GHG emissions impact of sustainable aviation fuels from the hydroprocessing of oilseed crops

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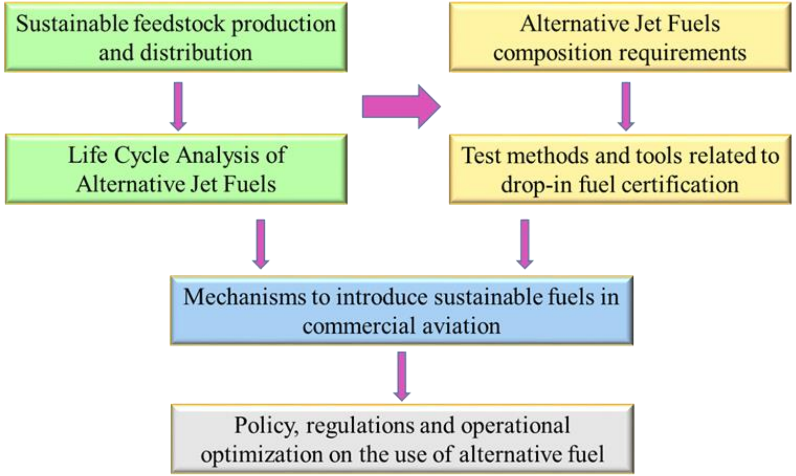
ACGA Cluster Workshop

Objectives

- Aim 1: Improve physical and climate models to include alternative aviation use.
- Aim2: A reliable and globally harmonized life cycle assessment (LCA) approach (including the impact of land use change).
- Aim 3: Reduction of the fuel cost and time cost in drop-in jet fuel certification.
- Aim 4: Providing protocols and guidance for alternative fuel introduction in the aviation sector.



Sustainable feedstock production and distribution

Alternative Jet Fuels composition requirements

Life Cycle Analysis of Alternative Jet Fuels

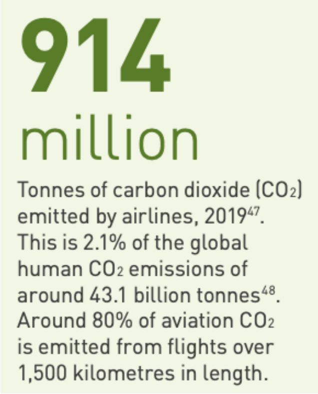
Test methods and tools related to drop-in fuel certification

Mechanisms to introduce sustainable fuels in commercial aviation

Policy, regulations and operational optimization on the use of alternative fuel

Aviation’s GHG Emissions

- Aviation: 2.1% of global greenhouse gas emissions in 2019.
  - International aviation: 1.3%
- ICAO (International Civil Aviation Organization)
  - Tracks emissions from international civil aviation
  - Aspirational goals
    - Short-term: 1.5% annual fuel efficiency improvement between 2009 and 2019.
    - Medium-term: Carbon neutral growth from 2020.
    - Long-term: Reduce net emissions to 50% of what they were in 2005 by 2050.



914

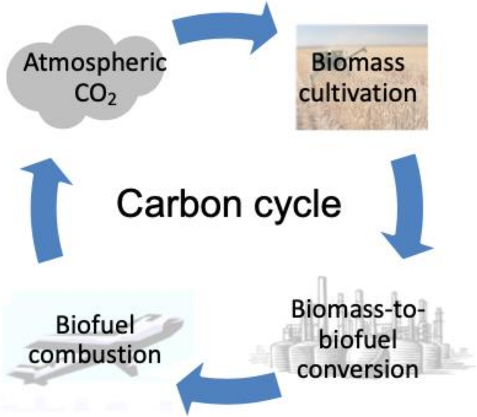
million

Tonnes of carbon dioxide (CO_2) emitted by airlines, 2019[47]. This is 2.1% of the global human CO_2 emissions of around 43.1 billion tonnes[48]. Around 80% of aviation CO_2 is emitted from flights over 1,500 kilometres in length.

