sustainability criteria. For the estimation of an aggregated technological sustainable potential, we select the crop with the highest energy yield.

South America's current (2020) technical potential compliant with RSB sustainability criteria is 12,214 PJ produced from prime (very suitable, VS) and good (suitable, S) land qualities. If demand and commodity prices are high, moderately suitable (MS) land may also be viable for farmers to invest in – with a larger spatial development footprint. Adding 8,200 PJ from MS land quality gives a total of 20,414 PJ.

These amounts could be produced from rain-fed feedstocks cultivated on 760 (VS+S) and 1,507 (VS+S+MS) thousand km^2. Hence, up to nearly one-third (32%) of South America's unprotected grass- and shrubland could be used to grow biofuel feedstocks that meet RSB sustainability criteria. Energy cane and intercropping macauba with *Brachiaria* grass are the main contributors to this potential. Due to the high productivity and resulting energy yields, some 69% of the current RSB compliant biofuel potential across South America comes from energy cane (14,089 PJ from 697 thousand km^2). Another 22% is from intercropping macauba with *Brachiaria* grass (4,568 PJ from 650 thousand km^2). The remaining 9% are mainly from miscanthus and macauba cultivated as single crop. In addition, some 759 Petajoules could be produced from carinata and camelina grown as winter fallow crop on cropland. Argentina alone contributes half of this potential (388 Petajoules).

Given its vast grass- and shrubland areas, some 61% of South America's total potential is concentrated in Brazil. In comparison to the remainder of South America, intercropping macauba with *Brachiaria* grass, well adapted to Brazil's tropical climate, has a higher feasibility, contributing almost one third to the overall potential of 12,419 PJ (VS+S+MS). Most of the remaining production potential is from energy cane, requiring 13% of Brazil's 3,358 thousand km^2 grass- and shrubland.

Climate change has a negative impact on South America's biofuel potential for almost all feedstocks examined. As a result, biofuel potential will generally decrease by 15 to 38 % by 2050, depending on the scenario. This impact is more significant on prime land, compared to moderately suitable areas. The exception is camelina

and carinata, which are cultivated as winter fallow on cropland. The impact of climate change on the overall productivity of these biofuels is very modest, ranging from a very small increase to a decrease of 20%.

Assuming that biofuels would be prioritized for aviation purposes due to the lack of alternative economically viable decarbonization options, we present an indication of the percentage of aviation fuel demand that could be produced in South America from the investigated feedstocks. The estimated sustainable annual biofuel potential is up to 12,214 PJ, i.e., 285 Mt jet fuel, for prime land use, with climate change decreasing this to 215-178 Mt by 2050. The main contributors are the intercropping of macauba palm with *Brachiaria* grass and energy cane. The former involves some intensification of unprotected grass- and shrubland currently used only for livestock feed. Due to the high energy yields, it is possible to convert grass- and shrubland to energy cane cultivation while still meeting the GHG savings criteria. In 2050, some 6% (289 thousand km^2) of current unprotected grass- and shrubland would need to be converted to energy cane.

By comparison, global aviation today consumes about 300 Mt of kerosene, expected to rise to about 500 Mt by 2050. Today, much (95%) of global annual jet fuel demand could come from South America's vast land resources. The combination of the adverse effects of climate change and the increase in demand for jet fuel is disrupting the balance between supply and demand. By 2050, only between 36 - 43% of the estimated annual jet fuel could be met by RSB-compliant biofuel produced in South America. Winter cover crops could contribute to 3.6% of current aviation demand and 2% of future demand, without requiring land conversion but intensifying cropland use.

The economics of feedstock production and necessary biofuel conversion methods may limit these upper sustainable technical potentials, and it is anticipated that technological development of power-to-X fuels may play an increasing role in the long term up to displacing biofuels. Regional implementation depends on many factors, including the interplay between agricultural and energy policies, energy prices, and potential competing demands for novel biomaterials. In certain places, additional areas may be designated for the conservation of biodiversity or other ecosystem functions.

1. Introduction

Aviation sector emission reduction needs

Climate change is the most severe crisis facing modern humanity, driven largely by anthropogenic emissions from the combustion of fossil fuels. Despite the fact that as little as 11% of people fly annually (Gössling and Humpe, 2020) aviation is no exception, with direct CO_2 emissions from the burning of jet fuels creating approximately 2.4% of all GHG emissions (Lee et al., 2021). The additional warming impact of high-level contrails and other elements is less well-bounded due to uncertainties, but best estimates suggest that the net radiative forcing for all aviation impacts are 3.1% of total anthropogenic emissions (1.5% - 4.8%; 95% confidence interval) (Lee et al., 2021).

The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC, 2018) has committed 186 signatory nations to undertake all efforts to limit climate change to 1.5 °C. To achieve this, it is essential that total global emissions drop 45% from 2020 levels by 2030, reaching net zero by 2050 (IATA, 2021). The governing body for international aviation, the International Civil Aviation Organisation (ICAO), a specialized agency of the United Nations, has recently adopted this target (ICAO, 2022c).

Today, global aviation kerosene demand is about 300 Mt per annum (13 EJ), almost back to pre-pandemic levels in 2019 and could increase to 430-530 Mt in 2050 (Batteiger et al., 2022; ICAO, 2022b). Including non-commercial aviation (general, private and military use), the aviation sector consumed over 14 EJ in 2019 (ICAO, 2022b). The International Energy Agency (IEA) reports for 2022, aviation accounted for 2% of global energy-related CO_2 emissions, having grown faster in recent decades than rail, road or shipping, reaching almost 800 Mt CO_2, about 80% of the pre-pandemic level (IEA, 2023b).

Globally, the aviation sector's emissions contribute about 12% of all transport emissions. In addition, non-CO_2 emissions also have a significant climate impact. Aircraft typically use jet kerosene, refined from crude oil accounting to almost 99.9% the energy consumption (ICAO, 2022b). Whilst there is some potential for electrification of very short haul flights, the volumetric energy density of even liquid hydrogen is far too low for long-distance jet travel.

To date, carbon offsets have been a key component of the ICAO's Carbon Offsetting and Reduction System for International Aviation (CORSIA) and have enabled large voluntary reductions from flights. However, to achieve global net-zero conditions, only offsets that result in real long-term removals are viable, and these currently represent a vanishingly small component of the overall global market. Moreover, there are real limitations to the volume of such high-quality, additional, and secure credits, and they can only therefore play a very transitional role in aviation emission reduction. Given these conditions, alternative aviation fuels will likely be the principal component of the industry's overall decarbonization moving ahead. Whilst such fuels still result in combustion emissions in flight, they can significantly reduce overall emissions if their manufacture involves the removal of atmospheric carbon.

Moreover, whilst current engines are limited under the ASTM standard[1] to blending mixes of between 5% and 50% of alternative fuels, Original Equipment Manufacturers (OEMs) are currently designing engines that can take much higher quantities, and testing of drop-in fuels has already demonstrated that certain fuel pathways result in fuels that are identical in all respects to current fossil-derived fractions. The ICAO Committee on

[1] ASTM is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

Aviation Environmental Protection (CAEP) estimates that from 2040, up to 100% of the international aviation fuel demand (that is, the majority of total global aviation fuel demand) could be met by sustainable aviation fuels (SAF).

Clearly, the challenge for aviation to abate GHG emissions is significant and SAF is expected to play a key role. SAF are liquid kerosene substitutes that can be used as 'drop-in fuels' at a maximum blend of currently 50% without major changes to equipment and infrastructure (Becken et al., 2023). SAF include biofuels derived from a variety of biomass or biogenic wastes, as well as synthetically produced Power to Liquid (PtL) synthetic kerosene. The latter convert two gases, "green" hydrogen, produced with renewable energy from water, and CO_2 from a non-fossil fuel source, through a synthesis process (e.g., Fischer-Tropsch) into synthetic PtL kerosene.

For example, the International Energy Agency's (IEA) 'Net Zero Emission Scenario' describes a rapid expansion in the use of non-fossil fuels. In this scenario, aviation energy consumption rises from 11 EJ (2022) to 15 EJ (2050), with biofuels and synthetic hydrogen-based fuels accounting for 33% (5.0 EJ) and 37% (5.6 EJ) respectively of final aviation energy consumption (IEA, 2023a). The RefuelEU aviation initiative has recently adopted legislation (EU, 2023) that mandates a share and type of SAFs in jet fuels starting with 2% SAF in 2025, 6% in 2030 (1.2% must be synthetic fuels), reaching by 2050 70% (35% synthetic).

Although the GHG emission potential for PtL is very high, major challenges remain, e.g., large quantities of renewable energy needed for hydrogen production and competing demand from other sectors, or production costs. Presuming that biofuels can be met from global bioenergy resources implies optimistic assumptions about agricultural yield improvements, global bioenergy policy, prioritization of the aviation industry for these purposes, and, critically, land availability for bioenergy production.

Whilst Power-to-X technologies[2] and direct air capture of carbon are horizon technologies that may provide a significant portion of SAF demand in the latter half of the century, all indications are that in the near-term alternative aviation fuels will primarily be met through conversion of biomass. The carbon, biodiversity, ecosystem function, social and water impact of such activities must all play a role in the determination of what "sustainable" means in the context of sustainable aviation fuels.

The focus of this study is on the potential for sustainable biofuels for the aviation sector produced in land-abundant South America. Delivering large volumes of low-carbon, biobased SAF will require an unprecedented scaling of the industry, and depending on the fuel feedstock, this in turn may require a massive spatial footprint. This land concern is significant. Land use change is the second largest driver of climate change after fossil fuel combustion, and the largest driver of biodiversity loss. Scaling will further tighten the link between agriculture and energy. Agricultural production systems may need to deliver multiple output per unit of land in emerging fossil-free bio economies.

Study rationale, aims and objectives

The repurposing of waste products such as cooking oil, low-quality product oils and various agricultural and forestry wastes has been the main focus of the aviation industry's growing demand for SAF. However, the rapidly growing industry is increasingly focusing on sourcing additional materials through various ASTM-approved pathways. The main opportunities for such materials are typically seen in land-rich regions of the developing world and emerging economies. However, it is not clear that this is true, given that significant land

[2] Power-to-X refers to various technologies for storing or otherwise using electricity surpluses in times of (future) oversupply of variable renewable energies such as solar energy, wind energy and hydropower.

use is already committed to various uses. Furthermore, because these countries are developing makes them more dependent on ecosystem services, and the preservation of biodiversity is essential for their long-term survival.

Building on a similar study undertaken for sub-Saharan Africa (Bole-Rentel et al., 2019; Fischer et al., 2019), this study aims to evaluate a realistic upper limit for the amount of biomass that might be utilized for SAF, considering important safeguards and set-asides to maintain ecosystem integrity and support long-term sustainability for human needs. South America has abundant fertile land resources and is a major global agricultural producer and exporter. However, the region faces significant sustainability challenges such as tropical deforestation, with a near term risk of a tipping point in Amazon forests to a savannah ecosystem (Amigo, 2020), biodiversity loss, and land degradation.

Exploiting the potential of SAF requires transition pathways for the cultivation of biofuel feedstocks grown by farmers and industry adopting novel supply chains and technologies. However, climate change may affect the potential for SAF production. An assessment of South America's potential supply of SAF today and in the future is critical to ensure that aviation industry mitigation pathways are sustainable.

The aim of this study is to assess the current and future (2050s) potential of South America to production SAF compliant with the relevant RSB sustainability criteria. Specific objectives include

- Review and methodological implementation of RSB sustainability criteria for SAF production
- Compilation of biophysical resource database (e.g., climate, land use, soil, and terrain conditions)
- Compilation of exclusion layer not considered for SAF cultivation
- Selection of biofuel feedstocks and technical implementation into modelling framework
- Calculation of the crop production potentials for selected biofuels under current (2020s) and future (2050s) conditions

Notably, this study will explore novel biofuel feedstocks energy cane, macauba and carinata. In addition, resulting from stakeholder consultations, we will assess a multifunctional agricultural system of intercropping macauba palm (for biofuels) with Brachiaria grass (for livestock feed).

2. Study approach, Methods, Data

Sustainability principles

The guiding principles for the sustainability assessment in this study are those developed by the Roundtable on Sustainable Biomaterials (RSB, see https://rsb.org/). 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. The RSB principles follow a hierarchic structure with 12 main elements: 1) Legality; 2) Planning, monitoring and continuous improvement; 3) Greenhouse gas emissions; 4) Human and labor 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. An additional optional criterion may allow implementers to consider indirect land-use change as a result of their action.

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 South America. 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 labor rights, or land rights must follow country-specific requirements and can only be assessed at the project level, although certain legislative requirements such as nationally required feedstock exclusions (where feasible) are included in this assessment. 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 into the biofuel assessment conducted in this study by defining constraints shown in Box 1.

Box 1. Implementation of constraints for compliance with RSB principles

Principle 3: **Greenhouse gas emission saving**

- Potential biofuels must deliver minimum 60% GHG emission savings compared to fossil fuels over a 20-year accounting period
- 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 to avoid erosion
- Biofuel feedstock production follows principles of conservation agriculture

Principle 9: **Water regime**

- No irrigated biofuel feedstock production

The application of these principles sets an upper estimate of the production potential for SAF. In practice, utilization of the full envelope estimated would likely be further reduced because of site-specific and local sustainability, social and economic criteria. Similarly, the availability of organic matter for soil supplementation for non-perennial crops may well be a limiting factor. Further sustainability considerations and concerns regarding the large-scale implementation of monoculture and large-scale bioenergy crops are highlighted in the "Biofuel feedstocks" section.

It must be noted that guidance from multilateral agreements such as the Kunming-Montreal Global Biodiversity Framework (GBF[3]) (UNEP, 2022) indicates that much larger areas must be set aside for conservation and natural systems to ensure long-term viability. The global target of 30% of land conserved by 2030 implies significant reductions in the available land per biome. While the GBF makes provisions for multi-functional landscapes as a component of "other effective conservation measures", the proper implementation of this agreement at the national level is likely to lead to a near-term increase in the sustainability exclusions included in this study. The

[3] See also: https://www.cbd.int/gbf

30% area conserved for nature and biodiversity must be "effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas…". Networked corridors and representation of all biomes will be an essential component of national biodiversity strategies and action plans, the main instrument for implementation and monitoring of the Framework.

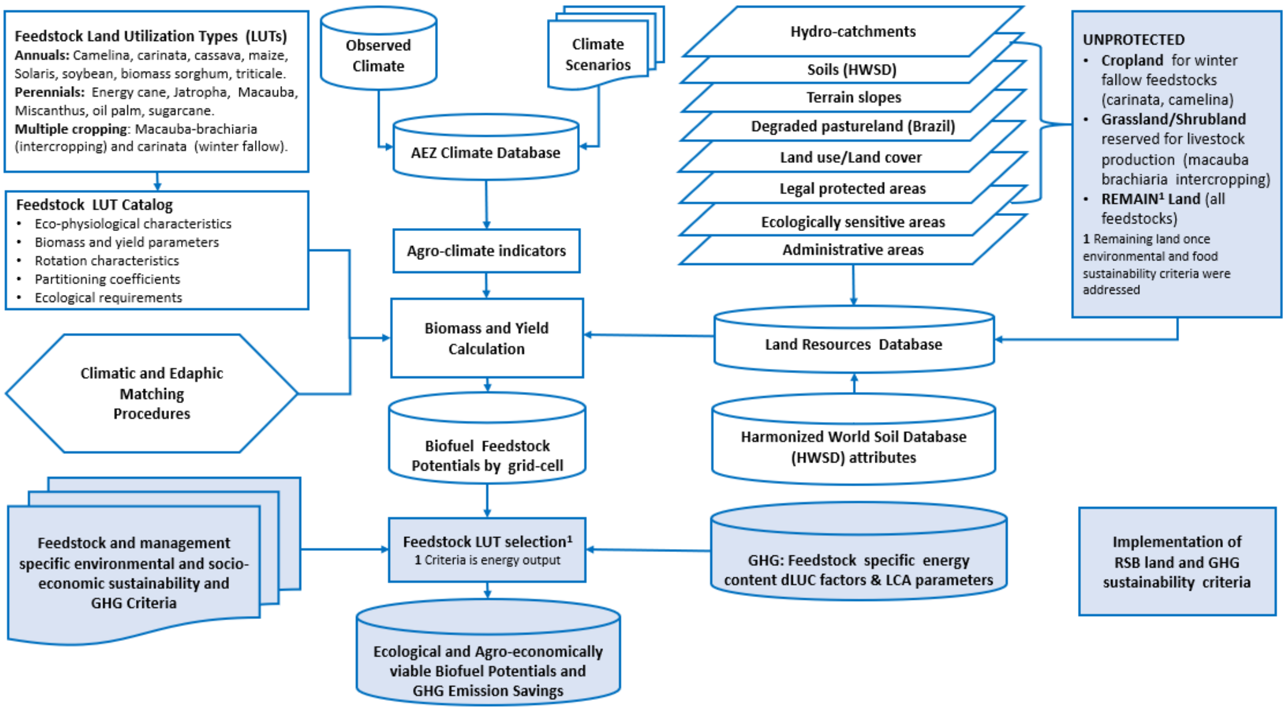
An additional critical sustainability consideration is the large-scale use of biomass for energy purposes. WWF guidance is currently that biofuel usage should be limited to hard-to-abate essential sectors, for which limited alternatives for decarbonization exist. Aviation is one such sector, as is shipping, whereas biofuels for land transport (where electrification provides a more efficient and lower-impact approach) should be avoided.

Global Agro-ecological Zones modelling framework

Variations in land quality combined with agronomic management determine biofuel feedstock cultivation potentials. The Global Agro-Ecological Zones (GAEZv4)[4] methodology (Fischer et al., 2021) is used to assess the agronomically attainable production of individual crops/feedstocks under given agro-climatic, soil and terrain conditions for specific levels of agricultural inputs and management conditions.

An overview of the GAEZ model structure and data integration is shown in Figure 1. Blue shading indicates the extensions to the GAEZ core processing steps used in this study for identifying biofuel potentials compliant with RSB land and GHG criteria.

Figure 1. Agro-Ecological Zones model overview



4 The FAO and IIASA have implemented the GAEZ modelling framework and databases. GAEZ v4 is the most ambitious global assessment to date, for which a Data Portal has been developed (see https://gaez.fao.org/) to make the database widely and easily accessible for users.

Crop requirements and land conditions are matched to identify crop/feedstock specific limitations of prevailing climate, soil, and terrain resources. Subsequent 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. These generic production systems, as defined by water supply (rain-fed or different irrigation systems) and levels of inputs and management circumstances, are used in the AEZ analysis and are referred to as Land Utilization Types (LUT).

Attributes specific to each 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.

The suitability of land for the cultivation of a given crop/LUT depends on crop/LUT requirements and prevailing agro-climatic and agro-edaphic conditions at a given location. AEZ systematically combines these two components by successively modifying grid-cell specific agro-climatic potential yields according to assessed soil limitations and location specific terrain characteristics.

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

- 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
- Integration of results into feedstock-specific grid-cell databases.

In response to stakeholder consultations, additional biofuel feedstocks were explored and integrated into the GAEZ modelling system, notably macauba palm intercropped with *Brachiaria* grass, and energy cane.

Biofuel feedstocks

Selected feedstocks

The assessment includes several potential biofuel feedstocks producing different biomaterials (Table 1) and used for different conversion pathways. Farmers can cultivate most of these feedstocks using well-established agronomic practices and know-how. There are extensive research and demonstration projects in place for novel feedstocks – macauba, Ethiopian rape (carinata), and energy cane – yet large-scale implementation requires support and extension services for farmers.

First-generation biofuel conversion pathways have a high market readiness and rely on the vegetable oil, sugar and starch components of the respective crops. Biofuel conversion processes are well-established and already extensively employed for industrial scale biofuel production for the road transport sector in Brazil (sugarcane to bioethanol), the United States (cereals, mainly maize for bioethanol), and Europe (vegetable oil to biodiesel).

The conversion of lignocellulosic biomaterial, often referred to as 'second-generation' biofuel conversion pathways, is more complex and requires additional processing steps. Though currently significantly less used compared to the 'first-generation' biofuel conversion pathways, Brazil's sugar industry has already proven experience and several plants already making use of this pathway. Sugarcane residues (bagasse and trash) can be used for electricity production or 2nd generation ethanol production using low cost enzymes (Furtado et al., 2020). In general, the speed and scale of future deployment is more uncertain for second-generation biofuels.

The majority of the feedstocks assessed were already included in previous research on sustainable aviation biofuels for Sub-Saharan Africa (Bole-Rentel et al., 2019; Fischer et al., 2019) and other global biofuels assessments (Fischer et al., 2009). Stakeholder consultations suggested that the following new feedstocks and land utilization types should be explored for South America, notably intercropping macauba palm with grass for livestock feed such as Brachiaria grass.

In addition to the individual feedstocks explored (Group A, Table 1), this study also identifies multifunctional agronomic practices aimed at integrated food and energy production (Group B, Table 1).

For the 'new' feedstocks, carinata, energy cane, and macauba palm, the AEZ crop/LUT specifications have been developed specifically for the purposes of this study. A brief introduction is given in the next section, with more details in Annex A.

Table 1. Biofuel feedstocks selected

Feedstock	**AEZ Produce** [assumed energy content for biofuel production]	Biomaterial
Group A. Crops for energy		
ANNUAL crops:		
Solaris tobacco (*Solanaceae spp.)*	Seed [12.3 MJ/kg]	Vegetable oil
Soybean (*Glycine max*)	Seed [7.24 MJ/kg]	Vegetable oil
Camelina (*Camelina sativa*)	Seed [12.6 MJ/kg]	Vegetable oil
Carinata (*Brassica carinata*[1])	Seed [14.0 MJ/kg]	Vegetable oil
Sweet Sorghum (*Sorghum bicolor*)	Stalk, grain [7.27 MJ/kg]	Sugar/Starch
Maize (*Zea mays*)	Grain / stover [11.1 MJ/kg]	Starch
Cassava (*Manihot esculenta*)	Root [10.9 MJ/kg]	Starch
Triticale (*Triticum X Secal*[2])	Grain [9.2 MJ/kg]	Starch
PERENNIAL crops:		
Jatropha (*Jatropha curcas*)	Seed [12.7 MJ/kg]	Vegetable oil
Oil palm (*Elaeis guineensis*)	Oil [34.3 MJ/kg]	Vegetable oil
Macauba palm (*Acrocomia aculeata*)	Oil [35.3 MJ/kg]	Vegetable oil
Sugarcane (*Saccharum officinarum*)	Sugar [15.8 MJ/kg]	Sugar
Energy cane (*Saccharum spp. X*)[3]	Above ground biomass [6.35 MJ/kg]	Lignocellulosic (2nd)
Miscanthus (*Miscanthus sinensis*)	Above ground biomass [6.35 MJ/kg]	Lignocellulosic (2nd)
Group B: Multifunctional (Food/energy integration)		
Intercropping macauba palm & *Brachiaria* grass	Oil [35.3 MJ/kg]	Vegetable oil
Carinata as winter fallow crop	Seed [14.0 MJ/kg]	Vegetable oil
Camelina as winter fallow crop	Seed [12.6 MJ/kg]	
Agric crop residues from food production	n.a.	Lignocellulosic (2nd)

[1] believed to be a hybrid between Brassica nigra and Brassica oleracea; [2] Triticale is a cross-bred hybrid of wheat (Triticum spp.) and rye (Secale spp.); [3] A new feedstock: "energy cane," focuses on energy content by shifting traits to higher biomass productivity and not on sucrose content as for sugarcane.

Novel feedstocks: Energy cane, Macauba, Carinata

Further details on the novel feedstocks, including biomass productivity results, can be found in Annex A and in a companion paper (van Velthuizen et al., forthcoming).

Energy cane

Energy cane is a cultivar developed from sugarcane (*Saccharum spp.*) with high fiber content, higher biomass productivity and resilience, having great potential as a bioenergy feedstock (Fanelli et al., 2020). Energy cane is a sugarcane variety bred to achieve high biomass production. It is a hybrid produced from crossing the wild species *Saccharum spontaneum* with either *S. officinarum* or existing commercial varieties or near-commercial clones (Matsuoka et al., 2014). Unlike conventional sugarcane (*Saccharum spp.*), energy cane contains more fiber than sucrose, achieved by modifying the genetic contribution of the ancestral sugarcane using traditional breeding methods. Ongoing research and breeding efforts continue to improve energy cane cultivars and expand the range of options available to growers and bioenergy producers.

In general, energy cane offers the ability to produce high yields of biomass per hectare. Energy cane exhibits resistance to common diseases and pests that affect sugarcane. Disease resistance helps maintain productivity and reduces the need for chemical interventions. Energy cane is also tolerant to environmental stresses such as drought and flooding, common challenges in sugarcane-producing regions. Its resilience to adverse conditions contributes to its overall productivity.

For this study, the research results of GranBio (see https://www.granbio.com.br/en/) on energy cane in Brazil were used, in particular two newly bred cultivars, Type1-Vertix3 and Type2-Vertix2, which may produce an average of up to 40 tons/hectare (dry weight) and almost 60 tons/hectare (dry weight) of biomass per year, respectively. This is substantially higher than, for instance, Miscanthus, which produces a maximum of 35 tons per hectare (dry weight) per annum.

Type 1 is described as a cane closer to the conventional sugarcane but having lower sucrose content and, lower purity and a higher fiber content; Type 2 is a cane with only marginal content of sugar but with fiber content higher than Type 1. Type 2 is to be used exclusively for biomass production.