Air Transport Action Group (ATAG)
Waypoint 2050 Report, 2020

Basket of Measures

- Technological advances
- Operational improvements
- Alternative sustainable aviation fuels (SAF),
  - Drop-in fuels → Seamless integration with existing infrastructure
- Market-based measures
  - e.g. CORSIA



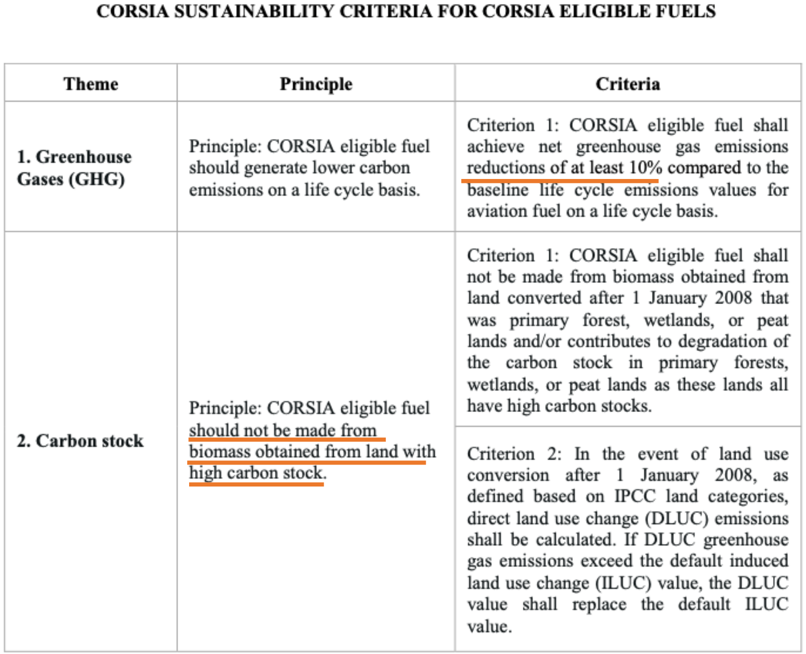

40
million

Litres of neat sustainable aviation fuel used by commercial flights in 2019 (32,000 tonnes). This was blended with traditional fuel in over 65,455 flights from five international airports (Los Angeles, San Francisco, Bergen, Oslo and Stockholm)[49]. Whilst this only represents less than 1% of the current fuel used in aviation globally, as this new source of fuel takes off, we will see this figure rise substantially.

Air Transport Action Group (ATAG)
Waypoint 2050 Report, 2020

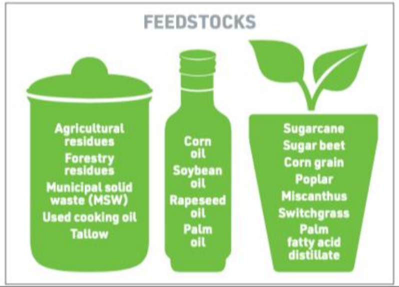
CORSIA

- Carbon Offsetting and Reduction Scheme for International Aviation
- Responsible parties: Airlines
    - Buying carbon credits
        - Credits generated by projects/prog
    - Using CORSIA Eligible Fuels (CEF)
    - SAF within CORSIA: Aviation fuel that h carbon emissions than conventional ke



CORSIA SUSTAINABILITY CRITERIA FOR CORSIA ELIGIBLE FUELS

Theme	Principle	Criteria
1. Greenhouse Gases (GHG)	Principle: CORSIA eligible fuel should generate lower carbon emissions on a life cycle basis.	Criterion 1: CORSIA eligible fuel shall achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.
2. Carbon stock	Principle: CORSIA eligible fuel should not be made from biomass obtained from land with high carbon stock.	Criterion 1: CORSIA eligible fuel shall not be made from biomass obtained from land converted after 1 January 2008 that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
		Criterion 2: In the event of land use conversion after 1 January 2008, as defined based on IPCC land categories, direct land use change (DLUC) emissions shall be calculated. If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value shall replace the default ILUC value.