One of the most prominent characteristics of energy canes is its high number of tillers and high ratooning ability. Research has shown that energy cane maintains high productivity for at least eight ratoons. This long-term ratooning ability is not least facilitated by a rhizomatous growth habit, which mitigates the adverse effects of crown damage caused by machinery during harvesting and hauling.

Because energy cane is similar to sugarcane, it can be promptly adopted with only minor management adjustments, both in the field and in industry. This makes energy cane an innovation with great economic advantages in the tropics and subtropics for the production of biofuels, either by first- or second-generation processes (Matsuoka and Rubio, 2019).

Sustainability considerations

Energy cane's high biomass yield per unit area makes it an attractive, potentially land-saving bioenergy crop. However, depending on the scale and location of production, there may be some adverse sustainability challenges.

The cultivation of energy cane may involve converting natural habitats into agricultural land which may lead to the loss of biodiversity. It typically involves large monoculture plantations, with negative impacts on biodiversity. Energy cane's rapid growth and nutrient uptake can deplete soil nutrients, making it challenging for follow-up crops to thrive without additional fertilization. Removing energy cane may have environmental implications as well, especially if the plant has invaded adjacent natural habitats or sensitive ecosystems.

Energy cane spreads through rhizomes and tillers, which are underground stems that can produce new shoots and roots. These structures can make removal challenging because even if you remove the main stalks, new shoots may emerge from the remaining rhizomes. The roots of energy cane can be strong and dense, which makes it difficult to remove energy cane without specialized equipment. Even where most of the energy cane plant is removed from the soil, any small root or rhizome fragments left in the soil can potentially regrow, requiring additional efforts to control or eradicate. To effectively remove energy cane dense rooting systems, a combination of techniques is required such as mechanical excavation, herbicide application, and ongoing monitoring to prevent regrowth.

Energy cane requires substantial water for growth. It will compete for irrigation water and cannot be recommended for areas with irregular rainfall where irrigation is required. Rain-fed production is restricted to areas with evenly distributed high rainfall.

Intensive breeding programs for energy cane prioritize certain traits like high biomass production and initial disease resistance as for example the Gran Bio Energy cane Type 2 Vertix2. Such highly productive cultivars, when cultivated on large scale, cause loss of genetic diversity, and in the long run, resistance to pest and diseases.

Like sugarcane, energy cane cultivation can have social and economic impacts on local communities, including changes in land use patterns, employment opportunities, and access to resources.

Macauba palm mono- and intercropping with Brachiaria grass

Macauba palm (*Acrocomia aculeata*) is an oil-producing palm native to tropical America, especially in grazing lands of the Brazilian Cerrado. Macauba palm displays intense fruiting which results in high fruit and oil yield. Macauba produces best in tropical and subtropical summer rain-fall regions with high precipitation and solar irradiation (da Silva César et al., 2015). Analysis of the macauba production system in terms of GHG emissions and CO_2 uptake shows energy conversion efficiency per unit area outperforming traditional energy crops such as sugarcane, oil palm, sunflower, maize or jatropha (Barbosa-Evaristo et al., 2018). Macauba pulp and kernel oil are considered promising alternatives for industrial applications.

Even though macauba can be grown as a main crop, a major advantage is its high suitability for intercropping including intercropping with improved pastures using *Brachiaria* grass. The novel intercropping LUT requires a conceptualization of the suitability classification for a multiple output (macauba and *Brachiaria* grass) on a piece of land. While for monocultures the suitability rating is defined as a percentage of the maximum achievable yield, for multi-cropping systems we propose to base it on the combination of the suitability ratings of the individual crops involved. As this study is primarily concerned with biofuel production, the suitability rating assigns a higher priority to the vegetable oil produced. Table 2 summarizes the assigned rating scheme, which can be modified if different priorities prevail.

Macauba palm grown as a monoculture assumes high-density plantations with non-competitive, non-productive undergrowth to prevent topsoil and soil nutrient erosion, similar to oil-palm plantations. A medium density of macauba palm plantation is anticipated for macauba palm intercropped with *Brachiaria* grass for animal grazing and/or fodder production. Higher yields are obtained in monocultures due to the difference in planting density as compared to intercropping. However, because intercropping produces both vegetable oil and feed, land sustainability restrictions may be less severe.

Table 2. Suitability classification of Macauba-Brachiaria Intercropping Land Utilization Type (LUT)

Macauba suitability*	*Brachiaria* suitability	Intercropping Macauba-*Brachiaria*
Very suitable (VS) > 80% of max production	VS	VS
	S	S
	MS	MS
	mS	mS
	vmS	vmS
	NS	NS
Suitable (S) 60-80% of max prod.	VS, S	S
	MS	MS
	mS	mS
	vmS	vmS
	NS	NS
Moderately suitable (MS) 40-60% of max prod.	VS, S, MS	MS
	mS	mS
	vmS	vmS
	NS	NS
Marginally suitable (mS) 20-40% of max prod.	VS, S, MS, mS	mS
	vmS	vmS
	NS	NS
Very marginally suitable (vmS) < 20% of max prod	VS, S, MS, mS, vmS	vmS
	NS	NS
Not suitable (NS)	VS, S, MS, mS, vmS, NS	NS

* Macauba intercropped with Brachiaria assumes a reduced density of plantations compared to monoculture, which technically results in a reduced leaf area index (LAI) and accordingly lower yields.

Sustainability considerations

Macauba's dense rooting system expands laterally approximate with the area of its crown projection, while rooting depth increases with age, with majority of root mass (> 80%) within 1 m depth when adult (Moreira et al., 2019). An adult monoculture macauba palm plantation (400-500 trees ha^{-1}) reaches more than 60 t C ha^{-1} per year corresponding to sequestration of about 225 t CO2 eq ha^{-1} per year. This substantial amount of stored carbon in above and below-ground biomass suggests that the macauba palm has significant potential to generate carbon credits and contributes to the mitigation of the effects of climate change (Moreira et al., 2020).

Apart from carbon sequestration macauba play important ecological roles, primarily for the restoration of degraded areas by improving marginal soil conditions (Mota et al., 2011). The macauba root system ameliorates nutrient availability by pumping nutrients from the subsoil, and together with the decomposition of leaf litter, contributes to the recovery of organic carbon status in the topsoil, which in turn, leads to the improvement of soil structure (soil micro-aggregates) and soil aeration, increased nutrient retention capacity, somewhat higher available soil moisture capacity and increased soil biodiversity. Together this promotes soil health and soil productivity.

Macauba plantations moderate micro- and meso-climate conditions. Macauba canopies reduce maximum temperatures, increase minimum temperatures and humidity, and reduce soil evaporation and irrigation requirements (Montoya et al., 2021). One of the assets of macauba, as a largely undomesticated species, is its genetic diversity and associated wide environmental adaptation capacity. This may be at risk in large-scale genetically uniform plantations.

Large-scale establishment of macauba monoculture plantations is likely to reduce biodiversity, even in moderately to severely degraded areas due to overshadowing and limitation of other indigenous species. Establishing macauba monocropping plantation with undergrowth on degraded land or land with poor soil conditions reduce topsoil and soil nutrient losses due to erosion, improves soil nutrient availability, soil nutrient retention capacity, soil oxygen availability as well as available soil water. In contrast, macauba plantations established after clean tillage hardly improve degraded soil conditions.

Macauba-*Brachiaria* intercropping relies on lower macauba palm densities and consequently reduced macauba yields. *Brachiaria* is adapted to moderate shading and produces well under macauba without major competition for nutrients and soil moisture. *Brachiaria* production under less dense macauba (< 300 trees ha^{-1}) is comparable to production in open field conditions. Palatability/digestibility of *Brachiaria* as feed remains high, also with medium plantation densities; however, quality of *Brachiaria* feed is best in open fields.

Macauba-*Brachiaria* intercropping plantations are therefore very effective for the rehabilitation of degraded lands. Organic carbon sequestration in the topsoil and soil quality and productivity in Macauba-*Brachiaria* intercropping plantations appear to be superior to macauba monocropping plantations with soil cover. Table 3 summarizes the rehabilitation potential of degraded soils for three macauba plantation types. Note that the impact on biodiversity increases significantly under monoculture growth conditions.

Table 3. Potential impact of macauba plantations on degraded soils

Impact on soil conditions	**Monoculture of *high density* macauba palms** (clean tillage, no undergrowth)	**Monoculture of *high density* macauba with non-productive/non-competing undergrowth***	**Intercropping of *medium density* macauba and Brachiaria grasses***
Organic Carbon	-/↑	↑	↑↑
Structure	-/↑	↑	↑↑
Aeration	-/↑	↑	↑↑
Nutrient availability	-/↑	↑	↑↑
Nutrient retention	-/↑	↑	↑↑
Water Holding Capacity	-/↑	↑	↑↑
Sealing	-	↑↑	↑↑
Erosion	-	↑↑	↑↑
	- No improvement; ↑ Marginal improvement; ↑↑ Substantial improvement		

* Land utilization applied in the assessment of this study

Carinata

Carinata (*Brassica carinata*) has been suggested as winter cover crop in temperate regions. *Brassica carinata* (Ethiopian or Abyssinian Mustard) is a species belonging to the Crucifer or Brassicaceae family. Most likely Abyssinian Mustard is a result of an ancestral hybridization event between *Brassica nigra* (Black Mustard) and *Brassica olearacea*. *B. carinata* was cultivated as a food crop in regions of Africa. Carinata is widely adaptable to diverse growing regions, cropping systems, and management regimes either as a spring or winter crop in double-cropped systems (Seepaul et al., 2021).

Among other uses for fuel, meal and co-products, *B. carinata* is being investigated for the development of an aviation fuel. In 2012 a first jet flight was performed using biofuel[5] made from *B. carinata*.

B. carinata is a short to moderate duration annual crop which grows well in temperate and sub-tropical climates. In temperate zones, *B. carinata* may be grown as spring crop planted as soon as mean temperatures reach 5°C (Canadian Food Inspection Agency, 2017). In subtropical areas *B. carinata* is grown through the winter, without hibernation with longer growth cycles (Seepaul et al., 2016a; Seepaul et al., 2016b).

Accordingly, we use different *B. carinata* varieties in the analysis, namely:

1) Spring *B. carinata* (SP) grown between spring and summer with durations between 105 and 150 days

2) Two sub-tropical varieties growing from autumn to spring,
   First, a variety adapted to growing in cool winter temperatures (ST) with longer durations between 165 and 210 days, and
   second, a 'rabi' variety (RB) is adapted to moderately cool winter temperatures with durations between 135 and 150 days.

B. carinata, like other brassicas has a high requirement for water, nitrogen (N) and sulfur (S). NUSEED company has set up experiments, which evaluate *B. carinata* performances under different nutrient supply and external environmental conditions as prevailing in the Pergamino site and the San Antonio de Areco site.

Sustainability considerations

Carinata has gained attention for its potential as a cover crop in sustainable agriculture. Like any agricultural crop, carinata cultivation and utilization present sustainability challenges.

Growing carinata requires significant amounts of water for optimal growth, which may strain soil moisture resources for follow-up crops. Carinata has high demand for nutrients. Intensive cultivation depletes soil nutrients and organic matter, leading to soil degradation and reduced agricultural productivity. This AEZ assessment assumes the implementation of sustainable soil management practices, such as crop rotation, cover cropping, and minimal tillage which helps to maintain soil health and fertility.

Monoculture practices associated with *B. carinata* cultivation negatively impact local biodiversity by reducing habitat diversity and promoting the proliferation of pests and diseases. Implementing agroecological principles, such as intercropping, and cover cropping as assumed in this assessment, supports biodiversity conservation.

Excessive use of chemical fertilizers and pesticides in *B. carinata* cultivation leads to environmental pollution, soil and water contamination, and adverse health effects on humans and wildlife. This assessment assumes crop rotations and minimum tillage limiting reliance on chemical fertilizer and biocides which in turn reduces environmental impacts. High input production and processing of *B. carinata* for biofuel purposes requires significant energy inputs, for machinery, transportation, and processing facilities. The current assessment assumes energy-efficient practices such as minimum tillage and reduced field operations for pest and disease eradication, weeding and fertilizing and therefore moderates the overall carbon footprint associated with *B. carinata* cultivation.

[5] The National Research Council of Canada, a government research and development organization, flew over Ottawa, Canada, during a one-hour flight on Oct. 29. The engines consumed ReadiJet, an unblended biofuel based on carinata. Earlier biofuel flights by other civil aircraft used a mix of alternative fuel and traditional petroleum-based jet fuel.

Greenhouse Gas emission savings

Even though biofuels may be thought of as carbon neutral because the plants used to produce them absorb CO_2 as they grow, some CO_2 emissions occur along the biofuel value chain. Feedstock cultivation, conversion of the biotic raw material to biofuels, and the distribution and transportation of biofuel feedstocks and fuels, all involve emissions. Moreover, changes in land use, whether direct or indirect, are likely to result in additional GHG emissions. A potential geographic shift in crop production because of the production and demand for biofuels is referred to as indirect land use change. The assumptions applied in this study avoid indirect land use changes because the existing and future cropland needed for food production and grassland for ruminant livestock feed are reserved up front ("food first" principle) and not considered for biofuel feedstock production.

Suitability and production potentials of biofuel feedstocks in individual grid-cells are analyzed for GHG saving potentials vis-à-vis fossil oil-based fuels based on IPCC guidelines for GHG accounting (IPCC, 2019) and RSB criteria, as follows:

(i) For life cycle GHG emissions, we assume best practice management meeting RSB 60% savings requirements.

(ii) For GHG emissions caused by direct land use change, i.e., here the conversion of shrub- or grass land to biofuel feedstock cultivation, we use the IPCC Tier 1 approach and 20-year accounting period. Although most losses occur at the time of conversion, soil, and vegetation carbon changes due to land use change are annualized for a 20-year period.

(iii) Sustainability oriented, yet feasible, biofuel feedstock land management options assume no tillage or reduced tillage and high (annual crops) or intermediate (perennial crops) input of organic matter (without manure) depending on feedstock and climate region. This is relevant for soil carbon stock changes and management options for the converted grass/shrubland when calculating direct land use changes.

Emissions generated along the supply chain are calculated in life-cycle assessments (LCA) and results vary significantly depending on several factors/assumptions, particularly the type of energy used in the biofuel conversion process. Crop cultivation emissions include N_2O from nitrogen fertilizer and manure, CO_2 from agricultural machinery, fertilizer and pesticide production, and the net soil organic carbon balance.

GHG emissions from direct land use change apply the RSB GHG Calculation Methodology and 2006 IPCC Guidelines. This requires i) an estimation of the changes in biomass, i.e., the above-ground plant material before and after the land use conversion and ii) an estimation of soil carbon stocks following the land use conversion. Soil carbon stock changes depend on the management options selected to produce biofuels on the converted grass/shrubland. Further, processing of biofuel feedstocks and conversion to biofuels often produces significant amounts of useful co-products, primarily 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. This study applies economic allocation, a common methodology used to partition GHG emissions in the product chain to the biofuels and the co-products.

Please refer to Annex B for details of i) the life cycle GHG emissions applied in this study for the different biofuel feedstocks and ii) calculations of GHG emissions from direct land use change according to the 2019 Refinement of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019).

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. The fossil fuel comparator is set at 94 g CO_2eq/MJ as per the RSB guidelines. Therefore, to achieve the minimum 60% saving criterion (i.e., 56.4 g CO_2eq/MJ), 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.

The first GHG criterion is tested according to equation:

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

where

$dCO2_{LUC}$	annualized CO2equ emissions due to direct land use change [g CO_2eq/MJ]
$eCO2_{LCA}$	lifecycle emissions of biofuel pathway (excluding land use change) [g CO_2eq/MJ]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [g CO_2eq/MJ]
s_{min}	minimum GHG saving rate expressed as share of comparator [dimensionless]

Using the grid-cell level results of the CO_2 emissions from the LCA and direct land use change, the GHG criteria described above (Box 1) are applied to test the GHG emission efficiency of the selected feedstock types. In this way, for each location (grid-cell), individual feedstocks are tested for compliance with the GHG criteria and their energy output can be compared.

Box 1. 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 (i.e., here 37.4. 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.

Considering that the assumed best-practice life cycle GHG emissions range between 14 and 37 g CO_2eq/MJ (see Table 40 in Annex B), 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 (Box 1). In addition, the repayment period for the dLUC carbon debt must be less or equal to half the accounting period, i.e., repayment 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 g CO_2eq/MJ (when life-cycle emissions approach the 60% saving threshold) to a theoretical maximum of 37.6 g CO_2eq/MJ (when life-cycle emissions are zero). In comparison, for compliance with the GHG 2 criterion, the permissible annualized dLUC emissions can be at least 28.2 g CO_2eq/MJ (when life-cycle emissions approach the 60% saving threshold) and have a theoretical maximum of 47 g CO_2eq/MJ (when life-cycle emissions are zero).

Although the achievable cumulative net GHG emission savings are similar in the long term for both criteria, the GHG 1 criterion helps to minimize the risk of net carbon losses if biofuel production ceases shortly after REMAIN land is converted to arable land for biofuel feedstock production. A detailed comparison of the two GHG criteria was presented in a former study (Fischer et al., 2019). The GHG 2 criterion, whilst providing the same net reduction threshold over a 20-year accounting period, does not meet RSB compliance requirements. Consequently, this report only includes results for GHG 1.

We refer to Annex B for GHG calculation details and the tabulated database to explore effects of using GHG 2.

3. Land sustainability considerations

Excluded ecologically sensitive areas

Protected areas and regions/area with a high biodiversity value are essential for the provision of regulating ecosystem services. In line with the RSB requirement that "Operations shall avoid negative impacts on biodiversity, ecosystems, and conservation values", formulated in Principle 7 on "Conservation", this study sets aside land for the environment and areas of biodiversity value. To this end, we have integrated spatial layers from various data sources to define land set-aside for environment and of high value for biodiversity to represent ecologically sensitive areas (Table 4).

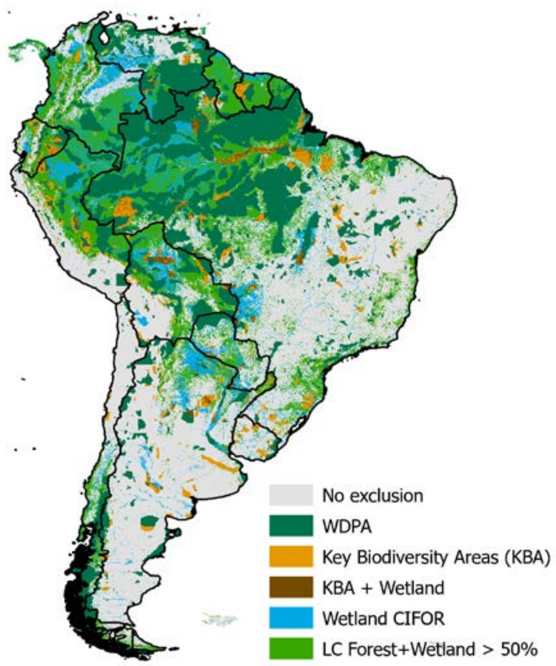
Table 4. Data included in the environment exclusion layer

Data domain	Reference
World Database of Protected Areas (WDPA)	www.protectplanet.net[1]
Key Biodiversity Areas (KBA) and Alliance for Zero Extinction (AZE) as included in the Integrated Biodiversity Assessment Tool (IBAT)	www.keybiodiversityareas.org ;www.ibat-alliance.org
CIFOR Wetland 2016[2]	Gumbricht et al. (2017)
Forest, Mangroves & Wetland is > 50% in in 30 arc-second grid cell of land cover/use map	See section 'Consolidated land use database'

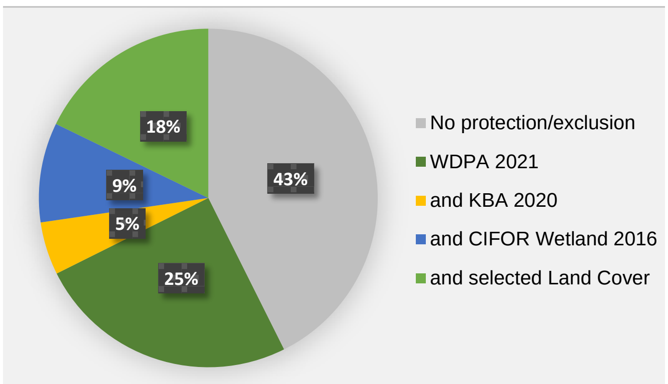
1 WDPA provides monthly updates. Data were accessed in February 2021; **2** https://www2.cifor.org/global-wetlands/

Figure 2 presents a map and chart based on the 30-arc second environment exclusion layer. Note, the map has been compiled by sequentially adding data domains as listed in Table 4. It does not show overlays of different environmental data domains. Thus, some areas showing WDPA may also be listed in the KBA database.

Figure 2. South America Environment Exclusion Layer



Total exclusion area: 10.2 million km^2



Note, the figures show successive exclusion of different data sources. *WDPA 2021*: Protected area recorded in WDPA 2021; *and KBA 2020*: Exclusion due to KBA 2020, but not in WDPA 2021; *and CIFOR Wetland 2016*: Exclusion due to CIFOR Wetland 2016, but not in KBA 2020 and WDPA 2021; *and selected Land Cover*: Exclusion due to 'Forest+Mangrove+Wetland' exceeding 50% of grid cell in LC share, but not in KBA 2020, WDPA 2021, and CIFOR.

Large areas in South America are of importance for the environment and biodiversity and are therefore not used for potential biofuel feedstock production. Areas mapped in the World Database of Protected Areas, as Key Biodiversity Areas or in the latest CIFOR wetlands cover 7 million km^2 or 39% of South America's land area. If not already designated in WDPA, KBA or CIFOR, we also exclude grid cells where more than half of the land cover/use is forest, mangrove or wetland, adding a further 3.2 million km^2 to the environment exclusion layer. In total, at least 10.2 million km^2 (57%) of South America is ecologically sensitive and therefore not considered for biofuel feedstock production.

As expected, half of the ecologically sensitive area is in Brazil (4.9 million km^2), the country covering half of South America's territory. The Other-SAM-North region (from Peru north and eastwards but excluding Brazil) has an extensive share of ecologically sensitive areas amounting to almost four-fifth (77%) of the total areas. In Brazil and the Other-SAM-South region (Bolivia southwards excluding Argentina) more than half (57% and 56%) are excluded. In Argentina and Uruguay only 30% and 32% are respectively designated for their environmental importance and therefore excluded.

Consolidated land use database

High resolution land use data

A land use/cover layer for South America has been compiled for the year 2020 based on the Global Land Cover data at 300 m resolution from the Climate Change Initiative Land Cover (CCI-LC) of the Copernicus Climate Change Service (Harper et al., 2022). For Brazil, Mapbiomas land use data (Collection 6[6]) (Mapbiomas, 2021; Souza et al., 2020) at the spatial resolution of about 30 meters were integrated. The consolidated new South America land use/cover layers features distributions of the original data in each 30 arc-second (about 1x1 km) grid-cell for 10 aggregated land use classes listed in Table 5.

Table 5. South America Land use/cover layer, classification and data sources

	LC-Class-SAM Consolidated	Hybrid LC 2020[1] for SAM except Brazil	MAPBIOMAS 2020 for Brazil
1	Cropland	Cropland	Cropland
2,3	Cropland in Mosaic	Mosaic Cropland-Natural veg.	Mosaic of Agriculture and Pasture
4	Urban	Urban areas	Urban area
5	Forest	Tree covered	Forest formation, Mangrove, Wooded Restinga[2]
6	Shrubland/Savanna	Shrubland	Savanna formation
7	Pasture	Grassland	Pasture
8	Grassland, natural (BRA)	Not applicable	Grassland, natural
9	Wetland	Natural vegetation flooded	Wetland
11	Sparsely vegetated	Bare or sparsely vegetated, Permanent snow and ice	Beach, Dune, Mining, Other non-vegetated areas, Permanent snow and ice
12	Water	Water bodies	Water

1 Climate Change Initiative Land Cover (CCI-LC) from Copernicus Climate Change Service based on Sentinel-3 earth observation satellite series developed by the European Space Agency; **2** CCI-LC includes two classes with different shares of cropland; **3** Restingas are coastal forests developing on sandy, acidic, nutrient-poor soils characterized by medium-sized trees and shrubs.

[6] The MapBiomas initiative was formed in 2015 by universities, NGOs, and Companies to develop a fast, reliable, and low-cost methodology to produce an annual temporal series of land cover and land use maps of Brazil from 1985 onwards. Collection 6 covers the years 1985 to 2020. See https://mapbiomas.org/

Ecologically sensitive areas compiled in the 'environment exclusion layer' described above were overlayed with the consolidated land use database. Figure 3 highlights the distribution of major land cover/use categories and their environmental protection status. Note, the category 'grassland' includes class 2 (Pasture in Mosaic, only for Brazil), 6 (Pasture), 7 (Grassland, Natural, only for Brazil) shown in Table 5. For the mosaic class 2, we assume a 50% share of grassland and cropland. 'Other land' is the sum of urban, sparsely vegetated, wetland and water.

Almost half (44% or 7.8 million km^2) of South America's total land (17.8 million km^2) is forest, most of it protected. Some 1.5 million km^2 (8%) are used for the cultivation of crops. Almost one fourth (23%, 4.1 million km^2) is grassland and another 14% (2.6 million km^2) are shrubland.

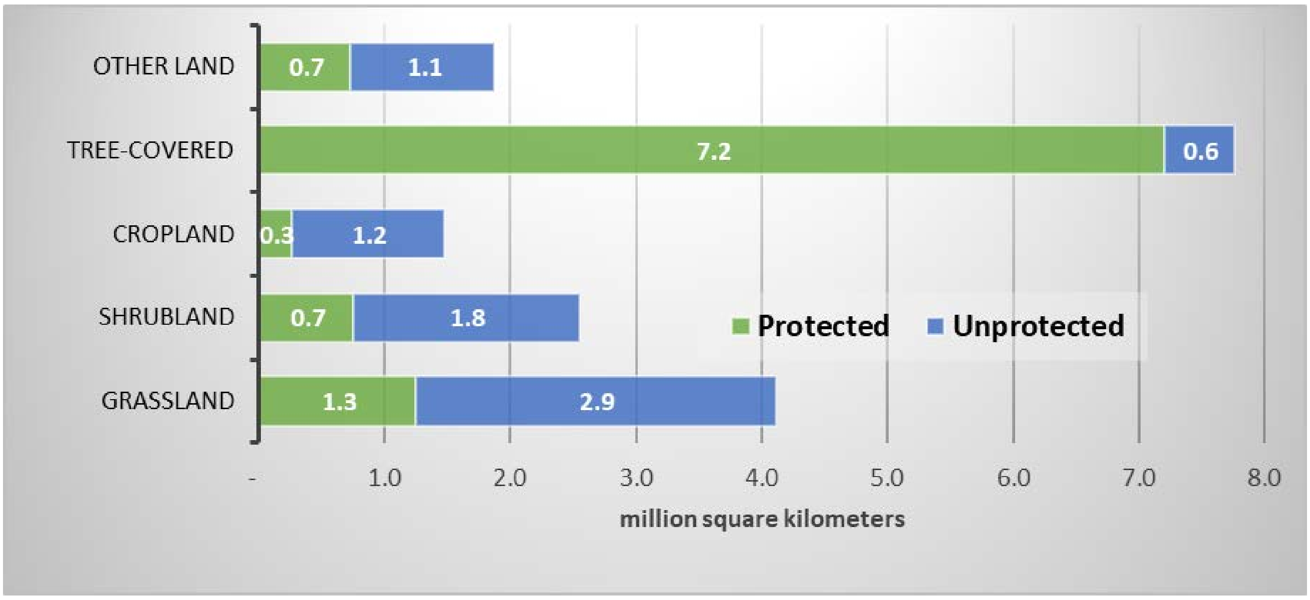
According to land related sustainability criteria, cropland (food security), all forests and wetland (carbon stocks) are not considered for the cultivation of biofuel feedstocks. Sparsely vegetated areas are also not suitable for the cultivation of rain-fed crops.

Therefore, unprotected grassland and shrubland may be considered for biofuel feedstock production amounting to 2.9 and 1.8 million km^2. Land suitability and compliance with GHG criteria for these 4.7 million km^2 grassland and shrubland areas is further explored for sustainable biofuel production. Land quality for individual biofuel feedstocks and compliance with GHG criteria determines whether a feedstock could be considered as sustainable production option in South America.

Some of the grass-/shrubland areas are used by livestock for grazing and are further excluded and not considered for biofuel feedstock production as described in the following section.

In the case of macauba (oil-bearing tree) cultivated together with *Brachiaria* grass, which is well suited for livestock feed, in principle all grass-/shrubland areas could be considered for biofuel feedstock production. *Brachiaria* species are shade tolerant and remain productive under the medium shade of intercropped trees such as macauba.

Figure 3. Major land cover classes in South America, environmental protection status, 2020



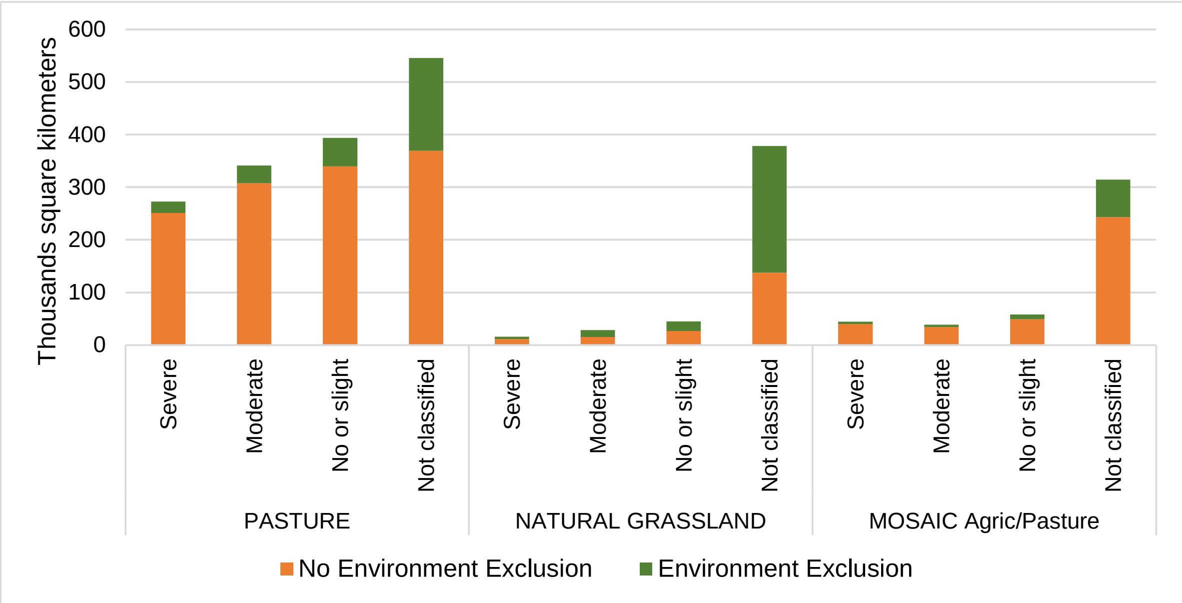
Brazil – Degraded pastureland

For Brazil, data on pasture degradation is available, which makes it possible to assess the potential cultivation of biofuel feedstocks by degradation status. The Mapbiomas pasture quality data[7] reports four classes: (i) severe degradation, (ii) moderate degradation, (iii) no or slight degradation, and areas that are (iv) not classified. These high-resolution degradation data (about 30 x 30m) were integrated in the South America land use database compiled for this study.

Figure 4 shows the distribution of degradation and environment protection for the land use classes potentially considered for biofuel feedstock production. As expected, degradation is concentrated on pasture areas with smaller amounts reported for natural grassland and the mosaic land use class of agriculture (i.e., cultivated land) and pastures. About half of Brazil's pasture, natural grassland and mosaic agriculture/pasture has been classified for its degradation status, the other half were assigned 'not classified'.

In Brazil, a total of 741 thousand km^2 were classified as degraded, of which 333 and 408 thousand km^2 were severely and moderately degraded, respectively. Thus, more than one third of the assessed area was classified as degraded. Unsurprisingly, degradation is concentrated in pastures, where 40% or 614 km^2 show signs of degradation. A smaller proportion (10%) of natural grassland falls into a degradation class. Degradation was observed in all pasture/grassland categories, including ecologically sensitive areas.

Figure 4. Land degradation database of Brazil



Source: Adapted from Mapbiomas

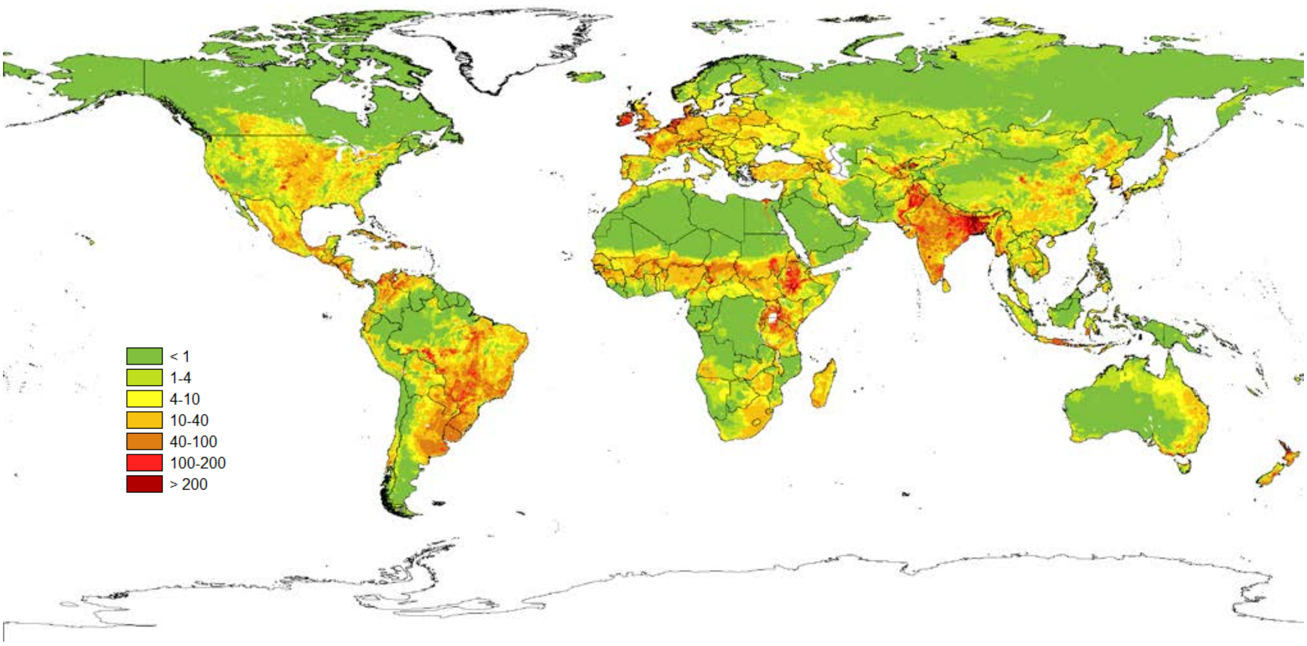
[7] The pasture quality module is still undergoing validation and evolution. For the current study we've downloaded pasture quality data for 2018 in November 2021. For latest information see https://mapbiomas.org/

Ruminant livestock feed and REMAIN land estimation

Complying with the RSB principle (6) to safeguard local food security requires safeguarding biomass from grassland/savanna areas required for feeding browsing ruminant livestock. We therefore set aside land for feed requirements of ruminant livestock when considering grassland and shrubland. The exception is an intercropping system (macauba with *Brachiaria* grass, see section below).

The extent of land to be reserved for ruminant livestock grazing requires a comparison of ruminants present in a grid cell with the land's fodder productivity. Gridded Livestock of the World (GLW 4[8]) is a spatial dataset that shows the global distribution of the major types of livestock (cattle, sheep, goats, pigs, chickens, horses, buffalo, ducks) for the reference year 2015. An example map of the distribution of cattle is shown in Figure 5. The methodology followed in the data compilation is described in Gilbert et al. (2018).

Figure 5. Distribution of Cattle in 2015



The map shows in classes the density of cattle (cattle per square km) in 2015. Source: Gilbert et al. (2022b)

Original livestock data are reported in heads of cattle (Gilbert et al., 2022b), sheep (Gilbert et al., 2022e), goats (Gilbert et al., 2022c) and other ruminant animals (Gilbert et al., 2022a, d) per grid-cell has been converted to "Livestock Units" (LU). A measure of ruminant livestock carrying capacity based on grass/shrub land productivity, augmented with residues available from crop land, has been used to estimate livestock grazing land requirements. Details of the calculations applied to determine the share of grassland/shrub land considered not available for non-food feedstock production due to the presence of ruminant livestock are described below.

The share of grassland/shrub land reserved for livestock is determined by means of a simple feed balance calculated according to:

[8] https://dataverse.harvard.edu/dataverse/glw_4

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

where

f_{LV}	Share of grassland/shrub land to be reserved for livestock feeding
F_{req}	Annual forage feed requirement of ruminant livestock [ton dry matter]
F_{sup}	Annual forage feed supply [t dry matter]

The forage feed requirement of ruminants in a grid cell is calculated using:

$$F_{req} = A * LU * (450 * 0.02667 * 365)$$

where

A	Total area of grid cell [km^2]
LU	Ruminant livestock density expressed in livestock units [LU/km^2]
F_{req}	Annual forage feed requirement of ruminant livestock [tDM]

In the calculation of forage requirements, the weight of a LU is defined as 450 kg and the daily feed requirement per kg live weight of an LU is 0.02667 kg DM (Dida, 2017), i.e., about 12 kg DM per LU per day. The ruminant livestock distribution in 2015 is derived from GLW 4 by aggregation of livestock numbers per grid cell of buffalo, cattle, sheep, goats and horses using region-specific relative weights, e.g., in South America respectively 0.7, 0.7, 0.1, 0.1 and 0.65.

The calculation of potential forage feed supply uses:

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

where

F_{sup}	Forage feed supply [t DM]
A	total area of grid cell [km^2]
Y_{grass}	average annual palatable forage/grass yield [kg DM/km^2]
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 crop land relative to potential grass yield [dimensionless]

In addition to estimating the potential forage available from the grassland, above equation accounts also for fodder from shrub land and/or crop land in a grid cell.

Combining the detailed consolidated land cover maps with the calculated forage requirements of the statistical ruminant livestock number, we estimate the proportion of grassland and shrub-covered land to be reserved for feeding ruminants, mainly cattle. In contrast to cropland, area extents and actual use of grassland and shrub-covered land are less frequently recorded and are often only poorly documented.

Definitions of grassland differ across countries and extents of grassland actually used for grazing and the intensity or duration of use have not been recorded in most countries. This is especially true for semi-arid climates and mixed grass-shrub-forest ecosystems. The uncertain extent of grassland and the distribution of livestock are sources of uncertainty in estimating the area demand for livestock feed (Tramberend et al., 2019).

Figure 6 indicates the areas in South America where grassland resources are to a large extent (shown in red) or fair extent (shown in orange) needed for livestock feeding.

Figure 6. Livestock pasture requirement factor in South America, 2010

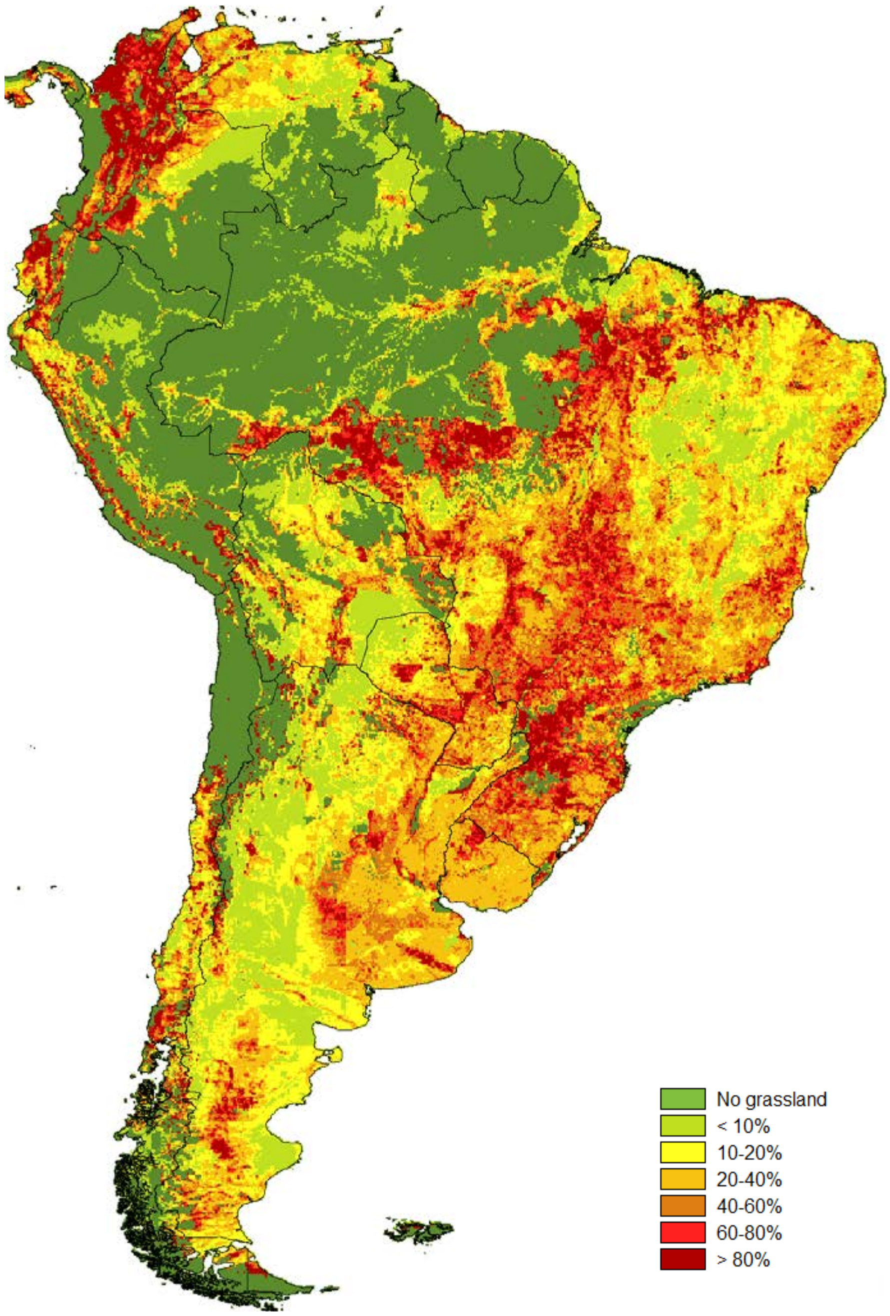


Table 6 and Figure 7 present a land use balance for grass- and shrubland of South America using the methods described above. Almost one third (2.0 mio. km^2) of South America's total 6.7 grass-/shrubland mio km^2 is protected and therefore not considered for vegetable oil production. Some of it is used for livestock grazing. On the remaining 4.7 mio km^2 unprotected grass-/shrubland areas, we estimate 1.5 mio km^2 is needed for roaming livestock. Thus, after consideration of environment and food security, a remaining land (termed REMAIN land) of 3.27 mio km^2 is explored for potential vegetable oil production.

Depending on feedstock and GHG criteria, some 1.777 mio km^2 REMAIN grassland and 1.397 mio km^2 REMAIN shrubland could be considered for vegetable oil production. Half of these areas are in Brazil, approximately corresponding to the overall share of grass-/shrubland in South America. In Argentina, shrubland plays an important role for REMAIN land estimation. Whether a crop can satisfy all RSB requirements will depend on the quality of the land, the yields that follow, and the ability to reduce GHG emissions.

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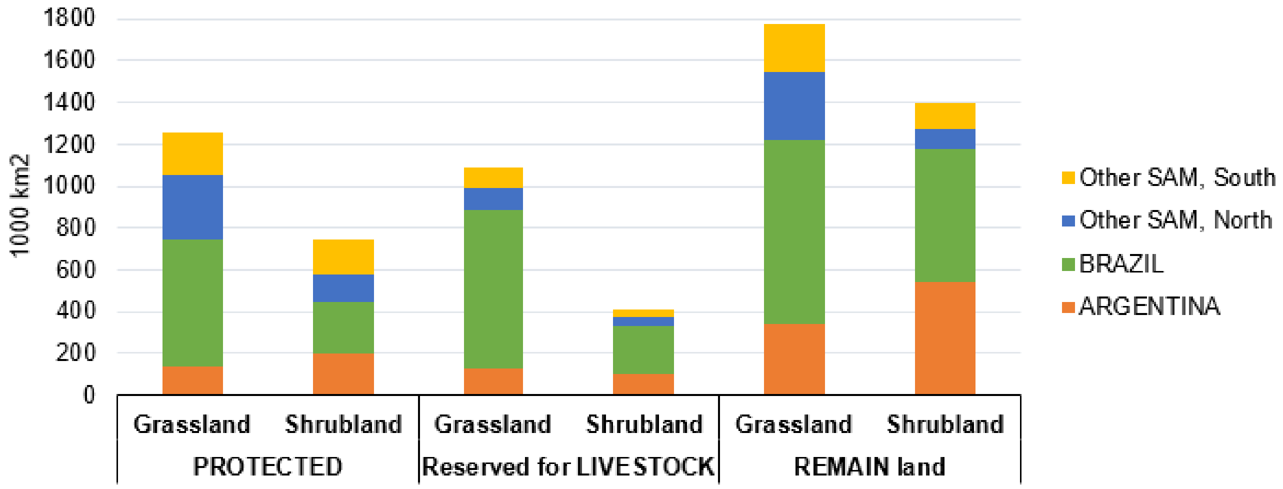
Table 6. Land use balance of grass- and shrubland in South America's major regions

1000 km^2		Argentina	Brazil	OtherSAM, North	OtherSAM, South	Total SAM
Protected	Grassland	140	606	307	200	1253
	Shrubland	195	248	132	172	748
	Total	335	854	439	372	**2,001**
Unprotected	Grassland	466	1,642	429	322	2,859
	Shrubland	645	862	138	159	1,804
	Total	1111	2,504	567	481	**4,663**
Total unprotected of which						
For Livestock	Grassland	125	760	104	97	1,086
	Shrubland	103	227	46	36	412
	Total	228	987	150	133	**1,498**
REMAIN land	Grassland	341	882	325	225	1,773
	Shrubland	541	635	92	123	1,392
	Total	882	1,517	417	348	**3,165**

Figure 7. Grass- and shrubland in South America, protected, reserved for livestock feed and REMAIN land



4. Biofuel production capacities

The assessment's results present the extent and quality of South America's land resources and associated biofuel production potentials that meet the RSB sustainability criteria, notably the land and GHG emission saving criteria. Estimates are presented for current climate conditions (1981-2010 average) and future climates (30-year average around the 2050s).

Scenario simulations

Calculations are undertaken using a geospatial grid with a resolution of 30 arc-seconds (about 1x1 km), although the spatially detailed biofuel feedstock evaluation maintains sub-grid cell distributions for a few variables (such as land use, soil information, and terrain slope). For presenting results, we tabulated the grid-level data for designated land suitability classes by region and country-level administrative unit. RSB sustainability criteria, notably land related and GHG criteria, together with biophysical land quality determine the technical potential for the cultivation of biofuel feedstocks. Technically, this employs the procedures outlined in Table 7.

Table 7. Assessment steps applied for the calculation of RSB compliant biofuels

	Assessment steps / RSB principles	**Output**
	Land related sustainability criteria	
1	Exclude areas of importance for the *environment* and biodiversity (Exclude grid-cells of the ENVIRONMENT layer); RSB Principle 7 (Conservation)	Unprotected areas
2	Exclude cropland (food security), forest (environment), built-up, water, bare/sparsely vegetated (not relevant for biofuels); RSB Principle 6 (Food security) and 7 (Conservation)	Share (and extents) of unprotected grass- and shrubland in grid-cell (i.e., LC class 2,6,7,8)
3	Estimate *livestock feed requirements* in grass- and shrubland grid-cells to determine areas not required for feed. RSB Principle 6 (Food security)	Share of REMAIN land[1] in grid-cell, recorded separate for grassland and shrubland
	Compliance with GHG criteria RSB Principle 3 (GHG emission saving)	
4.	Assess production potential and energy output for intercropping macauba – *Brachiaria*[2] for unprotected grass- and shrubland.	Area and energy potential in each grid-cell for all feedstocks compliant with GHG and land- and water-related RSB criteria
5.	Assess compliance of rain-fed production of 14 individual feedstocks with GHG criteria for REMAIN land. RSB Principle 9 (Water regime[3])	
	Select biofuel feedstock with **highest energy output**	
6.	*Umbrella crop*: Compare energy output of all biofuel feedstock opportunities (i.e., output step 4 and 5)	Area and energy production potential of the highest energy output biofuel opportunity in each grid-cell
	Tabulation of results	
7.	Aggregation of grid-cell level information (output of Step 6) to administrative units	Area requirement and energy production potential; Tabulation by land use, biofuel feedstock, and land suitability.

1 The remaining land once environment and food security sustainability criteria were addressed, we term REMAIN land; **2** Macauba-*Brachiaria* intercropping involves no land use conversion.

Unprotected grassland and shrubland that are not utilized as feed by grazing cattle may be considered to produce biofuel feedstock, according to RSB land-related sustainability requirements. Thus, we exclude ecologically sensitive areas and areas required for food production as described in section 3. These remaining land areas once environmental and food security criteria were addressed, we term 'REMAIN' land (Step 1-3).

For different biofuel feedstock alternatives, we estimate biofuel production potentials on REMAIN land compliant with the RSB GHG criteria of saving a minimum of 60% GHG compared to the use of fossil fuels. Because intercropping macauba with *Brachiaria* grass can be used for grazing livestock the entire extents of unprotected grass- and shrubland is considered for this biofuel production option. We address the RSB water regime principles by considering only rain-fed production potentials (Step 4,5).

Specific locations may be able to produce more than one biofuel feedstock. For example, some sub-tropical regions may provide good or moderate land quality for producing crops of energy cane, sugarcane and macauba palm, that all comply with sustainability criteria. The GAEZ uses the concept of an '*umbrella crop*', which determines the preferred crop in an area when more than one crops qualify for production. Selection criteria could be yield (tons), economic value ($), energy yield (GJ), food calories (Cal), or a combination of some of those. Since the focus of this assessment is to estimate sustainable aviation biofuel potential, we choose energy output (GJ) as the decision criterion where multiple crops are viable in each location. Thus, if more than one feedstock complies with RSB criteria in a specific grid-cell, the one that produces the greatest amount of energy is selected (Step 6). In this way we construct 'umbrella' results comparing all biofuel options *vis-à-vis* food security, environment and GHG sustainability criteria. Finally, we tabulate grid-cell results for administrative units (Step 7).