Feedstocks with CORSIA default life cycle values as of February 2019.*

*ICAO 2019 Environmental Report

ASTM Approved Fuel Conversion Pathways

ASTM reference	Year of certification	Conversion pathway	Feedstock type	Blend ratio by volume
D7566 Annex 1	2009	*FT-SPK*: Fischer-Tropsch synthetic paraffinic kerosene	Coal, natural gas, biomass	50 %
D7566 Annex 2	2011	*HEFA-SPK*: Hydroprocessed esters and fatty acids synthetic paraffinic kerosene	Fats, oils and greases	50 %
D7566 Annex 3	2014	*HFS-SIP*: Hydroprocessed fermented sugars to synthetic isoparaffins	Sugars	10 %
D7566 Annex 4	2015	*FT-SPK/A*: Fischer-Tropsch synthetic paraffinic kerosene with aromatics	Coal, natural gas, biomass	50 %
D7566 Annex 5	2016	*ATJ-SPK*: Alcohol to jet synthetic paraffinic kerosene	Sugar/starch producing feedstocks and cellulosic biomass	50 %
D1655 Annex 1	2018	Co-processing	Fats, oils and FT Biocrude	5 %
D7566 Annex 6	2020	*CHJ*: Catalytic hydrothermolysis synthesized kerosene	Fats, oils and greases	50 %
D7566 Annex 7	2020	*HC-HEFA-SPK*: Hydroprocessed hydrocarbons, esters and fatty acids synthetic paraffinic kerosene	Bio-derived hydrocarbons and lipids (Algae)	10 %

D7566: Standard specification for aviation turbine fuel containing synthesized hydrocarbons

Feedstocks for Alternate

Feedstock Type	Feedstock Name	CORSIA	New Feedstocks
Oilseed crops	Camelina	■	
	Carinata	■	
	Castor bean		●
	Corn oil (from DDGS)	■	
	Jatropha		● ○
	Microalgae		○
	Palm	■	
	Palm fatty acid distillate	■	
	Pennycress		●
	Rapeseed	■	
	Salicornia		●
	Soybean	■	
	Tobacco		●
	Xanthoceras		○

Non-edible vegetable oils

■ Feedstocks that have values under CORSIA and will be reviewed as needed for ALTERNATE
● Feedstocks that will be evaluated by the EU consortium of ALTERNATE
○ Feedstocks that will be evaluated by the Chinese consortium of ALTERNATE

Feedstock Type	Feedstock Name	CORSIA	New Feedstocks
Lignocellulosic biomass	Agricultural residues	■ ○	
	Forest residues	■	
	Giantreed		●
	Miscanthus	■	
	Reed canary grass		●
	Short rotation woody crops	■	
	Switchgrass	■	
Carbohydrate crops	Sweet sorghum		●
	Sugar beet	■	
	Sugar cane	■	
	Wheat		●
Wastes	Municipal Solid Waste (MSW)	■	
	Used cooking oil	■ ○	
	Tallow	■	
Fossil fuels	Crude oil		○
	Natural gas		○

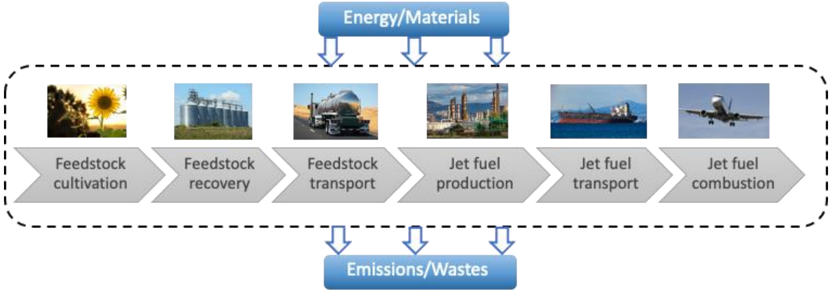
Oilseed feedstocks

Feedstock	Distribution	Av.Yield (t/ha-yr)	Oil content (wt %)	Jet fuel production potential (L/ha)[6]	Oil extraction co-products
Camelina	N. America, EU	1.9[1]	36.0	800-3,100	Meal
Castor	India, Brazil, China	1.1[2]	47.0	400-1,550	Meal
Jatropha	Asia, Africa, S. America	2.5[3]	35.0	1,200-4,600	Meal/ husk/shell
Palm	Malaysia, Indonesia	17.9[4]	22.4	10,000-39,000	Palm kernel meal
Pennycress	Eurasia, N. America	1.0[5]	34.0	450-1,800	Meal
Rapeseed	EU	3.4[4]	44.0	1,250-4,800	Meal
Salicornia	Africa, Middle East, S. America, China, US	2.0[3]	28.2	1,200-4,500	Meal / straw
Soybean	N. America, Brazil	3.2[4]	19.1	2,700-10,500	Meal
Energy tobacco	China, Brazil, India, US, Greece	2.1[5]	38.0	925-3,600	Meal