Three different 'umbrella' groups were created, each representing different technical and policy options. First, to estimate a technically sustainable upper ceiling for South America, we include all 15 feedstocks in this study that are grown on grass-/shrublands. Note, in addition to fields exclusively cultivated with macauba palm, we include one multi-functional land utilization assuming intercropping of macauba palm and *Brachiaria* grass. Only the intercropping variant allows use of areas needed to feed current livestock populations.

To highlight sensitivity, we also include one 'umbrella' for oil-based (7 feedstocks) and another for sugar/starch-based (5 feedstocks) biofuels. The former biofuel conversion route uses well-established practices, the latter includes 2nd generation biofuel techniques converting lignocellulosic material to liquid biofuels.

RSB compliant scenarios were evaluated for current and future 30-year average climatic conditions. GAEZ was forced with historic (average 1990-2010) and a scenario ensemble for four future (average 2041-2070) climate scenarios represented by the level of radiative forcing of the climate system as characterized by the Representative Concentration Pathways (RCPs) (Van Vuuren et al., 2011). RCP 2.6 radiative forcing trajectory and resulting climate changes portrays an open and co-operative world oriented toward sustainability. GHG mitigation policies are ambitious and may be sufficient to reach the Paris agreement of keeping global mean temperatures below 2°C by 2100. Three other RCPs (RCP 4.5, 6.0 and 8.5) represent increasingly stronger climatic change. RCP 4.5 represents modest efforts to curb climate change with the aim to avoid the most severe detrimental environmental impacts of the past decades.

Although climate variability and extremes can have a significant impact on biofuel feedstock production in individual years, this study aims to explore aggregate trends. Therefore, the modelling system is forced with the ensemble mean of five climate models available from the inter-sectoral impact model intercomparison project (ISI-MIP) (Warszawski et al., 2014). A potentially positive environmental impact of climate change is the direct effect of increased atmospheric CO_2 concentrations on crop yields, known as the CO_2 fertilization effect, because of the enhancement of photosynthesis rates and plant water use efficiency (Kimball et al., 2002). The scenarios generally assume a CO_2 fertilization effect. Under RCP2.6 conditions, which represents the lower end concentration pathway of the IPCC scenarios, the average atmospheric CO_2 concentrations in the 2050s (period 2041-2070) amount to 443 ppm compared to 493 ppm for RCP6.0.

The simulations kept the current land use in the 2020s constant because the study's goal was to determine how climate change will affect the possibility of producing biofuel feedstock. Future land use patterns may be influenced by alternative socioeconomic trends as outlined in the Shared Socio-Economic Pathways (SSPs). Less land will be available to produce biofuel feedstock if cropland, shrubland, or grassland experience net declines. Due to the uncertainty around the location and extent of the land use changes, additional scenario assumptions would be required.

Description of database

For all scenario simulations, grid-cell level results of crop production potentials are also tabulated by administrative unit, land cover/use class, environmental exclusion type, land degradation status, GHG criterion, and crop type. Land suitability ranges from unsuitable to highly suitable conditions for the respective crops and climates. GAEZ reports extents (area) and production (tons) by different suitability classes.

Administrative units: This study applies the Global Administrative Unit Layers (GAUL) distributed by the Food and Agricultural Organization of the United Nations (FAO, 2014). Original GAUL 2014 polygons were converted to a 30 arc-second grid database for aggregation and reporting of data. For presenting results, we tabulate grid-level data for total South America (SAM), by four major regions and country-level administrative unit shown below (Table 8). For Argentina and Brazil, province level results are also tabulated.

Table 8. Administrative units selected for tabulation of results

Major Region	Country and province sub-units
Argentina	Province-level data (24 provinces[1])
Brazil	Province-level (27 provinces[2])
Other SAM North	Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname, French Guiana
Other SAM South	Bolivia, Chile, Paraguay, Uruguay
Total SAM	All countries listed above

1 Buenos Aires, Buenos Aires D.f., Catamarca, Chaco, Chubut, Cordoba, Corrientes, Entre Rios, Formosa, Jujuy, La Pampa, La Rioja, Mendoza, Misiones, Neuquen, Rio Negro, Salta, San Juan, San Luis, Santa Cruz, Santa Fe, Santiago Del Estero, Tierra Del Fuego, Tucuman;
2 Acre, Alagoas, Amapa, Amazonas, Bahia, Ceara, Distrito Federal, Espirito Santo, Goias, Maranhao, Mato Grosso, Mato Grosso Do Sul, Minas Gerais, Para, Paraiba, Parana, Pernambuco, Piaui, Rio De Janeiro, Rio Grande Do Norte, Rio Grande Do Sul, Rondonia, Roraima, Santa Catarina, Sao Paulo, Sergipe, Tocantins

Land suitability and productivity

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 below.

Farm economics depend on the relationship between input costs for labor 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% ("Very suitable" or VS) and 60-80% ("Suitable" or S) maximum attainable yields. Moderately suitable land (MS) 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). Table 9 summarizes the land quality classification used in GAEZ.

Table 9. 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

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). Because of farm economics, this study considers only prime (VS), good (S) and moderate (MS) land qualities for biofuel feedstock production.

Environmental exclusion, land use and degradation: Results are tabulated by environmental exclusion class (Table 3), land cover/use (Table 4) and degradation class. For the land cover class ‘Mosaic of Agriculture and Pasture’ (LC class 2, only in Brazil), we assume a 50% share between cropland and pasture. The exclusion classes are assigned by priority, i.e., first WDPA, then KBA, Wetland and land dominantly LC classes Forest+Mangrove+Wetland (see Table 3). Organic soils are assigned when no other EXC class is indicated. RSB compliant results always assume class 1 ‘Land without exclusion status’. For pasture degradation classes (only available for Brazil) please refer to section ‘Brazil – degraded pastures’ and Figure 4.

GHG emissions saving criteria: The methods for estimating GHG emission savings have been described above (section on GHG emission savings). To comply with the RSB criteria, this report only includes results for GHG 1 (see also Table 2). We refer to the tabulated database to explore the effects of using GHG 2. In addition to GHG criterion 1 and 2, the tabulation lists related aspects as described in Table 10. As in all thematic tabulations (column in Excel files), the last criterion refers to ‘total land’, i.e., the theme is not considered. Note that for sake of convenience, GHG criterion 6 has been used to tabulate grassland or shrubland areas (i.e., LC class 2,5,6,7) that is se -aside for livestock feed (see section ‘ruminant livestock feed’).

Table 10. GHG emission criterion (column GHG) in the tabulated results

Criterion	
1	GHG from Lifecycle Assessment (LCA) and direct land use changes (dLUC) is 60% less compared to the fossil fuel comparator
2	GHG from LCA < threshold and repay period for LC conversion carbon debt < 10 years (i.e., half of accounting period)
3	VS, S or MS land for feedstock exists in grid cell but does not meet GHG criterion 1 or 2
4	Land not eligible; GHG criteria not applied (forest, wetland, built-up land, water LC classes)
5	No VS, S or MS land in grid cell
6	Land in grass or shrub LC set aside for livestock feeding
7	Total land

Current biofuel potentials considering all feedstocks

GHG-compliant feedstocks from unprotected grass- and shrubland

Current climate is represented by using historic (average 1991 – 2010) monthly climate characteristics for forcing the AEZ modelling system. This scenario selects the highest yielding feedstock in energy terms in each grid cell. A technical sustainable biofuel potential of up to 20,414 PJ could today be achieved in South America (Table 11). Energy cane supplies more than two-thirds of this potential (14,089 PJ), intercropping macauba-*Brachiaria* more than one fifth (4,568 PJ) and miscanthus another 1,509 PJ. Energy cane and miscanthus convert ligno-cellulosic material to biofuels, which is technically well-established but not yet used at large commercial scales. Fruits from macauba palm is used for vegetable oil production as input to biodiesel, a well-established technology. All three major crops would require extension services and support for farmers who are not yet familiar with their cultivation. Jatropha and single macauba cultivation could supply smaller amounts in some regions where other feedstocks are not possible or generate lower energy yields compared to other feedstocks. Figure 8 presents a map of the defining feedstock and energy production potentials across South America.

Table 11. South America's biofuel potential compliant with RSB land and GHG sustainability criteria

	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)[1:]	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km²)						
Sugarcane	0	1	1	0	1	1
Oil palm	0	0	0	0	1	1
Macauba	3	7	10	5	10	15
Jatropha	0	1	1	14	10	23
Solaris (tobacco)	0	0	0	0	1	1
Miscanthus	6	52	58	32	85	118
Energy cane	45	308	352	134	563	697
Biomass sorghum	0	0	1	0	1	1
Intercropping MB[2]	33	303	336	67	583	650
Total	87	673	760	253	1,254	1,507
Biofuels (PJ)						
Sugarcane	0	10	10	0	14	15
Oil palm	1	3	4	1	9	10
Macauba	34	87	121	52	107	159
Jatropha	1	2	4	33	23	56
Solaris (tobacco)	0	1	2	0	3	3
Miscanthus	84	872	956	324	1,185	1,509
Energy cane	1,069	7,330	8,398	2,494	11,594	14,089
Biomass sorghum	1	4	5	2	5	6
Intercropping MB[2]	261	2,452	2,713	464	4,104	4,568
Total	1,452	10,762	**12,214**	3,371	17,044	**20,414**

The table shows area needed and energy output by land use and biofuel feedstock

1 In Brazil, grassland includes i) pastures (LC=7); ii) mosaic of agriculture and pastures (LC=2), where we assume 50% pastures; and iii) natural grassland (LC=8). From these total 1,642 thousand km2 grassland, pastures account for 77%. **2** Intercropping macauba (producing oil for biofuels) and *Brachiaria* grass (livestock feed)

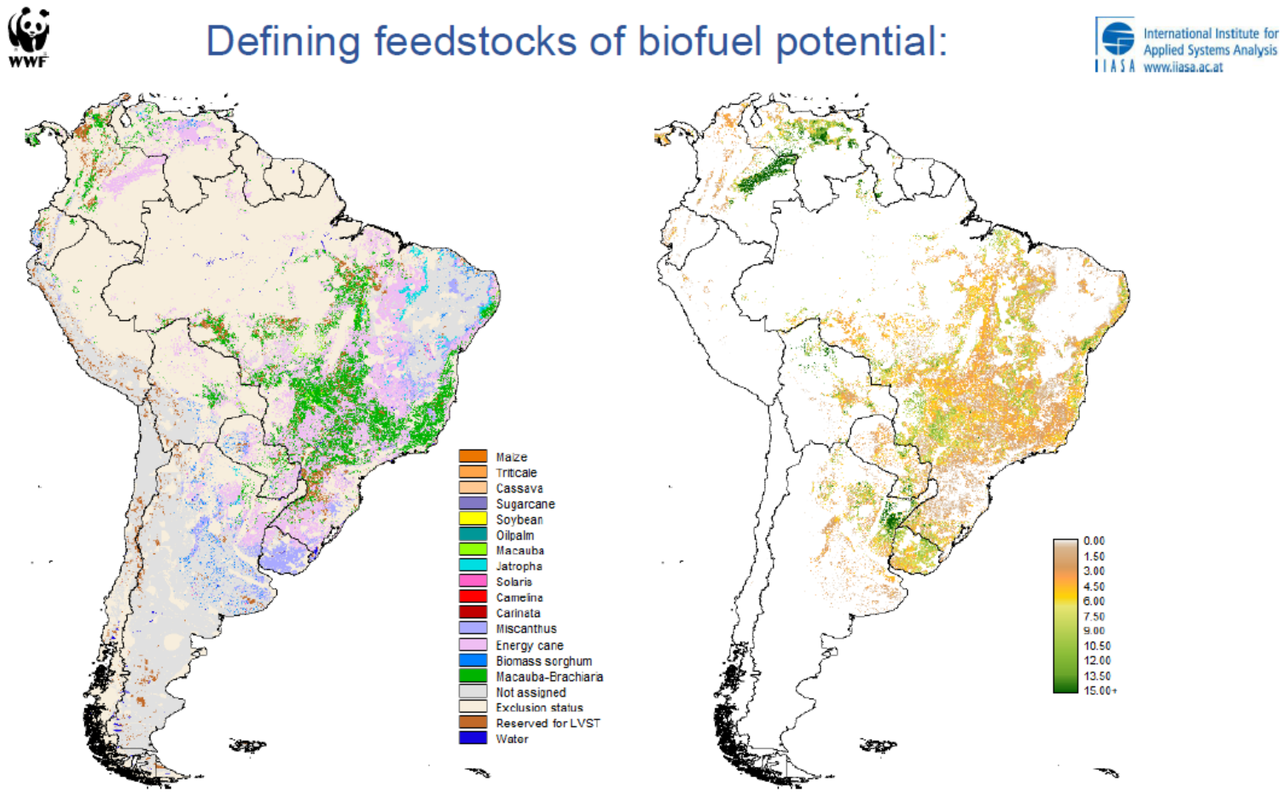
The intercropping of macauba palm with *Brachiaria* grass is concentrated in Brazil because of its large areas of grassland and shrubland (Table 12). Energy cane could be produced throughout South America.

Table 12. Biofuel potential from unprotected grass- and shrubland, by major region

Petajoules	Argentina	Brazil	Other Sam, North	Other SAM, South	SAM, Total
Sugarcane	0	14	1	0	15
Oil palm	1	7	3	0	10
Macauba	6	151	3	4	159
Jatropha	0	49	1	0	56
Solaris (tobacco)	0	3	0	0	3
Miscanthus	388	360	46	715	1,509
Energy cane	1,508	7,831	3,268	1,482	14,089
Biomass sorghum	0	1	1	4	6
Intercropping MB[2]	54	4,004	381	130	4,568
Total	1,958	12,419	3,702	130	**20,414**

Annual crop only rarely comply with GHG criteria when conversion of grass- or shrubland is involved. Although perennials (sugarcane, oil palm) comply with the GHG criteria in some areas, energy cane and macauba palm tend to be most common because of a higher energy output. Up to 1,507 thousand km^2 of land, primarily grassland, would be needed for the cultivation of bioenergy feedstocks to achieve these RSB-compliant potentials. About half of this land (650 thousand km^2) is used for intercropping macauba palm with *Brachiaria* grass, which allows dual use as livestock feed and energy crop production. Almost half, 697 thousand km^2, stems from energy cane. High yields of on average between 229 GJ/ha on prime and good land (VS+S) and 186 GJ/ha on prime, good and moderate land (VS+S+MS) make energy cane in these areas compliant with the GHG criteria even when conversion of grass- or shrubland is involved. In some temperate regions smaller extents (118 thousand km^2) of miscanthus cultivation can contribute to a sustainable biofuel potential.

Figure 8. Defining feedstocks of South America's RSB compliant biofuel potential, 2010



Defining feedstock of biofuel potential:
The map shows for each pixel with 'remaining' grassland and shrub land (land use in 2020) the best producing feedstock type subject to GHG Criterion 1.

Biofuel production potential:
The map shows for 'remaining' grassland and shrub land the rain-fed fuel energy production potential from VS, S and MS land (in TJ).

Winter fallow crops on cropland

In addition to sustainable production potentials from unprotected grass- and shrubland, winter fallow crops grown on cropland meet the food security criteria because the risk of indirect land use change is very low. Almost one fifth (18% or 260 thousand km^2) of South America's cropland has a designation for being of importance for the environment or biodiversity. These protected areas are concentrated in Northen SAM region and in Brazil's mosaic cropland/grassland land use class. The remaining 1,213 thousand km^2 cropland are explored for their potential to grow camelina or carinata during the winter fallow period.

In South America, among the feedstocks included in this study, camelina and carinata are likely candidates for cultivation as winter fallow crops. An overall potential of 759 PJ could be generated from camelina and carinata grown as winter fallow. A significant proportion of South America's unprotected cropland, 41% or 497 thousand km^2, is suitable for winter fallow crop production. Three fourth (75%) of this potential from Carinata cultivated in Brazil and Argentina and one fourth from Camelina, mainly from Argentina (Table 13).

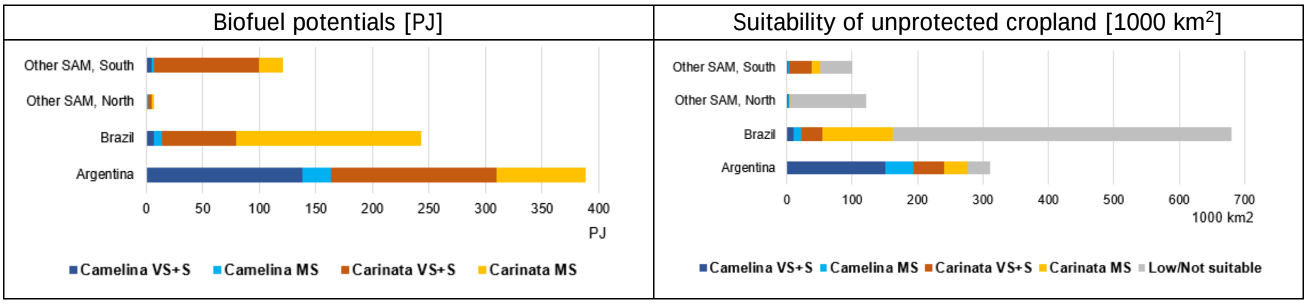
Table 13. Suitability and biofuel potentials for winter fallow crops on unprotected cropland

	Area	**(1000 km^2)**	**Total**	**Biofuels**	**(Petajoules)**
Land suitability	Prime and good land	Prime, good, moderate land	unprotected cropland	Prime and good land	Prime, good, moderate land
Region*	VS+S	VS+S+MS		VS+S	VS+S+MS
ARGENTINA					
Camelina	151	193		138	164
Carinata	48	84		146	224
Total	199	277	311	284	388
BRAZIL					
Camelina	11	22		7	13
Carinata	33	141		66	230
Total	44	163	680	73	243
Other SAM*					
Camelina	4	7		6	9
Carinata	34	50		95	119
Total	38	57	222	101	128
SAM, Total					
Camelina	165	222		151	186
Carinata	116	275		307	573
Total	281	**497**	1213	458	**759**

* Here the sum of Other SAM North and South is shown. The vast majority occurs in 'Other SAM, South'

The southern temperate regions of South America provide prime land quality and ample opportunities for winter fallow crop production. Argentina alone could supply 388 PJ, where almost two-thirds of cropland are of prime quality for camelina or carinata winter fallow crop production (Figure 9).

Figure 9. Biofuel potential of winter fallow crops cultivated on unprotected cropland



Climate change impacts

Climate forcing simulations from an ensemble of five climate change models are assessed for four RCP scenarios representing increasingly strong GHG emission pathways. Impacts of climate change on biodiversity areas are not considered, but we might reasonably expect that this would also lead to increase in potential protected areas or KBAs to accommodate shifting climate envelopes for indigenous species. Estimates below may therefore well be underestimates of potential reduction in yield.

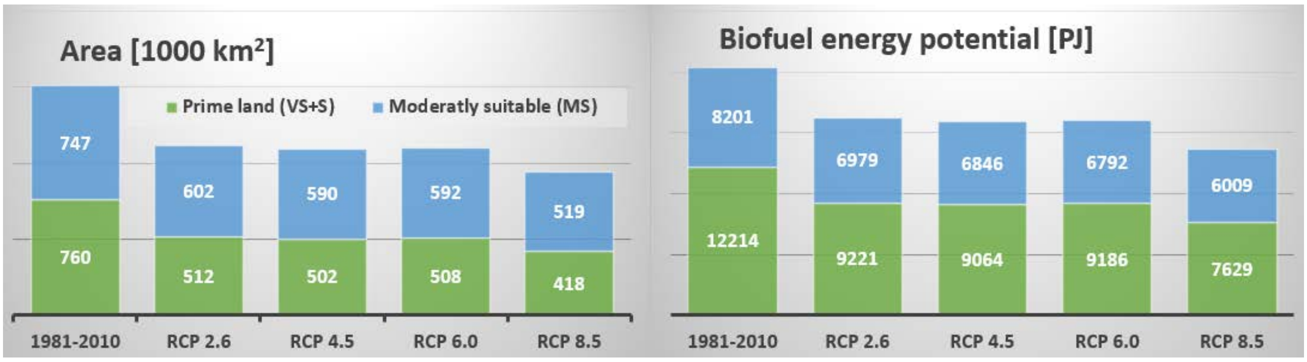
Potential from unprotected grass-/shrubland

Climate change has a detrimental effect on South America's ability to produce biofuels for almost all feedstocks explored. As a result, by the 2050s, the ability to produce biofuels on unprotected grassland and shrubland reduces generally by 15% to 38%, depending on the scenario and the condition of the land. Compared to moderately suitable land, prime and good land is more adversely affected. While up to 20,414 PJ may be reached under current climate, by the 2050s only 13,639 to 16,200 PJ are conceivable when prime, good and moderate land is considered (Table 14, Figure 10).

Table 14. Climate change impact on South America's potential to produce RSB compliant biofuels

	Prime & good land (VS+S)		**Prime, good and moderate land (VS+S+MS)**	
	Area (1000 km^2)	Biofuels (PJ)	Area (1000 km^2)	Biofuels (PJ)
1981-2010	760	12,214	1,507	20,414
2041-2070 (2050s)				
RCP 2.6	512	9,221	1,114	16,200
RCP 4.5	502	9,064	1,092	15,911
RCP 6.0	508	9,186	1,099	15,978
RCP 8.5	418	7,629	938	13,639

Figure 10. Climate change impacts on sustainable biofuel energy potentials



The figures show area use and biofuel energy potential from unprotected grass-/shrubland for current climate (1981-2010) and the 2050s for RCP scenario ensembles

Just as today, energy cane and intercropping macauba with *Brachiaria* grass are the main contributors to the sustainable biofuel potential. Table 15 presents the results for a medium scenario RCP 4.5 disaggregated by contributing feedstocks.

Table 15. South America's biofuel potential compliant with RSB land & GHG criteria, 2050, RCP4.5

	Prime and good land (VS+S)			Prime, good, moderate land (VS+S+MS)		
Land use (unprotected)	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000km²)						
Oil palm	0.0	0.0	0.0	0.0	0.0	0.1
Macauba	0.3	0.9	1.2	1.0	1.4	2.4
Jatropha	0.4	0.3	0.7	15.7	6.9	22.6
Miscanthus	4.3	26.7	31.0	20.3	52.0	72.4
Energy cane	29.1	260.2	289.3	78.6	526.4	604.9
Biomass sorghum	1.4	6.3	7.7	4.0	7.1	11.1
Intercropping MB[1]	9.0	162.8	171.8	23.4	355.1	378.5
Total	44	457	502	143	949	1,092
Biofuels (PJ)						
Oil palm	0	0	0	0	0	1
Macauba	4	11	16	10	16	26
Jatropha	1	1	2	36	16	52
Miscanthus	61	463	524	210	704	914
Energy cane	724	6,296	7,020	1,517	10,662	12,178
Biomass sorghum	12	57	69	28	62	90
Intercropping MB[1]	75	1,357	1,433	159	2,490	2,648
Total	878	8,186	9,064	1,961	13,950	15,911

1 Macauba intercropped with Brachiaria grass

Winter fallow crops on cropland

The impact of climate change on winter fallow camelina and carinata production is modest. Biofuel production is affected by a maximum of 20% reduction in production under the most extreme climate scenario (RCP 8.5) (Figure 11 and Table 16).

Figure 11. Climate change impacts on winter fallow crops in South America

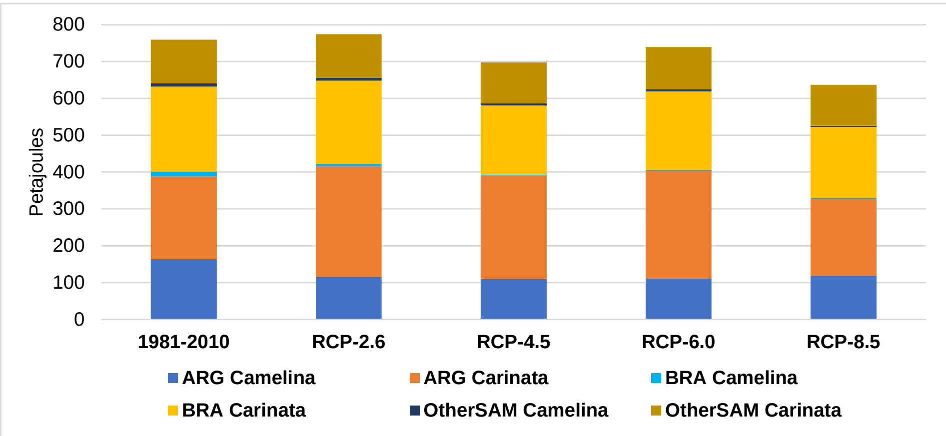


Table 16. Winter fallow crop grown on unprotected cropland in South America

Petajoules	**1981-2010**	**2050s RCP-2.6**	**2050s RCP-4.5**	**2050s RCP-6.0**	**2050s RCP-8.5**
Camelina	186	129	118	120	124
Carinata	573	645	580	619	513
Total	759	774	698	739	637

Sensitivity analysis, current climate

We may assess the sustainable biofuel production potential of various feedstock conversion techniques by defining selected "umbrellas" (i.e., combinations of crops). These represent different alternative biofuel opportunities. Results for the generation of biodiesel from oil-based feedstocks and bioethanol from starch- and sugar-based feedstocks under current climate are shown below.

Oil-based feedstocks

Conversion processes of oil-based feedstocks are well established and have been applied at large scales. This simulation compares all oil-based feedstocks including intercropping of macauba with *Brachiaria* grass. Note, single oil-based feedstocks are cultivated on REMAIN land and macauba-*Brachiaria* intercropping on all unprotected grass- and shrubland. In each grid-cell the highest yielding oil-bearing feedstock is selected.