[1]Angelini et al. 2020, [2]Carrino et al. 2020, [3]Stratton et al. 2010, [4]FAOSTAT, [5]Fatica et al. 2019 [6] Estimated using the product slate from Pearlson et al. 2013

Life cycle assessment (LCA)

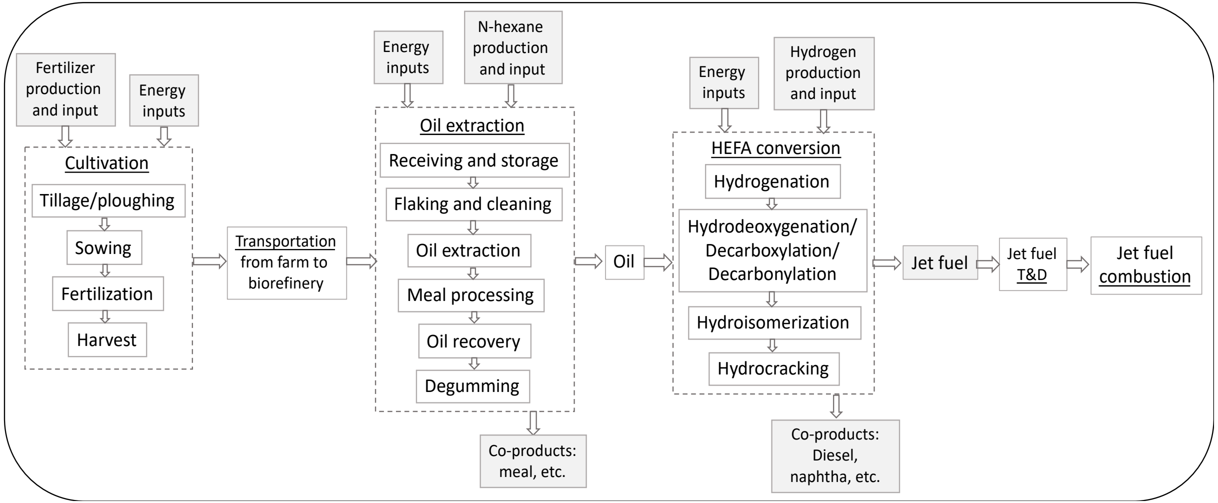
- Functional Unit: MJ jet fuel, emissions reported as: $gCO_{2\ equivalent}$/MJ jet fuel
- System Boundary: emissions from the complete fuel cycle (well-to-wake)



- Baseline: e.g. ICAO Baseline for jet fuel is 89 gCO_2e/MJ jet fuel
- Co-products: Emissions from the life cycle can be distributed/allocated among co-products using various allocation methods or displacement (system expansion).
  - e.g. ICAO: Energy allocation, distributes the life cycle GHG emissions based on the energy content (lower heating value) of the co-products and fuel
- Attributional LCA

Scope for the attributional LCA

- All the direct and indirect energy/material inputs will be considered within the following process steps for the oilseed crops.