If only oil-based biofuel feedstocks are considered, South America may produce up to 12,463 PJ annually (Table 17). It takes cultivation of a variety of feedstocks on 1,729 thousand km^2 of land to reach this biofuel potential. Notably, 1,059 thousand km^2 for intercropping macauba with *Brachiaria* do not require conversion of grass-shrubland to arable land. Thus, more than one third (37%) of the 4,663 thousand km^2 total investigated unprotected grass-/shrubland is suitable to produce sustainable biofuels. These extents include 1,498 thousand km^2 reserved for livestock and 3,165 thousand km^2 of REMAIN land (see Section 3, Table 5).

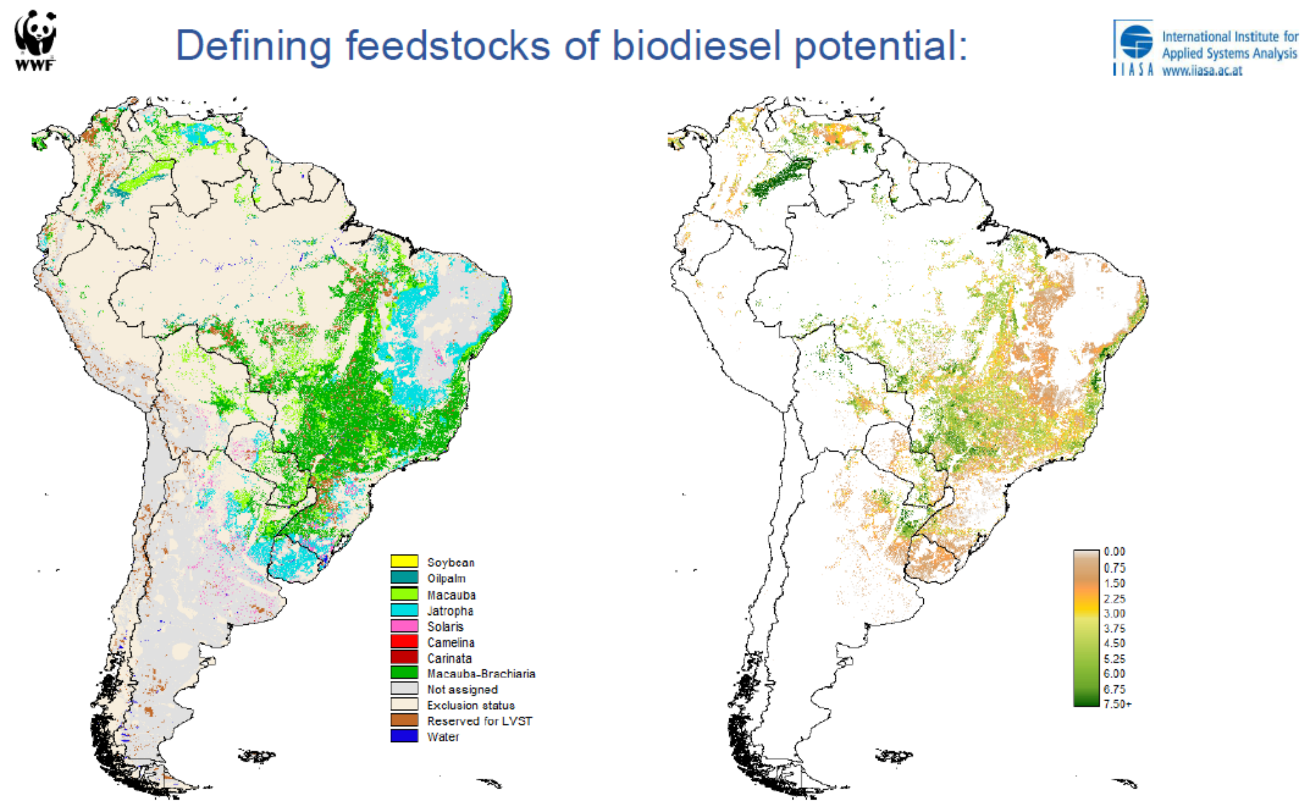
Table 17. Biodiesel potential for oil-based crops in South America compliant with sustainability criteria

	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)[1:]	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km^2)						
Oil palm	1	16	18	2	41	43
Macauba	28	142	170	63	239	302
Jatropha	25	74	100	128	195	323
Solaris (tobacco)	0	1	1	0	2	2
Intercropping MB	49	479	528	112	947	1,059
Total	104	712	816	305	1,424	1,729
Biofuels (PJ)						
Oil palm	20	272	292	26	589	615
Macauba	366	1,845	2,212	671	2,729	3,400
Jatropha	97	279	376	358	589	946
Solaris (tobacco)	1	4	5	1	7	9
Intercropping MB	398	3,950	4,348	771	6,722	7,492
Total	882	6,351	**7,233**	1,827	10,636	**12,463**

The table shows area used and biofuel potential of oil-based crops in South America compliant with RSB land and GHG criteria, for current climate and contribution by crop.

The largest contributor is the macauba palm produced on both unprotected grass- and shrubland intercropped with *Brachiaria* grass (7,492 PJ from 1059 thousand km^2) and cultivated as single crop (3,400 PJ from 302 thousand km^2). With relatively high yields per hectare produced from only 43 thousand km^2, oil palm adds an additional 615 PJ. In temperate regions Jatropha can add 946 PJ, albeit with comparatively low yields produced on 323 thousand km^2. Figure 12 highlights the spatial distribution of the defining feedstock and concentration of the sustainable biodiesel potential across South America.

Figure 12. Defining feedstocks of South America's biodiesel potential



Defining feedstock of oil-based biofuel potential:
The map shows for each pixel with 'remaining' grassland and shrub land (land use in 2020) the best producing feedstock type subject to GHG Criterion 1.

Oil-based biofuel production potential:
The map shows for 'remaining' grassland and shrub land the rain-fed fuel energy production potential from VS, S and MS land (in TJ).

Starch- and sugar-based feedstocks

The starch- and sugar-based simulation compares an umbrella of seven different biofuel feedstocks (Table 1). They include well established feedstocks using first-generation biofuel conversion routes with ample uses at industrial scale (sugarcane, maize, cassava, triticale, sweet sorghum). Miscanthus and energy cane are cultivated to produce above ground biomass and require second-generation biofuel conversion pathways. Although costs and efficiencies of conversion processes have improved, challenges remain including handling of bulky biomass and large-scale applications.

Up to 945 thousand km^2 of the 3,165 thousand km^2 REMAIN land are suitable for the development of prospective RSB-compliant biofuels with a biofuel production potential of 17,821 PJ (Table 18). The high achievable yields of energy cane clearly outcompete other feedstocks of the starch- and sugar-based umbrella.

Some 90% of the overall potential is attributed to energy cane. In more temperate regions miscanthus may play an important role. Although it thrives in tropical temperatures comparable to those of energy cane, sugarcane produces less energy fuel. Energy yields for sugarcane range between 92 to 153 GJ/ha, whereas energy yield for energy cane is much higher and range from 208 and 282 GJ/ha. Therefore, energy cane is usually selected when both sugarcane and energy cane are viable for RSB-compliant biofuels. For miscanthus energy yields range between 97 and 180 GJ/ha, and for biomass sorghum between 70 and 122 GJ/ha.

Table 18. Biofuel potential for starch- and sugar-based crops in South America

	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)[1:]	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km²)						
Sugarcane	0.1	3.9	4.0	0.2	10.3	10.5
Miscanthus	6.3	54.1	60.4	35.4	94.0	129.3
Energy cane	46.2	336.0	382.2	145.5	659.4	804.9
Biomass sorghum	0.1	0.4	0.6	0.2	0.5	0.7
Total	**52.7**	**394.4**	**447.1**	**181.2**	**764.2**	**945.5**
Biofuels (PJ)						
Sugarcane	1	49	51	2	107	109
Miscanthus	86	897	983	353	1,276	1,629
Energy cane	1,104	7,973	9,077	2,707	13,391	16,097
Biomass sorghum	1	4	5	2	5	6
Total	**1,192**	**8,923**	**10,116**	**3,064**	**14,778**	**17,842**

The table shows area use and biofuel potential for starch- and sugar-based crops in South America compliant with RSB land and GHG criteria, for current climate and contribution by crop.

Focus on Brazil

For Brazil alone, we estimate a current upper sustainable technical maximum of 12,419 PJ comprising of 5,788 PJ from prime and good land (VS+S) and another 6,631 PJ from moderate (MS) land (Table 19). Energy cane and macauba cultivated in intercropping with *Brachiaria* grass dominate these estimated sustainable potentials. Land requirements total up to 1,017 thousand km^2(VS+S+MS), less than half of Brazil's unprotected grass- and shrubland extents. Average energy yields from Brazil's prime and good land qualities are 230 GJ/ha for energy cane and 80 GJ/ha for intercropping macauba palm with *Brachiaria* grass (90 GJ/ha).

Table 19. Sustainable biofuel potential for BRAZIL, area requirements and energy output, current climate

	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)[1:]	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km²)						
Total	40	408	448	173	898	1,017
of which[2]						
Energy cane	10	133	143	86	334	420
Intercropping MB	26	261	287	57	522	579
Other	4	14	18	31	42	73
Biofuels (PJ)						
Total	463	5,325	**5,788**	2,009	10,410	**12,419**
of which						
Energy cane	215	3,067	3,281	1,421	6,409	7,831
Intercropping MB	205	2,078	2,282	384	3,620	4,004
Other	44	181	224	204	381	584wil

1 Brazil's total *unprotected* shrubland and grassland are 862 ths km^2 and 1642 ths km^2, respectively (see Table 6). In Brazil, grassland includes: i) pastureland (LC=7; 1,268 ths km^2), natural grassland (LC=8; 191 ths km^2) and grassland in a mixed cropland-pasture category where we assume 50% grassland (LC=2; 183 ths km^2);
2 Here we show only the key contributing crops. Additional suitable feedstocks compliant with RSB criteria were selected as the highest energy yielding possibility in smaller areas, including sugarcane, oil pam, jatropha, solaris, and macauba (single production).

Note, Brazil's grassland is comprised of three sub-land use categories. Thus the 10,410 PJ from prime, good and moderate land qualities from 898 thousand km^2 include:

i) pastureland: potential 7735 PJ from 707 thousand km^2;

ii) natural grassland: potential 1328 PJ from 81 thousand km^2; and

iii) a mixed cropland-pasture category, where we assume half of it being pasture, with a potential of 1347 PJ from 110 thousand km^2.

Stakeholders in Brazil highlight their interest in pastureland, already in agricultural use and potentially available for biofuel production. Therefore, below we explore biofuel potentials from Brazil's pastureland category.

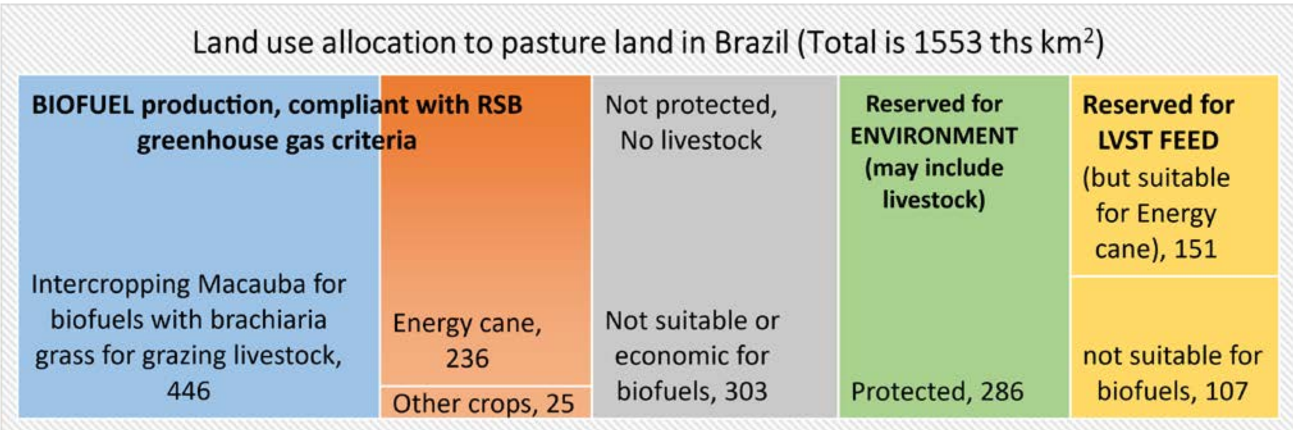
Potential from Brazil's pastureland

Figure 13 presents an overall land balance for Brazil's pastureland use class (LC=7) amounting to 1553,000 km^2. About one fourth (18%) or 286,000 km^2 has a designation status for protecting the environment and safeguarding biodiversity (green shade in figure). Another 303,000 km^2 are not suitable for economic biofuel production, even though these areas are neither protected, nor required for livestock feed (grey).

Almost half of current pastureland (46%) or 707,000 km^2 could be used for biofuel production compliant with RSB sustainability criteria. This includes 301,000 km^2 prime and good land and 406,000 km^2 moderate land for a range of biofuel feedstocks. The dominant feedstocks are intercropping macauba for biofuels with *Brachiaria* grass for livestock feed (light blue; 446,000 km^2) and energy cane (brown; 236,000 km^2). In some areas other crops compliant with RSB GHG criteria were selected as promising energy crops including sugarcane, oil palm, jatropha, Solaris and macauba cultivated as single crop (brown; 25,000 km^2).

Another 257,000 km^2 (17% of total pasture land) is reserved for feed of grazing livestock (yellow). Some 151,000 km^2 of those would be suitable for energy cane production and comply with the GHG criterion. However, because of the food security criteria these areas cannot be considered for biofuel feedstock production. The remaining 106,000 km^2 are not suitable for biofuels.

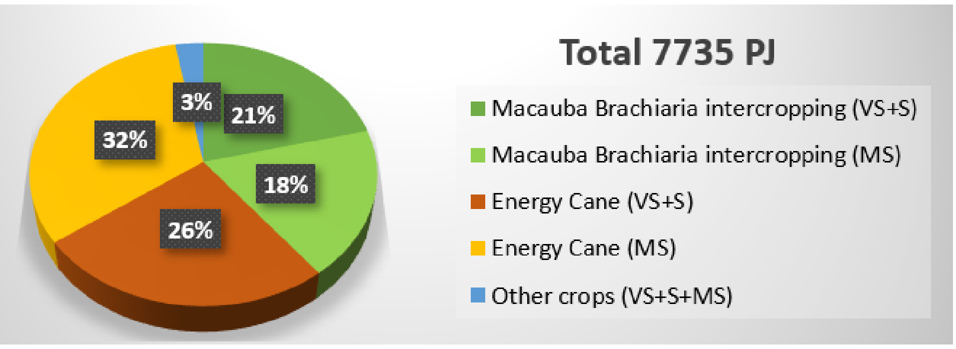
Figure 13. Pasture use allocation in Brazil, by main use type and biofuel feedstock



The numbers in the figure show 1000 km^2. The RSB compliant biofuel potential is from economically viable areas (VS+S+MS).

An upper technical maximum of 7735 PJ biofuels could be produced from Brazil's 707,000 km^2 of pastureland compliant with RSB land and GHG criteria. Figure 14 highlights the contribution of each feedstock according to land quality including very suitable and suitable (VS+S) prime land and moderately suitable (MS) land quality.

Figure 14. RSB-compliant biofuel potential from pastureland in Brazil, current climate



One fifth (21%) and one-quarter (26%) of the potential comes from pastureland with prime land quality (VS+S) for macauba-*Brachiaria* intercropping and energy cane, respectively. Half of the maximum potential could be sourced from moderate land qualifies, albeit with generally lower energy yields compared to prime land (Table 20). The energy output per unit area is almost three times higher for energy cane than for macauba-*Brachiaria* intercropping. This is in part because energy cane cultivation involves ploughing and conversion from pasture to arable land. Macauba-*Brachiaria* intercropping, on the other hand, maintains the permanent vegetation cover of the original pasture. It requires the sowing of *Brachiaria* to obtain an improved grassland.

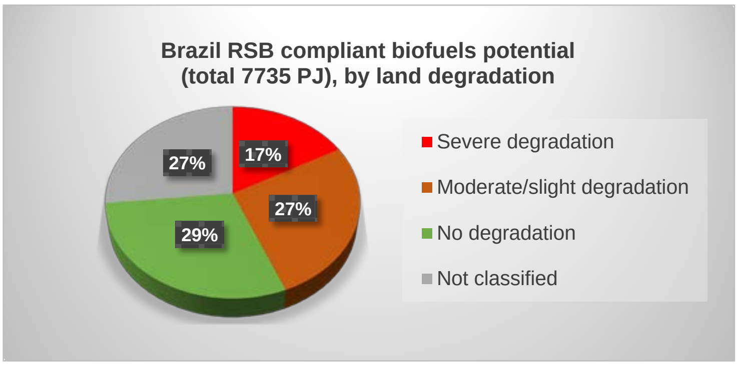
Table 20. Biofuels from pastureland in Brazil compliant with RSB land and GHG criteria, current climate

Biofuel feedstock	**Land quality***	**Biofuel** [PJ]	**Area** [1000 km^2]	**Yield** [EJ/km^2]
Macauba *Brachiaria* intercropping	VS+S	1,631	205	8.0
	MS	1,418	241	5.9
Energy cane	VS+S	1,985	88	22.6
	MS	2,479	148	16.7
Other crops	VS+S+MS	222	25	9.0
Total	VS+S+MS	7,735	707	10.9

* Prime land: Very suitable and suitable (VS+S); Moderately suitable land (MS)

Because Brazil has compiled a map showing degraded pastureland, it is possible to identify areas where RSB compliant biofuel production could be sourced from degraded land. Almost half (44%) of the identified RSB compliant biofuel potential from Brazil's pastureland is classified as severely (17%) or moderately or slight (27%) degraded. Some 29% of show no signs of pasture degradation and the remainder 27% could not be classified (Figure 15).

Figure 15. Biofuel potential from pastureland in Brazil compliant with RSB land and GHG criteria



Current potential, assuming oil-based feedstocks only

More than two-thirds (70%) of South America's total vegetable oil-based biofuel potential (see Table 17) is concentrated in Brazil alone, where up to 8,780 PJ could be produced, mainly sourced from grassland (Table 21). In Brazil, grassland is mainly composed of 'pastureland' and smaller areas of natural grassland and a mixed cropland-grassland category for which we assume a 50% grassland share (see Table 4).

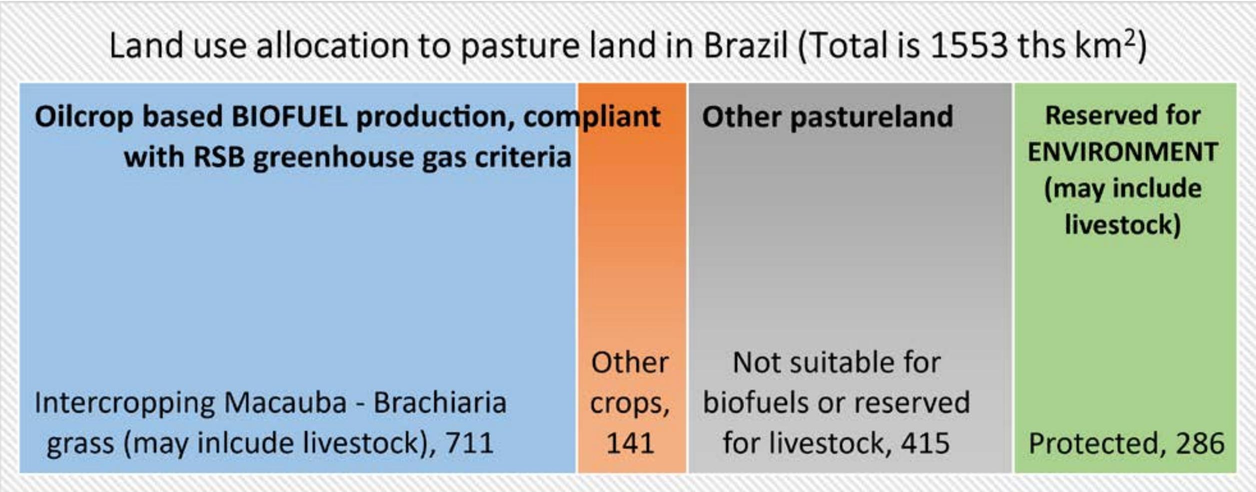
Table 21. Biodiesel potential in Brazil compliant with RSB land/GHG criteria, current climate

	Prime and good land (VS+S)			**Prime, good and moderate land (VS+S+MS)**		
Land use (unprotected)	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km²)						
Oil palm	0	2	2	0	22	22
Macauba	11	48	59	36	106	142
Jatropha	9	23	32	99	99	198
Solaris (tobacco)	0	1	1	0	1	2
Intercropping MB[2]	34	406	440	91	845	936
Total	54	480	534	226	1,073	1,299
Biofuels (PJ)						
Oil palm	0	36	36	0	285	285
Macauba	134	586	719	349	1,107	1,455
Jatropha	31	84	115	261	277	538
Solaris (tobacco)	1	4	4	1	6	7
Intercropping MB[2]	267	3,300	3,568	598	5,896	6,494
Total	433	4,010	**4,443**	1,209	7,571	**8,780**

2 Intercropping macauba with Brachiaria grass. Grazing livestock is possible in these areas, thereby relaxing the food security land use restrictions.

Figure 16 highlights the land allocation for pastureland, the main contributor to Brazil's total sustainable biofuel potential based on oilseed crops. Pastureland could produce about 6097 PJ on 852,000 km², predominantly by intercropping macauba with *Brachiaria* grass. Some 286,000 km² are reserved for the environment and 415,000 km² are either reserved for livestock or not suitable for the biofuel feedstocks explored.

Figure 16. Pastureland use in Brazil for scenario Oil-based biofuel production



The figure shows results for pastureland (LC=7) only and assumes production on prime, good & moderate land (VS+S+MS)

Focus on Argentina

Argentina is characterized by vast areas of shrub- and grassland (1,446,000 km^2). Almost one fifth (335,000 km^2) are excluded ecologically sensitive areas as defined in Chapter 3. This leaves a balance of 1,111,000 km^2, of which 228,000 km^2 are reserved for grazing of current livestock herds. As a result, REMAIN land amounts to 882,000 km^2 comprising of shrubland (541,000 km^2) and grassland (341,000 km^2).

Under current climate, up to 92,900 km^2 of unprotected grass-/shrubland could be used for RSB-compliant biofuel feedstock production with an annual biofuel potential of 671 Petajoules (Table 22). More than half of this energy potential is from macauba palm, the remainder from jatropha and intercropping macauba-*Brachiaria* grass. In other words, up to 10% of REMAIN land is prime, good or moderate land quality for the production of these energy feedstocks.

Table 22. Sustainable biofuel potential for Argentina, current climate, area requirements and energy output

	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)[1]	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km^2)						
Total	20	41	61	29.5	63.4	92.9
of which						
Macauba	5.8	15.3	21.1	8.5	22.2	30.8
Jatropha	11.4	17.4	28.8	16.8	26.2	42.9
Intercropping MB	2.5	8.4	8.4	4.2	15.0	19.2
Biofuels (PJ)						
Total	148	346	**494**	197	474	**671**
of which						
Macauba	79	204	283	104	269	373
Jatropha	46	67	113	60	91	151
Intercropping MB	23	75	98	33	114	147

1 Argentina's total unprotected shrubland and grassland is 645 and 466 thousand km^2 respectively.

In addition, up to 388 PJ could be produced from carinata and camelina grown as winter fallow on cropland (see Table 13). Winter fallow cultivation on current cropland therefore plays a significant role for sustainable biofuel feedstock production in Argentina.

5. Conclusions

This research assesses South America's capacity to produce sustainable biofuels pertinent to the aviation sector. The Roundtable on Sustainable Biomaterials (RSB) criteria serve as the foundational concept for defining sustainability. Although some criteria apply only at the local project level, this large-scale assessment considers food security, nature conservation, greenhouse gas emission savings, soil and water regimes. Cropland, grass- and shrubland needed for animal feed, forests and wetland are not taken into consideration for the development of biofuel feedstocks, according to RSB land-related sustainability criteria. All biofuels must comply with strict GHG saving criteria, which require a minimum of 60% GHG emissions savings relative to the fossil fuel comparator when using a 20-year accounting period.

We calculate the suitability and production potential of 16 different biofuel feedstocks using the Global Agro-ecological Zones methodology. Farmers are familiar with many of the feedstocks (e.g., sugarcane, soybean, maize, oil palm), but some may be emerging crops that are not yet cultivated on a large scale (macauba palm, energy cane). Intercropping of macauba palm with *Brachiaria* grass demonstrates multifunctional agriculture, producing livestock fodder and vegetable oil, assumed here to be used for aviation biofuels. Intercropping has fewer restrictions on land use, as less land needs to be set aside for feeding ruminants. Intercropping macauba with *Brachiaria* grass yields slightly lower compared to monocropping macauba, but more land becomes available for biofuel feedstock production while meeting food security sustainability criteria.

The spatially detailed biofuel feedstock assessment maintains a spatial resolution of 30 arc-seconds (roughly 1x1 km), with sub-grid cell distributions for selected variables (e.g., land use, soil information, terrain slope). In some areas the RSB sustainability criteria are met by various biofuel feedstocks. For the estimation of an aggregated sustainable potential, we establish for each grid-cell an "umbrella" crop and use energy output as the selection criterion. The biofuel feedstock with the highest energy output therefore contributes to the technological, sustainable potential in a specific location.