General system boundary for oilseed crops

Stochasticity

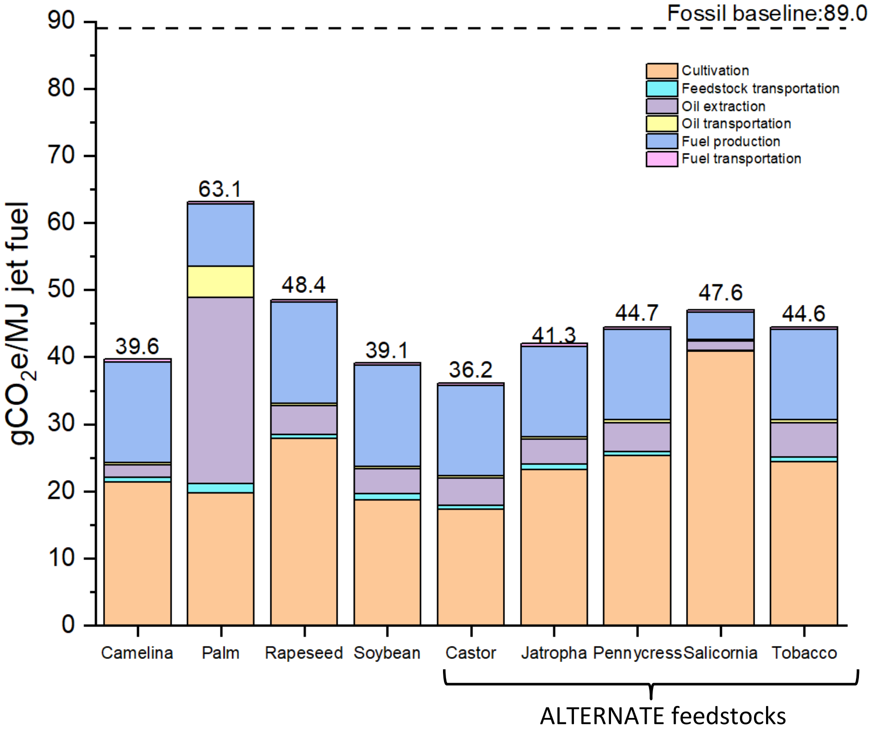
- Some of the technologies that will be assessed as part of this work are not yet fully commercialized. The data is sometimes limited, and **variability might be high**.
- For this reason, **probability density functions** were assigned into key parameters, using available data from the literature and industry sources.
- These distribution curves will then be used to conduct **Monte Carlo analysis** that samples values.

Example Life cycle inventory

Variable	Nominal Range[1]	Units	Distribution
Feedstock properties			
Seed lipid content	[29, 34, 36], a	%	Triangular
Seed moisture content	12, b	%	-
Loss factor for oil extraction	4, c	%	-
Material and energy inputs			
Cultivation			
N total	[27.8, 46.4, 138.9]	g/kg seeds	Beta
P_2O_5	[3.26, 0.64]	g/kg seeds	Lognormal
K_2O	[2.91, 0.48]	g/kg seeds	Lognormal
Diesel	[0.17, 0.17, 0.16]	MJ/kg seeds	Triangular
Oil extraction			
Feedstock to oil	(1-b)/a/(1-c)	kg/kg oil	-
Meal	(1-a-b)/b/(1-c)	kg/kg oil	-
HEFA Conversion			
Oil	[1.23, 1.25, 1.27]	kg/kg jet	Triangular
Natural gas	[0.08, 0.14, 0.19]	MJ/MJ jet	Triangular
Electricity	[0.0046, 0.0062, 0.0077]	MJ/MJ jet	Triangular
Hydrogen	[0.017, 0.054, 0.092]	MJ/MJ jet	Triangular

[1] Lognormal distributions: [log mean, log standard deviation]
Triangular/Beta distributions: [low, mode, high]