South America's **current (2020) technical potential** is estimated to be between 12,214 and 20,414 PJ, depending on agricultural market conditions. Economic production is feasible on prime and good land (VS+S, producing up to 12,214 PJ). If demand and raw material prices are high, moderately suitable land (MS) may also be viable for farmers to invest in. These marginally productive areas could add 8,200 PJ. These amounts could be produced from rain-fed feedstocks cultivated on 760 (VS+S) and 1,507 (VS+S+MS) thousand km^2 respectively of unprotected grassland and shrubland (Table 11). For comparison, the total area of grass- and shrubland is 6,664 thousand km^2, of which almost one third is protected, leaving a balance of 4,663 thousand km^2 unprotected grass- and shrubland (Table 6). Thus, up to almost one third (32%) of unprotected grass- and shrubland could be allocated to the cultivation of biofuel feedstocks and maintain compliance with RSB sustainability criteria.

Some 2,713 to 4,568 PJ could be obtained by intercropping macauba and *Brachiaria* grass, using some 336 to 650 thousand km^2 (Table 11). We estimate that today's ruminant livestock requires 1,498 thousand km^2 of grass- and shrubland. Significant parts of this area could therefore be used for intercropping macauba palm with *Brachiaria* grass. This highlights the potentially important contribution of multifunctional farming principles in the design of sustainable agricultural systems.

Energy cane is the highest yielding feedstock in most of the other half of the identified land compliant with RSB-criteria. Bred to achieve a high biomass yield, energy cane alone could produce about two-thirds, or 8,398 to 14,089 PJ, of the total potential. It could produce two-thirds of the total potential, with an average yield of 239 GJ/ha on prime and good land. However, a second-generation biofuel conversion route is required for energy cane biofuel production.

In smaller areas other feedstocks, mainly miscanthus and macauba (grown as single palm), have been selected as the highest-yielding feedstocks, with average yields on prime and good land of 165 and 121 GJ/ha respectively. Although overall contribution is smaller (981 to 1,758 PJ), in some areas these feedstocks might be competitive if biofuel production is the objective.

With 2,504 thousand km^2, **Brazil** alone accounts for more than half of South America's unprotected grass- and shrubland. Given its vast land area, up to 12,419 PJ (Table 13), or 61% of South America's total potential is concentrated in Brazil. Energy cane is the largest contributor (7,831 PJ) due to its high yield, averaging 229 GJ/ha on prime and good land. Despite achieving lower yields of 80 GJ/ha, intercropping of macauba palm with *Brachiaria* grass contributes another 4,004 PJ. Both biofuel production systems comply with RSB sustainability criteria, yet the agricultural production strategy is differing. Energy cane represents a more concentrated biofuel production system using less land extents but monocropping. Intercropping macauba palm with *Brachiaria* grass is an example of a multifunctional approach where next to biofuels also livestock feed is produced. The concomitant challenge with this approach is that it results in a more disperse supply chain to the processor, and consequently would require more localized oil-pressing facilities.

Overall, the **climate change** analysis reveals worsening conditions for South America's biofuel potential. Ensemble modeled climate forcing suggests fewer areas suitable for biofuel feedstock production. By the 2050s, even the most optimistic RCP 2.6 scenario estimates production of only up to 16,200 PJ (Table 14). Depending on scenario and considered land qualities some 20% to 38% less biofuels can be produced compared to current conditions, with more extreme scenarios (RCP 8.5) reducing production considerably. Except for biomass sorghum, all feedstocks are negatively affected by climate change due to a combination of higher temperatures and, in some areas, lower precipitation.

With half of South America's RSB-compliant biofuel potential coming from Brazil, the adverse effects of future higher temperatures and reduced rainfall in much of Brazil are a key driver of the negative impacts of climate change. A case in point is energy cane. Higher temperatures increase the evaporative water demand, while rain-fed production is hampered by reduced rainfall in Brazil's cane producing regions. As a result, less and less acreage is appropriate for producing rain-fed energy cane economically. Approximately one-third of Brazil's grass- and shrubland currently suitable for energy cane production will be lost due to climate change. Adaptation to climate change will therefore be critical to the development and sustainability of large-scale biofuel production in South America. It should be noted that ensemble models do not adequately capture tipping points, and a sudden shift in Amazon rainforest cover due to negative feedback loops could have strongly negative impacts on agricultural productivity (Bochow and Boers, 2023).

The RSB's 'food security' criteria generally exclude cropland from biofuel feedstock production, and the selected modelling approach avoids indirect land-use change by systematically prioritizing land for food production. One exception, however, is the cultivation of cover crops during winter fallow periods. Such intensification of cropland has a very low risk of indirect land use changes. Winter fallow coverage can provide co-benefits for the soil water regime by increasing infiltration of winter rainfall and improving water storage. Like other commonly cultivated crops (e.g., winter wheat) a winter cover serves to limit soil erosion. A significant proportion of total unprotected cropland – 41% or 497 thousand km^2 – is suitable for camelina or carinata **winter fallow crop** production. Winter fallow cultivation on cropland can add up to 759 PJ, with Carinata (573 PJ) being the main contributor. Camelina is concentrated in the temperate regions of Argentina. Climate change results in a modest (~20%) reduction in biofuel energy in the most extreme scenario, or even very small positive impact on winter fallow crop production.

Sustainable aviation fuels have an important role to play in the **aviation industry's** quest for a net-zero future. A key goal of this study was to assess the sustainable biofuel potential, assuming prioritization of biofuels for the hard-to-decarbonize aviation sector. The air transport industry, represented by the Aviation Transport Action Group (ATAG) committed to achieving net zero carbon emissions by 2050 (ATAG, 2021). Even though we do not consider potential alternative uses of the identified RSB-compliant biofuel potential, e.g., in the transport sector, we provide an indication below of the proportion of aviation fuel demand that could be produced in South America based on the investigated feedstocks. Except for carinata and camelina as winter cover crop, ATAG, in its recent 'Waypoint 2050' report (ATAG, 2021) considers other sources for sustainable aviation fuels, compared to the feedstocks investigated in this study.

Assuming only use of prime land quality for the feedstock production, this study estimates an RSB compliant sustainable biofuel potential of about 12,214 PJ (285 Mt[9] jet fuel). By 2050, depending on scenario, climate change is expected to decrease this potential to between 9,064 (215 Mt) and 7,629 PJ (178 Mt). Aviation, today,

[9] Metric tons (Mt) Assuming a typical energy content of jet fuel (kerosene) of 42.8 MJ/kg

demands about 300 Mt of jet fuel annually, as reported by e.g., (Batteiger et al., 2022) or Shell Company[10]. This is expected to increase to about 500 Mt by 2050 (Batteiger et al., 2022; ICAO, 2022b; McKinsey, 2022).

To give an indication of the technically sustainable potential, a significant portion of global annual jet fuel demand could be met today from the vast land resources of South America. To realize this potential of 285 Mt of jet fuel, some 760 thousand km^2 of unprotected grass- and shrubland would have to be used for the aviation sector. About half of this area would be used for energy cane production and the other half for intercropping of macauba palm with *Brachiaria*. These areas represent 16% of unprotected grass- and shrubland and 11% of total grass- and shrubland in South America.

The combination of the adverse effects of climate change and the increasing demand for jet fuel disrupt the balance between supply and demand. By 2050, an upper limit of 36 - 43% of the estimated global annual jet fuel demand could stem from RSB-compliant biofuel produced in South America. These 178-250 Mt sustainable biofuels would require roughly between 400 and 500 thousand km^2 of unprotected grass- and shrubland, and a significant expansion of infrastructure to support such a continental scale expansion.

In comparison, winter cover crops on cropland provide smaller amounts of some 11 Mt biofuels. Thus, only some 3.6% of current aviation demand or 2% of future demand could stem from winter cover crop production. These biofuel feedstocks do not require land use conversion but an intensification of the current use of cropland.

Depending on the policy strategy, biofuels may be sourced from smaller areas of concentrated energy production (e.g., cultivating energy cane) or from larger areas of multifunctional agriculture producing more than one commodity (e.g., Macauba-*Brachiaria* intercropping). Although climate change impacts will decrease current potentials, biofuels could make a significant contribution to achieving sustainable aviation fuels.

It should be noted that, depending on the region, the identified technical potentials may be constrained by the economics of feedstock cultivation and biofuel conversion pathways. Feedstock cultivation challenges include farmer know-how and willingness to convert to biofuel feedstocks. Energy cane requires conversion from lignocellulosic material to biofuels, thus dealing with bulky material that typically requires decentralized production hubs. Large-scale monoculture of energy cane can also pose biodiversity and environmental challenges, especially if invasion into adjacent natural habitats or sensitive ecosystems is not controlled.

Finally, climate change implications for current ecosystems, and the Kunming Montreal Global Biodiversity Framework will likely require significant additional exclusions of natural land, further reducing the realistic upper limits for biofuel production. Against this backdrop, many scenarios see an increasing role for synthetic kerosene, also known as power-to-liquid (PTL) fuels, in the provision of sustainable aviation fuels over this period. Early moves in EU legislation support this transition. PTL uses renewable energy sources (wind, solar, hydro) to electrolyze water to produce hydrogen. This "green" hydrogen can be combined with waste carbon sources, using processes such as FT synthesis to produce hydrocarbons, including a jet fraction. Although industrial scale up has yet to be proven, the main challenge being high costs, if successful, it is evident that the biodiversity, water and spatial impacts of synthetic kerosene are likely to be much lower compared to biofuels. For this reason, a roadmap for SAF is likely to start with biofuels and peak in the short to medium term, with SAF provision increasingly provided by alternative means.

[10] Global aviation fuel demand is expected to fully recover to pre-pandemic levels of 300 million tonnes per year in the next one to two years, the head of aviation at Shell. Reuters, 27 Sep 2022.

Annex A: Novel feedstocks considered in this study

In addition to the introduction of novel feedstocks in Section 2, here we present agronomic details.

Energy cane (*Saccharum spp.*)

Energy cane is a cultivar developed from sugarcane (*Saccharum spp.*) bred to increase biomass yield. Compared to sugarcane, energy cane produces more yield, more fiber, and less sugar in the juice. Energy cane is a semi-perennial belonging to the C4 crop group (C4 I), which is characterized by optimum photosynthesis and growth at temperatures between 30°C and 35°C. Temperatures above 35°C lead to reduced photosynthesis and temperatures above 45°C cause heat stress and eventually plant damage. Both result in lower biomass yields.

Energy cane may be classified into two categories: Type 1 and Type 2 with differences in potential uses (Table 23). Type 1 is described as a can-e closer to conventional sugarcane but with a lower sucrose content, lower purity and a higher fiber content; Type 2 is a cane with only marginal content of sugar but with fiber content higher than Type 1, Type 2 is to be used exclusively for biomass production. An energy cane field looks similar to a conventional sugarcane field. However, there are some strikingly different plant characteristics: a narrower leaf blade, a thinner stalk, and a more abundant tillering which is especially typical for biomass producing energy cane (Type 2) clones.

Table 23. Produce and use of Energy cane

Feedstock	Produce	Intermedia	Industrial use	Potential uses
Energy cane	**Above ground biomass (Cane)**	**Energy cane Type 1**: Biomass (fiber), sugar in juice, fiber in bagasse	**Sugar/Ethanol 1G*** Heat (firing and co-firing of bagasse) → Electricity	Jet fuel, bioethanol, biodiesel, biogas, methanol, syngas and phenol (food/ cosmetics/ plastics/ pharmaceuticals/ chemicals/ prehydrolysate/stillage → animal feed (concentrates)
				Bagasse: energy store and supply through pellets or briquettes and consumables, e.g. paper cardboard Other by-products: alcohol, yeast Residues: livestock feed
		Energy cane Type 2: Biomass (fiber)	**Ethanol 1G , 2G*** Biochemicals/ Biomethane and Electricity	Jet fuel, bioethanol, biodiesel, biogas, methanol, syngas and phenol (food/cosmetics/ plastics/ pharmaceuticals/ chemicals/ prehydrolysate/stillage → animal feed (concentrates)

*1G First generation bioethanol plants utilize Sugarcane juice and molasses, byproducts in the production of sugar, as raw material, while 2G plants (second generation conversions) utilize biomass (fiber). Source: (Susmozas et al., 2020).

Energy cane environmental requirements

Table 24 presents rainfall, humidity, and temperature requirements for Sugarcane (SC) and Energy cane (EC) T1-Vertix 3 and T2-Vertix2.

Energy cane requires well-distributed annual water supply. For rain-fed production rainfall between 110 mm and 180 mm per month is ideal. High air humidity may cause diseases. Energy cane T1-Vertix 3 is susceptible to sugarcane whip smut. Especially under very wet (per-humid) conditions, damage can be substantial.

Whip smut disease develops strongest at temperatures between 25°C and 30°C and concurrent high relative humidity (Mansoor et al., 2016). Energy cane Type 2 has been reported resistant.

Table 24. Rainfall, Temperature and Relative Humidity requirement for Energy cane production

	Optimum Conditions	Range Conditions	Marginal / Not suitable
10-day rainfall (mm)	>60	30-60	<30
Total annual rainfall	>1500	900-1500	<900
Mean day-time temp (ºC)	22-32	18-22 and 32-35	<18 and >35
Relative humidity (%)	40-90	35-40 and >90	<35

Source: Adapted from SYS et al (1993), (Verheye, 2010), GAEZv3: (Fischer et al., 2012), GAEZv4: (Fischer et al., 2021) and José Bressiani of GranBio company, personal communication (2020).

Environmental requirements of Energy cane vary with inputs and field management applied. It produces relatively well in soils low in nutrients but grows best on well drained well-structured and aerated deep soils with loamy to clay loam textures. Energy cane grows also well on soils with coarser and finer textures. Coarser textured soils have the disadvantage that nematode populations may build up, fertilizer may leach out and lower water-holding capacity may cause water stress and yield loss. Fine textured soils may have drainage problems and are susceptible to soil compaction hindering root development.

Energy cane is moderately sensitive to soil salinity and soil sodicity. Under high inputs and advanced management (see Box below*), soil reaction must be in the range of pH 4.1 to 8.5, ideally between pH 5.5 and 7.5. Requirements of energy cane vary by inputs and field management. Table 25 presents an overview of basic soil requirements for Sugarcane and Energy cane T1-Vertix 3 and T2-Vertix 2.

Box.* ***High level inputs*

Under a high level of input (advanced management assumption), the farming system is mainly market oriented. Commercial production is a management objective. Production is based on improved or high yielding varieties, is fully mechanized where possible with low labor intensity and uses optimum applications of nutrients and chemical pest, disease and weed control.

Energy cane productivity

Research on energy cane (GranBio research site Barra de São Miguel, NE Brazil) shows considerably higher biomass productivity potential compared to locally adapted sugarcane. In addition, several aspects of energy cane's tolerance to environmental stresses appear to be superior to those of sugarcane. According to GranBIO[11] , the main production characteristics and environmental adaptability compared to sugarcane include:

- Potential to produce 2 to 3 times more biomass than sugarcane
- Potential to achieve more than 10 harvests in one cycle (2.0x sugarcane)
- More resistant to pests and diseases
- High cellulosic composition (>70%)
- More competitive production costs compared to other biomass sources like eucalyptus, sorghum, sugarcane and other grasses
- Environment friendly: adapted to marginal lands, less demanding in soil, water and nutrients
- Genetic variability permits selection of Type 1 or 2 varieties, depending on purpose and production environment
- Increasing agro-industrial feasibility through increased biomass yield and extended operational time (number of cuts)
- More suitable for rain-fed production and higher tolerance to poor (sandy) soils

[11] https://www.granbio.com.br/en/

Table 25. Soil Requirements for Sugarcane (SC), Energy Cane Type1-Vertix3 (ECV3), Type2-Vertix2 (ECV2)

HWSD Attributes	Cane Type	Input/management level	Optimum Conditions	Range Conditions	Marginal/ Not Suitable
Soil pH (H_2O)	SC, ECV2 and ECV3	High	5.0-7.5	4.1-5.0 and 7.5- 8.5	<4.1 and >8.5
		Low/Intermediate	5.5-7.5	4.5-5.5 and 7.5- 8.5	<4.5 and >8.5
CEC_{clay} (cmol/kg clay)	SC, ECV2 and ECV3	High	>16	<16	n.a.
		Low/Intermediate	>24	<16-24	<16
CEC_{soil} (cmol/kg soil)	SC, ECV2 and ECV3	High	>8	2-8	<2
		Low/Intermediate	>10	4-8	<2
Base Saturation (%)	SC, ECV2 and ECV3	High	>35	20-35	<20
		Low/Intermediate	>50	35-50	<35
TEB (cmol/kg soil)	SC, ECV2 and ECV3	High	>3.5	2.0-3.5	<2.0
		Low/Intermediate	>5.0	2.0-5.0	<2.0
Texture*	SC	High	C-SCL	Cm and SL-LS	S
		Low/Intermediate	C-SCL	SL-LS	Cm and S
	ECV2	High	C-SL	Cm and LS	S
		Low/Intermediate	C-SL	LS	S
	ECV3	High	C-SL	Cm and LS	S
		Low/Intermediate	C-SL	LS	S
Soil depth (cm)	SC, ECV2 and ECV3	High	>90	70-90	<70
		Low/Intermediate	>90	40-90	<40
CaCO3 (%)	SC, ECV2 and ECV3	High	<25	25-50	>50
		Low/Intermediate	<25	25-50	>50
Gypsum (%)	SC, ECV2 and ECV3	High	<6	6-20	>20
		Low/Intermediate	<6	6-20	>20
Soil drainage**	SC, ECV2 and ECV3	High	E-I	P	VP
		Low/Intermediate	E-MW	I- P	VP
Salinity (dS/m)	SC, ECV2 and ECV3	High	<5	5-10	>10
		Low/Intermediate	<5	5-10	>10
Sodicity (ESP %)	SC, ECV2 and ECV3	High	<10	10-20	>20
		Low/Intermediate	<10	10-20	>20
Organic Carbon (% weight)	SC, ECV2 and ECV3	High	>1.0	0.3-1.0	<0.3
		Low/Intermediate	>1.0	0.3-1.0	<0.3

* Cm = Heavy clay; SiC = Silty Clay; C = Clay; SICL= Silty Clay Loam; CL= Clay Loam; Si = Silt; SiL = Silt Loam; SC = Sandy Clay; L = Loam; SCL= Sandy Clay Loam; SL = Sandy Loam, LS = Loamy Sand, and S = Sand
** E = Excessive, SE = Somewhat Excessive, W = Well, MW = Moderately well, I = Imperfectly, P = Poor, VP = Very poor.

Source: Adapted from SYS et al (1993), (Verheye, 2010), (Fischer et al., 2008), (Fischer et al., 2013), GAEZv3: (Fischer et al., 2012), GAEZv4: (Fischer et al., 2021), and personal communication with José Bressiani of GranBio.

The types of energy cane used in the assessment are referred to as: T1-Vertix 3 and T2-Vertix 2. Table 26 summarizes characteristics of energy cane T1-Vertix 3 and T2-Vertix 2 and Table 27 compares production performances of those vis-à-vis sugarcane.

Table 26. Energy cane characteristics

Energy cane Type 1-Vertix 3	Energy cane Type 2-Vertix 2
111 kg sugars in juice per ton of biomass	82 kg sugars in juice per ton of biomass
21 % Fiber/t of biomass	23.5 % Fiber/t of biomass
High tillering biomass	High tillering biomass
High ratooning	High ratooning
	Sugarcane smut resistant
	High rhizomes production

Source: GranBio, Brazil

Table 27. Comparison productivity of Sugarcane and Energy cane Type1-Vertix3 and Type2-Vertix2

Characteristics	Sugarcane	Energy cane Type 1-Vertix 3	Energy cane Type 2-Vertix 2
Yield (X)	X	> 1.5 X	> 2.0 X
Sugar (kg/t)	150	> 100	< 100
Fiber (%)	15	18 - 22	> 25
Cuts	4 - 5	8 - 10	> 10
Resistance to pest & diseases	-	+	++
Industrial Use*	Sugar and Ethanol	Sugar, Ethanol 1G and Electricity	Ethanol 1G, 2G, Bio-chemicals, Electricity and Bio-methane

*1G bioethanol plants utilize Sugarcane juice and molasses, byproducts in the production of sugar, as raw material, while 2G plants utilize surplus biomass (Susmozas et al., 2020)

Potentials and climate change impacts in the 2050s

In this scenario simulation, only energy cane is selected as a biofuel feedstock. In compliance with the RSB land and GHG sustainability criteria, all unprotected grass- and shrubland not required for ruminant livestock feed is explored for its potential to produce energy cane. Results should be considered as theoretical indicative only because large-scale energy cane monocultures may be detrimental to biodiversity and sustainability in many locations.

Table 28 and shows area and biomass potential for South America by major region and land quality. Of the total unprotected grass- and shrubland not required for livestock feed in South America (3165 thousand km^2, see Table 6), up to 12% (369 thousand km^2) is of prime and good land quality, and up to 28% (873 thousand km^2) of prime, good and moderate land quality for energy cane production. In accordance with Brazil's large tropical grassland extents, more than half of the energy cane biomass production potential is concentrated in Brazil.

Table 28. Energy cane (v3), land use of 2020, current climate (1981-2010)

Rain-fed, high input	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)	**Shrubland**	**Grassland**	**Total**	**Shrubland**	**Grassland**	**Total**
AREA (1000 km^2)						
Total	50	320	**369**	184	689	**873**
of which						
Argentina	18	41	59	27	54	81
Brazil	9	145	154	119	432	550
Other SAM, North	9	86	95	20	149	168
Other SAM, South	13	47	61	18	54	73
Dry matter biomass (Mt)						
Total	125	716	**840**	413	1685	**2098**
of which						
Argentina	56	134	190	74	160	234
Brazil	25	410	435	241	995	1236
Other SAM, North	24	235	259	46	367	414
Other SAM, South	41	148	189	51	163	215

However, climate change has a negative impact on energy cane production, notably in Brazil (Table 29). For South America as a whole, the biomass potential of energy cane is 20% to 30% lower compared to the current climate. Tropical Brazil is even more affected. By the 2050s, Brazil could only produce 70% or even 50% (RCP8.5) of its energy cane production potential under current climate conditions. The exception is the higher latitude southern regions of South America, where higher temperatures are conducive to energy cane production resulting in higher biomass potentials compared to today.

Table 29. Climate change impact on biomass production potential for energy cane (v3)

Dry matter biomass (Mt) from VS+S+MS	**ARG**	**BRA**	**Other SAM, North**	**Other SAM, South**	**SAM, Total**
1981-2010	234	1236	414	215	2098
2041-2070 (2050s**)**					
RCP 2.6	258	899	334	230	1721
RCP 4.5	265	876	308	258	1707
RCP 6.0	287	864	291	271	1713
RCP 8.5	234	692	277	271	1475

Results show biomass production compliant with RSB land and GHG criteria from prime (VS), good (S) and moderate (MS) land quality.

Macauba palm (*Acrocomia aculeata*) and Brachiaria grass

Macauba palm is being extensively researched in Brazil (Colombo et al., 2018; da Silva César et al., 2015). Although the domestication and utilization in extensive farming as an agroforestry crop is still at an early stage, it shows promising potential. Table 30 summarizes produce and use of Macauba palm.

Table 30. Produce and use of macauba feedstock

Feedstock	Produce	Intermediate	End product	Potential uses
Macauba	Fruit	Pulp and kernel oil	Vegetable oil	Food/cosmetics/pharmaceuticals/ chemicals
			Bio-diesel/jet fuel	Transport/aviation
		Pulp and kernel cake (meal)	Feed, biogas, organic fertilizer	Livestock/energy/agriculture
	Husk and shells	Biomass	Solid fuel, biogas. organic fertilizer, chemical compounds	Energy/agriculture/chemicals

Macauba palm temperature requirements

Macauba belongs to C3 plants (C3 II), characterized by optimum photosynthesis and growth at temperatures between 25°C and 30°C; maximum growth rates are between 30-40 g $m^{-2}day^{-1}$ and is adapted to tropics and sub-tropical summer rainfall areas with warm temperatures. Optimum temperatures for photosynthesis and growth are 25-30°C. it grows and produces well within the temperature range of 15-35°C. However mean temperatures above 30°C result in lower photosynthesis and heat stress both leading to substantial lower yields. Macauba, survives temperatures of 3°C .

Macauba could be cultivated on degraded lands[12] and is a candidate to become an important feedstock for biofuel production. Macauba pulp and kernel oil are considered promising alternatives for industrial applications. The main geographic distribution of Macauba palm is in Latin America between 22º North (Mexico) to 28º South (Argentina).

[12] Today, 172 million hectares of Brazilian land are used for grazing, of which 30 million hectares of these lands are degraded due to poor land use, 6 million in the state of Minas Gerais, in Brazil.

Brachiaria is a perennial grass species native to tropical Sub-Saharan Africa from 25ºS to 12ºN, now widely naturalized in the humid and sub-humid tropics, where its natural habitat are grassland valleys and open woodlands. It produces high tonnage of foliage biomass, possess large root systems, sequester carbon into soils, is adapted to drought and low fertility soils, and provide several environmental benefits and ecosystem services (Djikeng et al., 2014; Njarui et al., 2016). Table 31 summarizes potential uses and key sustainability characteristics.