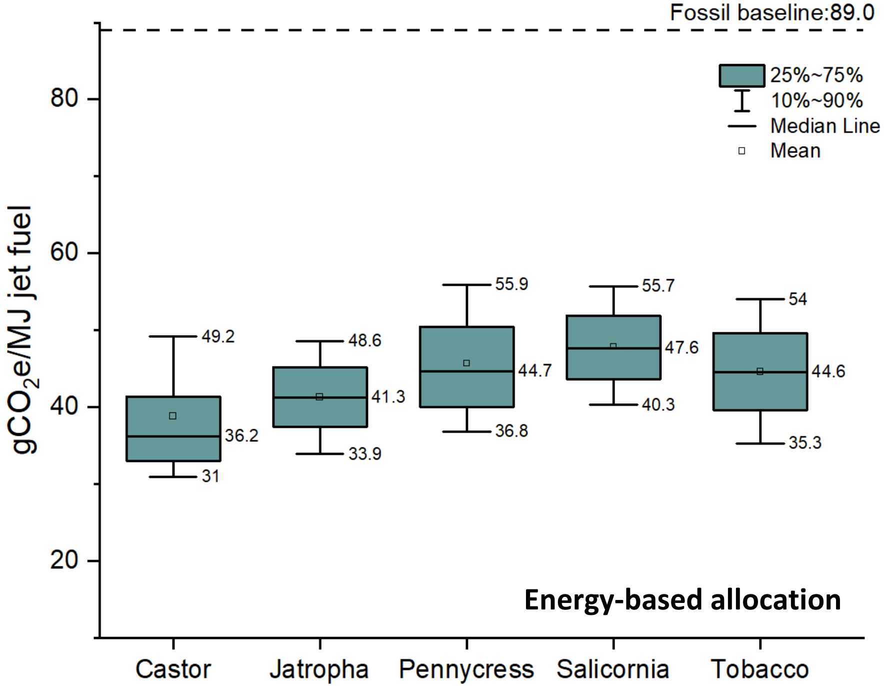
Attributional results without land-use change



- The attributional LCA results for the ALTERNATE feedstocks show life cycle greenhouse gas emissions below the ICAO fossil-fuel baseline of 89.0 gCO$_2$e/MJ (Median values from the stochastic analysis are shown here).
- **Energy-based allocation** was applied in order to distribute the emissions between the co-products that are produced during the fuel production processes.
- ➢ The main contributors to the results are cultivation and fuel production steps. Oil extraction step is also important due to the amount, and energy content of by-products produced.
- The difference in the results is due to the cultivation step in most cases, where fertilizer/diesel use is the main factor.

PRELIMINARY RESULTS- PLEASE DO NOT CITE

Stochastic uncertainty analysis



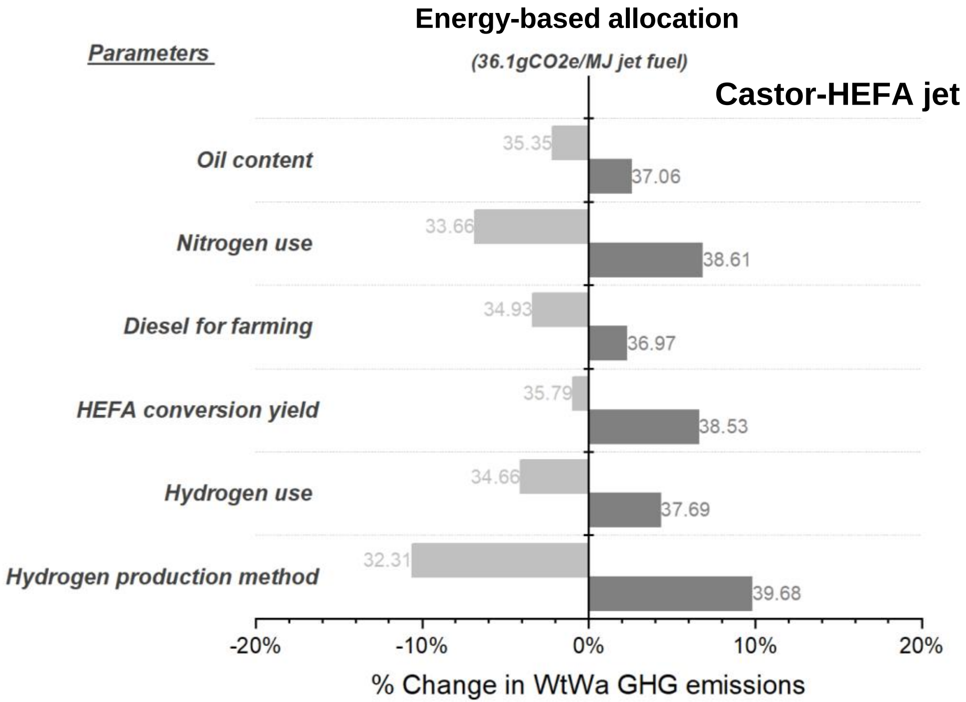
- **Monte-Carlo simulations** approach, based on 20,000 randomized trials, was used to evaluate the uncertainties caused by the variability of input parameters.
- The results show at least ±15 % variability.
- Local sensitivity analysis have been done to determine the impact of certain parameters on the emissions.