Table 31. Produce and use of Brachiaria Grasses

Fodder	Produce	Potential uses	Sustainability
Brachiaria spp.	Above ground consumable biomass	Sedentary livestock feed (forage)	Multi-purpose land utilization
		Ruminant grazing	Erosion control

Brachiaria decumbens, *B. brizantha* and *B. decumbens* perform well in medium shade. Three major acclimation responses to shade have been observed: a) a reduction in the respiration rate, b) an increase in the shoot to root partitioning and c) an increase in the specific leaf area with a relatively low leaf mass ratio (Guenni et al., 2008; Montoya et al., 2021).

Brachiaria temperature requirements

Brachiaria spp. are C4 (C4 I) African tropical grasses with distinct growth habits. Main species are: B. brizantha is a bunch plant, B. dictyoneura growing flat on the soil surface and B. decumbens a semi-erect plant. Brachiaria spp. are characterized with optimum photosynthesis and growth at temperatures between 25°C and 35°C. maximum growth rates between 30-60 g $m^{-2} day^{-1}$. Operative temperatures range between 15°C -40°C. Temperatures above 40°C lead to lower photosynthesis and in addition temperatures above 45°C cause heat stress and eventually plant damage. Both are leading to lower biomass yields.

Macauba and Brachiaria environmental requirements[13]

Environmental requirements of Macauba palm and Brachiaria grasses vary with inputs and field management applied.

Macauba performs best with annual rainfall amounts between 1000 and 2500mm. Rainfall between 800 and 1000 mm reduces yield substantially; annual rainfall of more than 2500 mm combined with high humidity reduces yields as well. Macauba grows on a variety of soils. Rain-fed macauba requires deep permeable well-structured soils. Well drained loamy to sandy soils with high organic matter content are preferred. Coarse textured soils have the disadvantage that nematode populations may build up and fertilizer may leach out and lower water-holding capacity may cause water stress and yield loss. Fine textured soils may have drainage problems and soil compaction hinders root development.

[13] Detailed requirements and tolerances of Macauba palm and Brachiaria pasture grasses are contained in the GAEZ land utilization types (LUT) database that was updated and extended for this study. The methodology for the calculation of potential net biomass and yields is based on eco-physiological principles as outlined in GAEZv4 Model Documentation. For biomass and yield parameter calibration, calculations were performed for research locations near Araponga, Minas Gerais, Brazil.

Macauba grows relatively well in soils low in nutrients, is however sensitive to acidic soil conditions. Under high inputs and advanced management * optimum soil pH (H_2O) is 5.6 -7.5. Sub-optimum soil pH, due to acidity are in the range of 4.8-5.6 and in alkaline conditions in the range 7.5-8.2; beyond these (soil pH<4.8 and pH>8.) acidity and alkalinity constraints are severe. Macauba is sensitive to soil salinity and soil sodicity and to excess calcium carbonate and gypsum. Further Macauba is susceptible to waterlogging, high groundwater tables and flooding.

Brachiaria are warm-season grasses growing from sea level up to an altitude of 2000 m in the tropics, and up to 1000 m at higher latitudes in sub-tropics. Optimum temperature for growth is in the range of 25-35°C. The leaves are frost-sensitive, but the plant survives light frost. Brachiaria brizantha grows best with 1500-3500 mm average annual rainfall, though it tolerates less than 1000 mm rainfall and can withstand dry seasons of 3-6 months during which it remains green, unlike other tropical grasses. It is more productive under light shade, particularly when soil N is low. It is a suitable grass in coastal regions where it combines with coconut. It can grow on a wide range of soils from light to heavy textures, with a wide range of soil nutrient availability. However, production increases as soil nutrients increase. Flood tolerance is generally poor, depending on the variety.

Below we present requirements of Macauba palm and Brachiaria grasses for rainfall (Table 32), temperature and relative humidity (Table 33) and soils (Table 34).

Table 32 Rainfall requirements (Rain-fed production)

	Species	Optimum Conditions	Range Conditions	Marginal / Not suitable
10-day rainfall (mm)	Macauba	>40	20-40	<20
Total annual rainfall		>1200	800-1200	<800
10-day rainfall (mm)	Brachiaria	>50	30-50	<30
Total annual rainfall		>1500	600-1500	<600

Table 33. Temperature and Relative Humidity requirements

	Species	Optimum Conditions	Range Conditions	Marginal / Not suitable
Mean day-time temp (ºC)	Macauba	22-32	18-22 and 32-35	<18 and >35
Relative humidity (%)		40-90	35-40 and >90	<35
Mean day-time temp (ºC)	Brachiaria	25-35	15-25 and 35-40	<15 and >40
Relative humidity (%)		60-90	40-60 and >90	<40

Table 34. Soil Requirements and tolerances of Macauba and Brachiaria pasture grasses

HWSD Attributes	Crop	Input / management level	Optimum Conditions	Range Conditions	Marginal / Not Suitable
Soil pH (H_2O)	Macauba	High	5.6-7.6	4.7-5.6 and 7.6- 8.2	<4.7 and >8.2
	Brachiaria	High	5.5-6.9	4.5-5.5 and 6.9- 7.9	<4.5 and >7.9
	Macauba	Low/Intermediate	6.0-7.6	5.2-6.0 and 7.6- 8.2	<5.2 and >8.2
	Brachiaria	Low/Intermediate	6.1-7.6	4.5-6.1 and 7.6- 7.9	<4.5 and >7.9
CEC_{clay} (cmol/kg clay)	Macauba	High	>16	<16	n.a.
	Brachiaria	High	>16	<16	n.a.

	Macauba	Low/Intermediate	>24	<16-24	<16
	Brachiaria	Low/Intermediate	>24	<16-24	<16
CEC_{soil} (cmol/kg soil)	Macauba	High	>6	2-6	<2
	Brachiaria	High	>8	2-8	<2
	Macauba	Low/Intermediate	>8	2-8	<2
	Brachiaria	Low/Intermediate	>10	2-10	<2
Base Saturation (%)	Macauba	High	>35	20-35	<20
	Brachiaria	High	>35	20-35	<20
	Macauba	Low/Intermediate	>35	20-35	<20
	Brachiaria	Low/Intermediate	>50	35-50	<35
TEB (cmol/kg soil)	Macauba	High	>3.5	2.0-3.5	<2.0
	Brachiaria	High	>5.0	2.0-5.0	<2.0
	Macauba	Low/Intermediate	>5.0	2.0-5.0	<2.0
	Brachiaria	Low/Intermediate	>8.0	3.5--8.0	<3.5
Texture*	Macauba	High	C-SL	Cm and LS	S
	Brachiaria	High	C-SL	LS	Cm and S
	Macauba	Low/Intermediate	C-SCL	Cm and LS	S
	Brachiaria	Low/Intermediate	C-SCL	LS	Cm and S
Soil depth (cm)	Macauba	High	>90	40-90	<40
	Brachiaria	High	>85	35-85	<35
	Macauba	Low/Intermediate	>90	40-90	<40
	Brachiaria	Low/Intermediate	>70	35-70	<35
$CaCO_3$ (%)	Macauba	High	<25	25-50	>50
	Brachiaria	High	<15	25-35	>35
	Macauba	Low/Intermediate	<25	25-50	>50
	Brachiaria	Low/Intermediate	<15	25-35	>35
Gypsum (%)	Macauba	High	<6	6-20	>20
	Brachiaria	High	<4	4-20	>20
	Macauba	Low/Intermediate	<6	6-20	>20
	Brachiaria	Low/Intermediate	<4	4-20	>20
Soil drainage**	Macauba	High	E-I	P	VP
	Brachiaria	High	E-I	P	VP
	Macauba	Low/Intermediate	E-MW	I-P	VP
	Brachiaria	Low/Intermediate	E-MW	I-P	VP
Salinity (dS/m)	Macauba	High	<2	5-10	>10
	Brachiaria	High	<2	5-8	>8
	Macauba	Low/Intermediate	<2	5-10	>10
	Brachiaria	Low/Intermediate	<2	2-8	>8
Sodicity (ESP %)	Macauba	High	<10	10-20	>20
	Brachiaria	High	<15	10-25	>25
	Macauba	Low/Intermediate	<10	10-20	>20
	Brachiaria	Low/Intermediate	<15	10-25	>25
	Macauba	High	>1.0	0.3-1.0	<0.3

Organic carbon (% weight)	Brachiaria	High	>0.8	0.4-0.8	<0.4
	Macauba	Low/Intermediate	>1.0	0.3-1.0	<0.3
	Brachiaria	Low/Intermediate	>0.8	0.4-0.8	<0.4

* Cm = Heavy clay; SiC = Silty Clay; C = Clay; SICL= Silty Clay Loam; CL= Clay Loam; Si = Silt; SiL = Silt Loam; SC = Sandy Clay; L = Loam; SCL= Sandy Clay Loam; SL = Sandy Loam, LS = Loamy Sand, and S = Sand

** E = Excessive, SE = Somewhat Excessive, W = Well, MW = Moderately well, I = Imperfectly, P = Poor, VP = Very poor.

Macauba and Brachiaria productivity

Macauba has not yet been domesticated. Its large phenotypic variability has been associated with different environmental conditions and genetic diversity (Abreu et al., 2012). Despite its economic potential, native populations have not been sufficiently characterized, neither has the potential effect of climatic/edaphic conditions on oil productivity and quality. Research already confirms that productivity is related to environmental conditions and genetic variability (Ciconini et al., 2013).

Best performance was found in regions with higher precipitation and mild temperature. Macauba is tolerant of dry periods and nutrient-deficient soils. Macauba is reported to significantly contributing to restoration of degraded and marginal soils (da Silva César et al., 2015). Importantly, to date, there are no reports of significant impact of pest and diseases affecting Macauba palm populations (Colombo et al., 2018; Plath et al., 2016).

The commercialization of macauba production requires further selection and breeding of the most suitable genotypes for the specific locations, to be guided by knowledge of genotype and environment interactions. Currently, breeding of genetically improved species with increased productivity and high drought tolerance is subject of research in Costa Rica and Brazil (Alfaro-Solís et al., 2020; Cardoso et al., 2017; Colombo et al., 2018). A first commercial plantation of macauba is in Minas Gerais State (Imbuzeiro et al., 2017).

Reported attained oil yields (pulp + kernel oil) vary widely by genotype, environmental conditions and planting density. Reported good yields in well managed plantations are in the order of 2.5 t/ha oil. Maximum yields reported for optimum tree densities are around 5 t/ha (personal communication Carlos Colombo and Sergio Motoiki, May 2020).

Macauba appears most suitable for integration into agricultural production systems that benefit from increased yields of concomitant crop - for example the successful use of macauba shade trees in arabica coffee plantations. It has also been shown that cultivation of macauba in agroforestry systems increases the productivity and yield of the co-cultivated crops (Moreira et al., 2018). As alternative to agroforestry production, the viability of macauba – *Brachiaria* pasture grasses intercropping is investigated (Montoya et al., 2021) and findings of this research are promising:

> "The intercropped Macauba–*Brachiaria decumbens* system can be considered a viable alternative for feeding cattle under low or moderate grazing pressure, but its success will depend on the density of trees. The presence of Macauba in the intercropped system influenced the growth and development of the forage; this effect was significant at different spacings but not between the evaluated seasons (dry and rainy seasons). The distance between the Macauba plants affected the microclimate conditions of the understory, reflecting the growth and development of the forage component. In the denser areas, there was a significant reduction in the passage of light through the canopy of the Macauba plants, leading to different leaf/stem ratios between the treatments with different spacing and the dry and rainy seasons. At lower densities (i.e., 357 and 312 Macauba plants ha^{-1}) the values of forage dry biomass were similar to those obtained in the pasture only areas, validating the system as a viable alternative in terms of land use change". (Montoya et al., 2021)

Brachiaria grass is a perennial grass species of African origin. It produces high tonnage of foliage biomass, possess large root systems, sequester carbon into soils, is adapted to drought and low fertility soils, and provide several environmental benefits and ecosystem services (Djikeng et al., 2020; Njarui et al., 2020). It produces produces on annual basis up to 6 cuts as monocrop under high light intensity (PFD =100%), and can produce between 45 to 50 t/ha fresh weight of consumable above ground biomass or 35-40 t/ha dry weight (Tarekegn et al., 2023). In intercropping mode with medium light intensity (PFD = 60%) 25-30 t/ ha.

For the assessment of suitability and productivity of Macauba sole cropping and Macauba/*Brachiaria* intercropping, we assume high inputs and advanced management based on:

(i) best locally adapted Macauba genotypes and *Brachiaria* pasture grasses

(ii) Macauba with optimum rotation lengths and *Brachiaria* pasture grasses with optimum cutting regime or controlled grazing

(iii) adequate applications of nutrients and chemical pest, disease and weed control

(iv) up-to-date harvesting, transportation and storage facilities, and

(v) rain-fed conditions only.

Two separate assessments are undertaken, namely: (i) Macauba grown as the sole crop with adequate spacing and leaf area for optimum growth and production, and (ii) Macauba grown in combination with *Brachiaria* pasture. Spacing and leaf area are arranged to allow simultaneous profitable Macauba vegetable oil and *Brachiaria* pasture production and/or livestock grazing:

(i) Sole cropping of Macauba LUT is assuming a density of 500 trees per hectare (20 m^2 per tree) depending on soil moisture and soil fertility conditions. This equates to an approximate equivalent Macauba leaf area index (LAI) of 4.

(ii) Macauba-*Brachiaria* intercropping LUT with best adapted *Brachiaria* pasture grasses (i.e., B. *brizantha*, B. *decumbens*, B dictyoneura) used for hay production or direct controlled livestock grazing. Macauba density of 300-350 Macauba trees per hectare (± 30m^2 per tree) equates to an approximately LAI of 2. Remaining medium light intensity and reduced photosynthetically active radiation (PAR) for the pasture intercrop understory is in the order of 60% of high light intensity (Guenni et al., 2008; Montoya et al., 2021; Moreira et al., 2018), which, we assume, provides photosynthetic active radiation comparable to an average LAI of 3 for grass growth.

The shade tolerance of *Brachiaria* species is linked to nutrient availability. Hence sufficient nutrients, especially nitrogen, is vital for optimal grass growth. This suggests considering *Brachiaria* – Macauba intercropping under high and medium input production systems. Low input production systems lacking nutrient management are not recommended.

Scenario simulation results: Macauba palm

In this scenario simulation, we assume that only macauba palm is considered as feedstock for RSB compliant biofuel production.

Under current climate, up to 28% (873 thousand km^2) of South America's total unprotected REMAIN land (3,163 thousand km^2) could be used for commercial macauba palm production (Table 35). From those areas some 210 Mt vegetable oil could be produced. About half of this potential or 107 Mt are from prime and good land qualities (VS+S) and the remainder from moderately suitable (MS) land. Production potentials are concentrated on Brazil's grassland where up to 99 Mt vegetable oil or almost half of the overall potential of 210 Mt could be produced.

Table 35. Macauba Palm, land use of 2020, current climate (1981-2010)

Rainfed, high input	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)	**Grassland**	**Shrubland**	**Total**	**Grassland**	**Shrubland**	**Total**
AREA (1000 km^2)						
Total	320	50	369	689	184	873
of which						
Argentina	41	18	59	54	27	81
Brazil	145	9	154	432	119	550
Other SAM, North	86	9	95	149	20	168
Other SAM, South	47	13	61	54	18	73
Vegetable oil (Mt)						
Total	93	15	**107**	168	41	**210**
of which						
Argentina	13	5.6	19	16	7.4	23
Brazil	41	2.5	43	99	24.1	124
Other SAM, North	23	2.4	26	37	4.6	41
Other SAM, South	15	4.1	19	16	5.1	21

Climate change has a negative impact on the potential to produce macauba palm vegetable oil in South America. Decreases in precipitation combined with higher temperatures result in less favorable water balance conditions for rainfed macauba palm production in the South America's main potential regions, notably in Brazil. Compared to historic climate conditions, by the 2050s, vegetable oil production potentials in SAM decrease by 20% to 30%. Depending on scenario, only between about 150 Mt and 170 Mt could be produced under rainfed conditions. Only in higher latitudes in the South (ARG and Other SAM, South) where higher temperatures are conducive to macauba palm production (Table 36) production potentials increase. However, these areas only provide less than one third of South America's overall macauba production potential.

Table 36. Climate change impacts on energy production potential from Macauba Palm in South America

Million tons vegetable oil; Rainfed, high input	**ARG**	**BRA**	**Other SAM, North**	**Other SAM, South**	**SAM, Total**
1981-2010	23	124	41	21	210
2041-2070 (2050s**)**					
RCP 2.6	26	90	33	23	172
RCP 4.5	26	88	31	26	171
RCP 6.0	29	86	29	27	171
RCP 8.5	23	69	28	27	147

Results show biomass production compliant with RSB land and GHG criteria from prime (VS), good (S) and moderate (MS) land quality.

Scenario simulation results for macauba palm intercropped with Brachiaria grass

In this scenario simulation, the sole feedstock for sustainable biofuel production is macauba intercropped with *Brachiaria*. Because ruminant livestock herds can graze on macauba intercropped with *Brachiaria*, large areas meet RSB food security criteria compared to macauba palm alone. Therefore, all unprotected grass- and shrubland is explored for macauba-Brachiaria intercropping amounting to 4,663 thousand km^2 (see Table 6).

Up to 31% (1,465 thousand km^2) of South America's total unprotected grass-shrubland could be used for macauba palm production intercropped with Brachiaria, significantly more compared to macauba sole cropping systems (873 thousand km^2). Correspondingly, about 42% more vegetable oil amounting to 298 Mt, could be produced from macauba-Brachiaria intercropping systems than from macauba plantations alone (Table 37).

Table 37. Macauba intercropped with Brachiaria, land use of 2020, current climate (1981-2010)

Rainfed, high input	Prime and good land (VS+S)			Prime, good and moderate land (VS+S+MS)		
Land use (unprotected)	**Grassland**	**Shrubland**	**Total**	**Grassland**	**Shrubland**	**Total**
AREA (1000 km²)						
Total	474	84	558	1233	232	1465
of which						
Argentina	27	10	37	47	19	66
Brazil	316	47	363	954	159	1113
Other SAM, North	83	10	94	169	28	197
Other SAM, South	48	17	65	63	25	89
Vegetable oil (Mt)						
Total	115	20	**135**	252	46	**298**
of which						
Argentina	7	2	9	10	4	14
Brazil	75	11	85	190	30	220
Other SAM, North	20	3	23	37	6	42
Other SAM, South	13	4	17	16	6	22

As for macauba sole cropping, there is a negative impact of climate change on macauba vegetable oil production from the intercropped system. By the 2050s, we estimate between 169 and 211 Mt vegetable oil compared to 298 Mt under current climate, a reduction of up to 60% depending on scenario (Table 38).

Table 38. Climate change impacts on vegetable oil production from Macauba intercropped with Brachiaria

Million tons Vegetable oil	**ARG**	**BRA**	**Other SAM, North**	**Other SAM, South**	**SAM, Total**
1981-2010	14	220	42	22	**298**
2041-2070 (2050s)					
RCP 2.6	17	136	35	20	208
RCP 4.5	19	138	32	22	211
RCP 6.0	21	135	31	22	210
RCP 8.5	18	99	29	22	169

Results refer to the biofuel production from unprotected grassland and shrubland compliant with RSB land and GHG criteria from prime, good and moderate (VS+S+MS) land quality. ‘

Carinata (*Brassica carinata*)

Brassica carinata (Ethiopian or Abyssinian Mustard) is a species belonging to the Crucifer or Brassicaceae family. Most likely Abyssinian Mustard is a result of an ancestral hybridization event between Brassica nigra (Black Mustard) and Brassica oleracea (species include cabbage, cauliflower and broccoli). *B. carinata* was cultivated as a food crop in regions of Africa. The plant is originally cultivated as a leafy vegetable (Ferraris et al. 2019). *B. carinata* is being investigated for the development of an aviation fuel. In 2012 a first jet flight was made with biofuel produced from B. carinata.

Brassica carinata is a C3 plant (including C3 I and C3 II cultivars). C3 I cultivars (spring and winter crops) are characterized by optimum photosynthesis and growth at temperatures between 15°C-20°C; maximum growth rates between 20-30 g m^{-2} day^{-1}. Operative temperatures range between 5°C-30°C. C3 I cultivars are adapted to temperate and subtropical winter rainfall zones. Temperatures substantially above 30°C lead to lower photosynthesis and heat stress, which both substantially reduce yields.

C3 II cultivars (non-hibernating winter crops) are characterized by optimum photosynthesis and growth at temperatures between 15°C-25°C with maximum growth rates between 30-35 $gm^{-2}day^{-1}$. Operative temperatures range between 10°C and 35°C. C3 II cultivars are adapted to subtropical and tropical zones with cool or moderately cool winter temperatures. Temperatures above 35°C lead to lower photosynthesis and heat, stress both leading to substantial lower yields.

Produce and use of the *B. carinata* feedstock

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

Environmental requirements

B. carinata seed germinates at mean temperatures of above 5°C and is moderately susceptible to early and late frost occurrences. *B. carinata* like other Brassicas is a nutrient and water demanding crop. It requires at least 350-400 mm rainfall during its growth cycle (Annex 2). Recommended N fertilization is 80kg/ha assuming fertile soils. *B. carinata* is susceptible to imperfect drainage and demonstrates moderate sensitive to soil salinity, sodicity, calcium carbonate and gypsum. Nevertheless, *B. carinata* adapts moderately well to different environmental conditions. It performs on a range of soils, e.g., it tolerates a soil pH range as wide as 4.8 to 8.2; optimum pH values are 5.6 to 7.0. It is best suited to deep, well drained, silt loams. For details see section soil requirements for B. carinata.

B. carinata has similar requirements for water and nutrients compared to other members of the Brassica family. *B. carinata* is reported to be successfully grown on relatively marginal land, it responds well to added nutrients (nitrogen-sulfur-phosphorous), provided good soil moisture availability prevails. Rotations or combinations with soybean, groundnut, maize, and possibly wheat, barley, peas and lentils are required (in Argentina *B carinata* is mostly combined with soybean). Rotations with canola, mustard, etc. increase carry-over risk of insect and disease problems that are common with these crops and is to be avoided. Due to insect and disease problems *B. carinata* should ideally be grown only every four years in the same field. Since *B. carinata* produces fair amounts of root biomass and residues, has relative high ground cover compared other brassicas and may well be grown under zero or minimum tillage, *B. carinata* is relatively appropriate for preventing/combatting soil erosion.

B. carinata productivity

B. carinata productivity has been developed based on personal communications of Glenn Johnston and Rina Cerrato, Global Regulatory Carinata of NUSEED and Rick Bennett, NUSEED's Breeding Lead Carinata, and research data provided by NUSEED for carinata trials in Argentina.

We use three different *B. carinata* varieties for the analysis, namely: Spring *B. carinata* (SP) grown between spring and summer with durations between 105 and 150 days and two sub-tropical varieties growing from autumn to spring, one variety adapted to growing in cool winter temperatures (ST) with longer durations between 165 and 210 days and a 'rabi' variety (RB) adapted to moderately cool winter temperatures with durations between 135 and 150 days. NUSEED further reports that although plant development slows down during the cool winter periods, hibernating has not been observed. In fact, current *B. carinata* varieties are moderately susceptible to frost damage. Therefore, unlike for winter rape, hibernating cultivars have **not** been considered in the AEZ analysis.

B. carinata, like other brassicas, has high requirements for water, nitrogen (N) and sulfur (S). NUSEED has set up experiments for evaluating *B. carinata* productivity under different nutrient supply and external environmental conditions in the Pergamino and the San Antonio de Areco sites in central Argentina (Ferraris et al., 2019). *B. carinata* farm trials suggest achievable farm seed yields of on average 2 t/ha depending on varying rainfall conditions. Reported 2019 yields, depending on fertilization, range at Pergamino trials between 1.3 and 3.0 t/ha and for nearby San Antonio de Areco between 1.6 and 2,5 t/ha. At these locations predominantly zero tillage or very minimal tillage is applied. Since *B. carinata* cannot be grown continuously on the same field and needs to be part of annual rotations of summer crop-winter crop-fallow combinations, in Argentina *B. carinata* most likely will continue to be grown in a preferred combination/rotation with soybean. Other promising options are rotations/combinations with groundnut or maize as summer crops.

In the on-farm trials 'adequate' fertilizer and pest and disease treatments are applied, Adequate synthetic fertilizer application means striking a balance between yields achieved and greenhouse gas benefits. NUSEED's fertility experiments suggest that 80 kg/ha of N applied + 30 kg/ha N available in the soil results in approximately 2.5 t/ha *B. carinata* seed yield. Slightly higher yields could be achieved when more N is added, but limiting N fertilizer to the proposed levels benefits growers economically and limits greenhouse gas emissions.

For pest and disease treatment, a preventative fungicide is applied mainly for combatting sclerotinia, which is currently the most serious fungal disease threat to reducing yield potential in *B. carinata*. Most fields do not require much pesticide applications, these are applied as needed to mainly combat harmful insect populations.

On a farmer's field basis for Uruguay and Argentina, average yields using the current varieties, are in the order 1.5 t/ha. In Uruguay yearly averages are ranging between 1.3 and 1.8 t/ha. Due to lack of experience with carinata and adverse weather conditions on some farms lower yields were achieved. Nevertheless, NUSEED expects that given the recommended field operations and inputs, individual farmers fields could achieve up to 2.2 – 2.4 t/ha. On R&D basis, variety trials yield 1.5 – 3.5 t/ha, with an overall average of 2.5 t/ha.

NUSEED is developing hybrid varieties that will soon be introduced. These hybrids may increase yields, with same management practices, by about 20-25%. The expectation is that when the switchover to hybrids is made average farm yields may be consistently around 2 t/ha, with many farms achieving even better yields.

Research in the US reports yields of 4 t/ha (Seepaul et al., 2016a). NUSEED confirms these yield levels have also been achieved in Uruguay in small plot testing. For AEZ calibration purposes NUSEED recommends utilizing data provided, i.e., maximum attainable yields levels between 2.5 to 3.0 t/ha.

B. carinata Land Utilization Types

For the assessment of suitability and productivity *B. carinata* high inputs and advanced management are assumed. These are based on:

(i) high seed/oil yielding varieties;

(ii) adequate applications of nutrients and chemical pest, disease and weed control when and where required;

(iii) full mechanization with medium/low labor intensities.

Under a high level of input (advanced management assumption), the farming system is mainly market oriented. Commercial production is a management objective. Production is based on improved or high yielding varieties, is fully mechanized where possible with low labor intensity and uses adequate applications of nutrients and chemical pest, disease and weed control.

Ten different *B. carinata* LUT/growth cycle combinations are considered to match local environmental conditions, namely:

(i) Four temperate spring LUTs (SP1-4) planted in spring with growth cycles of 105, 120, 135 and 150 days;
(ii) four subtropical LUTs (ST1-4) grown through winter period adapted to cool winter temperatures (5-15°C) with long growth cycles of 165, 180, 195 and 210 days, and
(iii) two subtropical/tropical LUTs (RB1-2) grown through winter period adapted to cool and moderately cool winter temperatures (5-20°C) with growth cycles of 135 and 150 days.

Requirements and tolerances of *B. carinata* are contained in the GAEZ land utilization types (LUT) database. The methodology for the calculation of potential net biomass and yields is based on eco-physiological principles as outlined in GAEZv4 Model Documentation. Calibration and testing were done with data available for NUSEED research locations near Pergamino and San Antonio de Areco.

Scenario simulation results. Carinata, winter types

In this scenario simulation, the sole feedstock for sustainable biofuel production is assumed to be the winter types of *B. carinata* cultivated as winter cover on cropland. Up to 61 PJ could be produced in South America under current climate. Climate change has no or a moderate negative impact on this production potential (Table 39).

Table 39. Climate change impacts on energy production potential from winter cover Carinata

	ARG	BRA	Other SAM, North	Other SAM, South	SAM, Total
Energy (Petajoules)					
1981-2010	28	21	0.6	11	**61**
2041-2070 (2050s**)**					
RCP 2.6	29	21	1.5	10	61
RCP 4.5	27	17	1.6	10	55
RCP 6.0	29	19	1.7	10	60
RCP 8.5	22	18	1.7	9	51
Area (1000 km^2)					
1981-2010	163	184	5	63	**415**
2041-2070 (2050s**)**					
RCP 2.6	166	174	10	63	413
RCP 4.5	155	148	11	61	375
RCP 6.0	169	163	11	60	403
RCP 8.5	135	150	12	54	351

Results refer to the biofuel production from carinata cultivated as winter cover on current cropland from prime, good and moderate (VS+S+MS) land quality.

Annex B: GHG emission savings

A primary objective for the use of biofuels is that they can substitute for fossil fuels and thereby lower GHG emissions and that they provide a 'renewable' fuel source. Following the brief overview in Section 2, we present here further details of the calculations and factors used.

Life cycle GHG emissions

Life cycle supply chain GHG emissions arise 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). Cultivation-related emissions include N_2O from nitrogen fertilizers and manure, CO_2 from agricultural machinery, emissions associated with 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 fossil fuel-fired) and on the allocation of the GHG burden to different co-products (e.g., vegetable oil versus oilseed press cakes for livestock feed). Due to the challenge of compiling emission estimates for a large number of individual companies and production circumstances, a variety of defaults, standards and guidelines have been established in different legislation (EU, 2009; RTFO, 2013).

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 40). Note, the values in Table 40 refer to the respective biofuel supply chain but do not include the GHG burden resulting from possible land conversion.

Table 40. Supply chain life cycle GHG emissions applied in this study

Feedstock	**Emissions (g CO_2 eq / MJ)**		
	Range	Source	Assumed value
ANNUAL crops			
Solaris	22.7	Sunchem, assuming local supply chain	22.7
Soybean	27 – 59	EU-RED; EU-RED2; SEI; Stratton; RFTO	37.0
Camelina	20 - 44	SEI; Sustainable Oils	34.4
Carinata	26 - 44	ICAO; Alam et al. (2021)	34.4
Sweet sorghum	30.6	CARB	31.0
Maize	30 - 56	EU-RED; EU-RED2; SEI; RFTO	33.0
Cassava	44 - 62	RTFO	35.0
Triticale	31 - 60	EU-RED2	35.0
PERENNIALS			
Jatropha	22 - 62	EU-RED; SEI	30.0
Oil palm	21 - 70	EU-RED; EU-RED2; SEI; Stratton; RFTO; ICAO	32.0
Macauba palm			30.0
Sugarcane	10 - 32	EU-RED; SEI; Stratton; RFTO; ICAO	24.0
Energy cane	11 - 24	Ortiz-Reyes and Anex (2020); Cavalett et al. (2017)	23.4
Miscanthus[1]	14 - 44	SEI; ICAO	28.0

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

Source: EU-RED Directive[14] 2009/28/EC (EC, 2009); EU-RED2 (EC, 2017); ICAO International Civil Aviation Organization(ICAO, 2022a); 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;

[14] See European Commission Renewable Energy Directive

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 may cause additional GHG emissions. The accounting of GHG 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 GHG Inventories (IPCC, 2006).

The amount of annual CO_2 emissions due to direct land use change (dLUC) expressed in gCO_2eq/MJ can be calculated according to equ (1):

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

where

$dCO2_{LUC}$	annualized CO_2equ 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_S	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 equ (2):

$$dC_B = dC_{AGB} + dC_{BGB} = (C_{B0} - C_{Bfuel})/T \tag{2}$$

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 equ (3) and (4):

$$dC_S = (C_{S0} - C_{Sfuel})/T \tag{3}$$

$$C_S = SOC_{ref} * f_{LU} * f_{MG} * f_{IN} \tag{4}$$

where

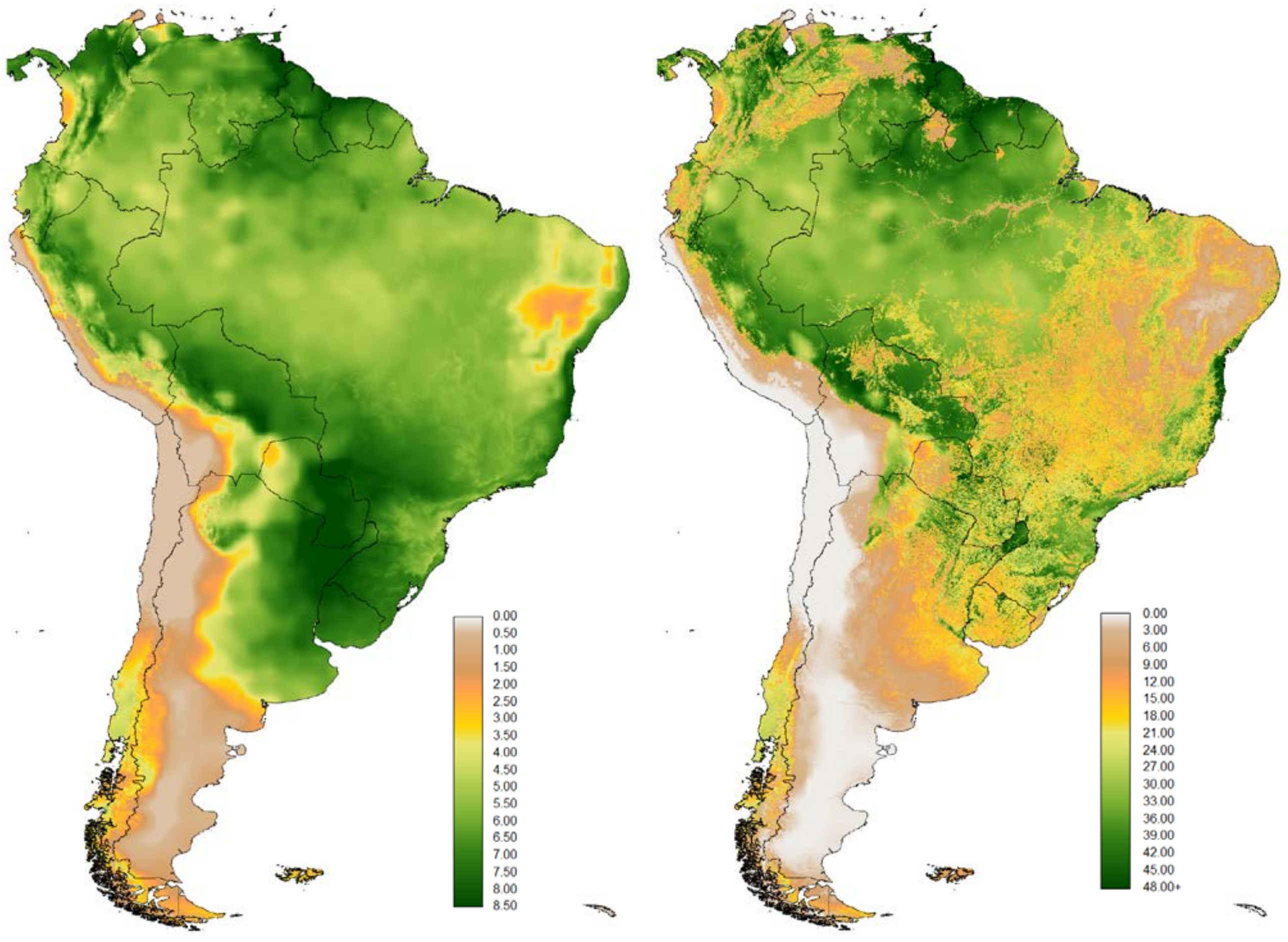
dC_S	annualized changes in carbon stocks of mineral soils due to land use change [ton C/ha]
C_{S0}	carbon stocks of mineral soils under land use before conversion [ton C/ha]
C_{Sfuel}	carbon stocks of mineral soils of new land use at end of assessment period [ton C/ha]
SOC_{ref}	reference carbon stocks 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}.

Biomass carbon stock changes

For the calculation of changes in biomass carbon stocks, spatial layers with estimates of carbon stocks C_{B0} prior to conversion were compiled respectively for grassland and shrub land based on IPCC reference values, woody vegetation cover percent according to the MODIS Vegetation Continuous Field (VCF) product for 2017 to 2019 (Townsend and DiMiceli, 2015), and spatial gradients of land productivity modelled in GAEZ v4, as shown in Figure 17.

*Figure 17. Biomass carbon stock C_{B0} in grassland and shrub land**



a) Carbon stock C_{B0} in grassland (ton C/ha) b) Carbon stock C_{B0} in shrub land (ton C/ha)

*Note that grid cells may contain multiple land classes at the 30 arc second scale.

The applicable biomass carbon stock C_{Bfuel} 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 practices 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 41.

Table 41. Biomass carbon stocks C_{Bfuel} applicable after conversion to perennial feedstocks [ton C/ha]

Climate region	Sugarcane	Energycane	Miscanthus	Oil palm	Macauba palm	Jatropha
Temperate, moist	5.0	16.4	16.4	50.0	37.5	25.9
Temperate, dry	4.8	14.9	14.9	30.0	22.5	17.5
Tropical, montane	4.6	16.4	16.4	50.0	37.5	25.9
Tropical, wet	5.0	17.9	17.9	60.0	45.0	34.3
Tropical, moist	4.6	16.4	16.4	50.0	37.5	25.9
Tropical, dry	4.2	14.9	14.9	30.0	22.5	17.5

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

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 equ. (2) 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.

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 dL_{fire} due to land use change in equ. (1) 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 emissions from savannah fires decrease after land is converted to biofuel feedstock production.

Soil carbon stock changes

A spatial layer of reference carbon stocks SOC_{ref} in the top 0-30 cm of the soil profile has been compiled from a recently released global soil database, SoilGrids250m v2 (Hengl et al., 2017), as shown in **Error! Reference source not found.**. 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.

The 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 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and RSB GHG Calculation Methodology (Version 2.1), as summarized in Table 42.

Table 42. Soil carbon stock change factors for cultivation of annual and perennial feedstocks

Climate region	Land use factor (f_{LU})		Tillage factor (f_{MG})			High input (f_{IN})	
	Annual crops	Perennial crops	Full tillage	Reduced tillage	No tillage	With manure	Without manure
Temperate, moist	0.69	0.87	1.00	1.05	1.10	1.44	1.11
Temperate, dry	0.76	0.87	1.00	0.99	1.04	1.37	1.04
Tropical, montane	0.90	1.01	1.00	1.04	1.10	1.41	1.08
Tropical, moist/wet	0.83	1.01	1.00	1.04	1.10	1.44	1.11
Tropical, dry	0.92	1.01	1.00	0.99	1.04	1.37	1.04

Source: (IPCC, 2019)

Selecting an applicable set of management conditions and combining the respective factors listed in Table 42 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, SOC_{ref}.

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 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 equ. (3) and (4) estimates a soil carbon loss of 40*(1.0-0.92*0.99*1.04) = 2.1 ton C ha^{-1}, or on average 0.106 ton C ha^{-1} per year for the accounting period of 20 years. With application of high fertilizer inputs and manure the total estimated soil balance would turn into a gain: 40*(1.0-0.92*0.99*1.37) = 9.9 ton C ha^{-1}, i.e., a gain of 0.50 ton C ha^{-1} per year.

Selection of management options for converted grass/shrub land

Recuperation 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. It includes annualized changes in soil and vegetation carbon stock and requires total GHG emissions of a biofuel option to be less or equal 40% compared to the use of fossil fuels. Following the IPCC methodology, the annual CO2 emissions due to direct land use changes are calculated from:

(i) reference carbon stock of mineral soils[15],
(ii) a carbon stock change factor related to land use (f_{LU}),
(iii) a carbon stock change factor related to field management (f_{MG}), and
(iv) a carbon stock change factor related to input of organic matter (f_{IN}).

Reference carbon stock (SOC_{ref})

Estimates of soil carbon stocks were applied at grid-cell level and have been taken from available global soil databases (see Figure 18).

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

IPCC proposed guideline values for cropland carbon stock change factors related to land use (f_{LU}) vary, depending on climatic conditions, for annual crops between 0.69 and 0.92 (IPCC, 2019). For perennials the f_{LU} factors range from 0.72 to 1.01. For sugarcane, f_{LU} is taken as the average of annual and perennial factor values and varies between 0.78 and 0.965 (Table 43).

Table 43. Soil carbon stock change factors for land use, management practices and input level

Climate region	Land use factor (f_{LU})			Tillage factor (f_{MG})		Input factor (f_{IN})	
	Annuals crops*	Sugarcane, Energycane	Perennial crops	No tillage	Reduced tillage	Annual crops**	Perennial crops***
Temperate, moist	0.69	0.780	0.87	1.10	1.05	1.11	1.00
Temperate, dry	0.76	0.815	0.87	1.04	0.99	1.04	1.00
Tropical, montane	0.90	0.955	1.01	1.10	1.04	1.08	1.00
Tropical, wet	0.83	0.920	1.01	1.10	1.04	1.11	1.00
Tropical, moist	0.83	0.920	1.01	1.10	1.04	1.11	1.00
Tropical, dry	0.92	0.965	1.01	1.04	0.99	1.04	1.00

* includes Cassava; ** assumes high input level without manure; *** assumes intermediate input level

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

Field management factor (f_{MG}) is related to soil tillage[16] which comprises of full, reduced or no tillage, where:

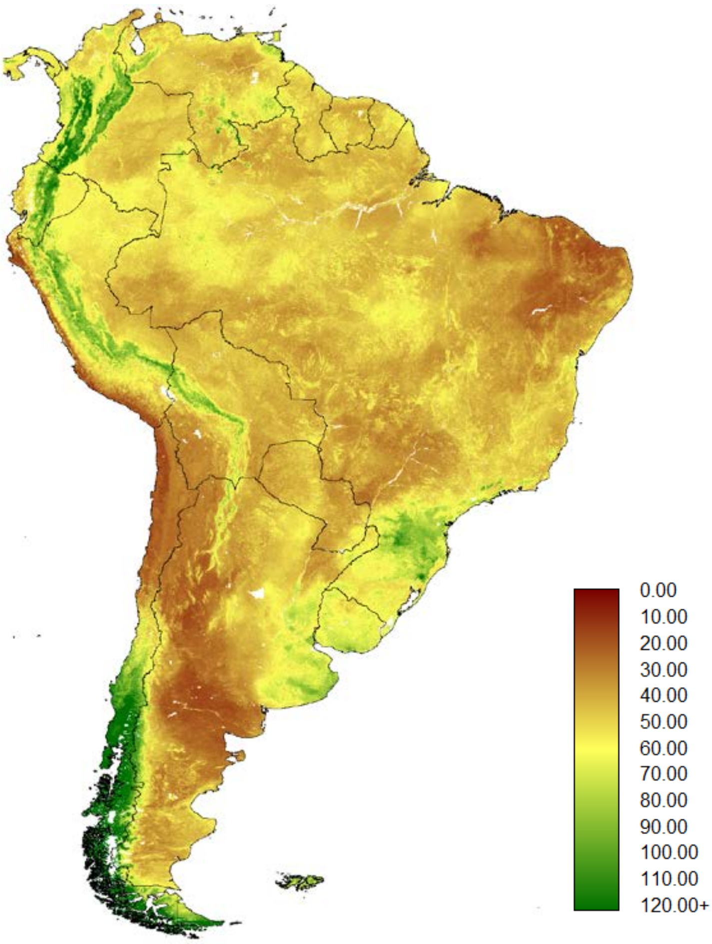
[15] Due to GHG implications, all organic soils were excluded from possible conversion.
[16] Tillage is used for seedbed preparation, weed control, evaporation suppression, water infiltration enhancement, and erosion control.

Full tillage refers to conventional soil tillage that turns 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 no-tillage (slot planting), mulch tillage, strip or zonal tillage, ridge till (including no-till on ridges).

Figure 18. Carbon stock of 0-30 cm top soil layer [ton C/ha]



IPCC field management factors f_{MG} for full tillage are set to 1.0. Depending on climatic conditions, coefficients are set respectively between 0.99 and 1.05 for *reduced tillage*, and between 1.04 and 1.11 for *no tillage* (see Table 43). 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 (non-degraded) grassland or shrub land for feedstock production and therefore the *full tillage* option has not been further pursued here.

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

IPCC coefficients related to input of organic matter (f_{IN}) 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 f_{IN} factors for annual crops vary between 1.04 and 1.11 (Table 9). 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 f_{IN} factors set to 1.

Table 44 summarizes the resulting 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 44. Relative soil carbon stock change factors used in this study, by IPCC climate region

	Annuals*		**Sugarcane, Energycane***		**Perennials****
Climate region	**No tillage**	**Reduced tillage**	**No tillage**	**Reduced tillage**	**No tillage**
Temperate, moist	0.842	0.804	0.952	0.909	1.15
Temperate, dry	0.822	0.782	0.882	0.839	1.10
Tropical, montane	1.069	1.011	1.135	1.073	1.16
Tropical, wet	1.013	0.958	1.123	1.062	1.22
Tropical, moist	1.013	0.958	1.123	1.062	1.22
Tropical, dry	0.995	0.947	1.044	0.994	1.17

*Assumes high input without manure; ** assumes intermediate input level

Co-product allocation of GHG emissions

Processing of biofuel feedstocks and conversion to biofuels often produces significant amounts of useful co-products, primarily for use as animal feed or electricity production. 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. Protein content of oil cakes and suitability for livestock feeding vary by crop type. Soybean meal is the most important and preferred source of high quality vegetable protein for animal feed manufacture (FAO, 2004). A major advantage is its high content of proteins (48-50%) and lysine, a limiting amino acid, which is required for optimizing the growth of animals for the production of meat. There are many other oil crops in addition to soybean, each with strengths and weaknesses for vegetable oil and protein meal supply.

Ethanol fermentation of starchy feedstock consumes the grain’s starch, while the protein, minerals, vitamins, fats and fiber 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 45 summarizes value shares applied in this study for the allocation of the GHG emissions due to direct land use changes. 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 liters ethanol and 0.315 tons DDGS at representative prices of 0.4 US$/l ethanol and 100 US$/ton DDGS.

Table 45. 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	65 %	35 %
Vegetable oil[1]	Jatropha	80 %	20 %
Vegetable oil[1]	Oil palm	85 %	15 %
Vegetable oil[1]	Macauba palm	85 %	15 %
Vegetable oil[1]	Soybean	35 %	65 %
Vegetable oil[1]	Camelina	75 %	25 %
Vegetable oil[1]	Carinata	75 %	25 %
Sugar	Sugarcane	85 %	15 %
Sugar and starch	Sweet Sorghum	85 %	15 %
Starch[2]	Maize	85 %	15 %
Starch	Cassava	85 %	15 %
Starch	Triticale	85 %	15 %
Biomass	Energy cane	90 %	10 %
Biomass	Miscanthus	90 %	10 %

1 see also Table 46**;** **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.

Oilseed processing produces vegetable oil, which can be used for biofuel production, and meals and press cakes with different amounts of protein content and suitability for livestock feeding. Technical coefficients provide oil and meal/cake extraction rates per unit of harvested oilseeds. 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 (see Table 46).

Table 46. Co-product specifications used for oil crops

Feedstock	Cake/Meal Extraction rate	Cake/Meal Protein content	Protein to Oil price ratio[1,2]	Cake/Meal Relative Price[3]	Oil Extraction rate	Oil Value Share[4]
Solaris	65 %	32 %	0.614	0.196	33.5 %	0.72
Jatropha	45 %	63 %	0.307	0.193	35 %	0.80
Palm kernel	52 %	17 %	0.696	0.118	46 %	0.88
Macauba[5]	38 %	25 %	0.696	0.174	55 %	0.89
Soybean	79 %	48 %	0.850	0.406	18 %	0.36
Carinata[6]	50 %	45 %	0.614	0.288	48 %	0.75
Camelina	62 %	32 %	0.614	0.198	36 %	0.75

1 Calculated as long-term (15 years) average of FAOSTAT export unit values for vegetable oils and cakes/meal. Values for Solaris, Camelina and Carinata are based on averages of export unit values calculated for seven oilseed crops; **2** Value for macauba used as calculated for oil palm; **3** Calculated as (Protein content) * (Protein to Oil price ratio); **4** Calculated using extraction rates and relative co-product prices; **5** Oil and protein extraction rates based on Colombo et al. (2018); **4** Oil and protein extraction rates based on Barbosa-Evaristo *et al.* (2018).

Application of GHG emission criteria

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. We apply as fossil comparator in this study a value of 94 gCO2eq/MJ. The first GHG criterion is tested according to equ. (5):

$$eCO2_{LCA} + dCO2_{LUC} \leq (1 - s_{min}) * eCO2_{fossil} \qquad (5)$$

where

$dCO2_{LUC}$	annualized CO2equ emissions due to direct land use change [g CO_2eq/MJ]
$eCO2_{LCA}$	lifecycle emissions of biofuel pathway (excluding land use change) [g CO_2eq/MJ]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [g CO_2eq/MJ]
s_{min}	minimum GHG saving rate expressed as share of comparator [dimensionless]

Considering the soil carbon stock change factors discussed above, 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. First, 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. Second, it requires that the carbon debt encountered 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 equ. (6) and (7):

$$eCO2_{LCA} \leq (1 - s_{min}) * eCO2_{fossil} \qquad (6)$$

and

$$T * dCO2_{LUC} \leq \frac{T}{2} * (eCO2_{fossil} - eCO2_{LCA}) \qquad (7)$$

where

$eCO2_{LCA}$	lifecycle emissions of biofuel pathway (excluding land use change) [g CO_2eq/MJ]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [g CO_2eq/MJ]
$dCO2_{LUC}$	annualized CO2equ emission due to direct land use change [g CO_2eq/MJ]
s_{min}	minimum GHG saving rate expressed as share of comparator [dimensionless]
T	length of accounting period [years]

When both GHG criteria 1 and 2 cannot 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 biofuel crops, the selection of best performing feedstocks 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’).

The selection of best performing feedstock in a grid cell either maximizes fuel energy production among viable feedstocks or can select feedstocks in order to maximize GHG emission savings. Note, by using, for instance, relative price weights for energy produced and emissions avoided, the two separate objectives can be combined into a more general weighted objective function. In mathematical terms the grid cell level optimization can be written as in equ. (8):

$$\max_{i}\{A_i * Y_i * [p_e + p_{CO2} * (eCO2_{fossil} - eCO2_{LCA,i} - dCO2_{LUC,i})], i \in I_{GHG}\} \qquad (8)$$

where

Y_i	attainable annual fuel yield of projected land use [MJ/ha]
A_i	suitable area of projected land use [ha]
p_e	fuel energy price weight [$/MJ]
p_{CO2}	GHG saving price weight [$/gCO2eq]
$eCO2_{LCA,i}$	lifecycle emissions of biofuel pathway i (excluding land use change) [g CO_2eq/MJ]
$eCO2_{fossil}$	lifecycle emissions of fossil comparator [g CO_2eq/MJ]
$dCO2_{LUC,i}$	annualized CO2equ emissions due to land conversion to land use i [g CO_2eq/MJ]
I_{GHG}	index set of feedstocks meeting required GHG criterion

When constructing an ‘umbrella’ crop database by grid cell according to equ. (8), the specifically selected feedstock defines the suitability attributes, productivity and GHG outcomes of that grid-cell when mapping and tabulating the results.

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