PRELIMINARY RESULTS- PLEASE DO NOT CITE

Sensitivity Analysis

Parameters	Change from base value	
Oil content	-20%	+20%
Nitrogen fertilizer	-20%	+20%
Diesel for farming	-20%	+20%
Hydrogen	-20%	+20%
HEFA conversion yield (current: 80%)	71.9%	-
Hydrogen production technology (current: natural gas SMR)	Electrolysis	Coal

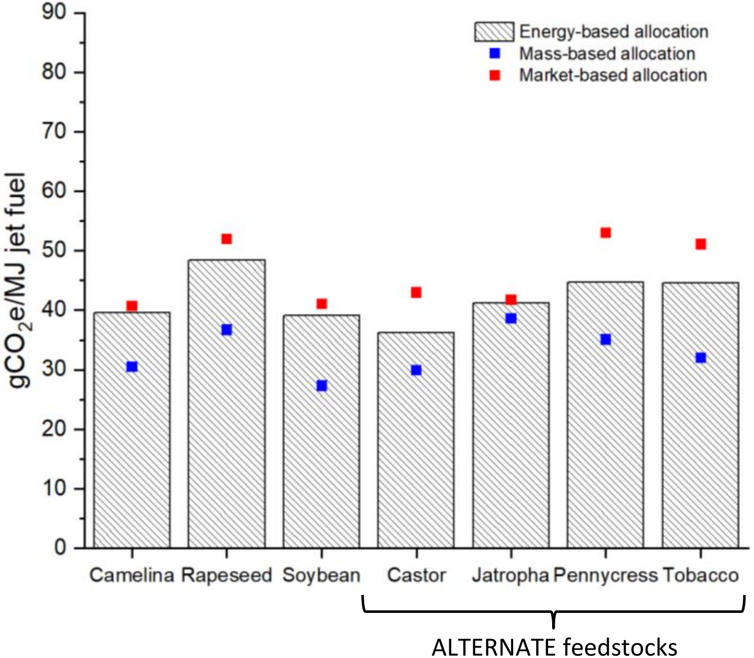
- Sensitivity to changes in nitrogen use, hydrogen production technology, and HEFA conversion efficiency have been observed.



PRELIMINARY RESULTS- PLEASE DO NOT CITE

Effect of allocation method on LCA results

Main results: energy-based allocation using median values



- Emissions were allocated on oil extraction co-products (e.g. meal) using market- and mass-based allocation methods. Energy-based allocation was used for fuel co-products in all cases.
- **Energy allocation** assigns a relatively small share of the emissions to the meal, whereas **mass allocation** allocates a high share of emissions due to large amount of meal produced in most cases.
- For the new feedstocks **market-based allocation** is done based on calculated prices from the literature and/or using soybean meal as proxy. Meal prices are generally low, resulting in increased allocation of emissions into the oil.

Direct land use change (DLUC)

- Direct land use change (DLUC): conversion of land **from previous uses to agricultural production** (e.g., to grow biofuel feedstock).
- DLUC can **increase life cycle GHG emissions** when land carbon stocks decrease, e.g., when feedstock production entails natural land cover loss
- CORSIA establishes that:
  - SAF should not be produced at the cost of **land classified as primary forests, wetlands and peatlands** after 1 January 2008.
  - Still, CORSIA does not provide a protocol for DLUC calculation, besides IPCC guidelines
- IPCC's Tier 1 procedure: GHG emissions from DLUC estimated as **differences in land carbon stocks before and after the land conversion**
  - Considering **25 years as amortization period**, in line with ICAO

Method for DLUC estimation

- GHG sources from changes C pools → Equation 2.1 (IPCC 2006)
  - Above-ground biomass (AGB) and below-ground biomass (BGB)
  - Dead organic matter in dead wood (DW) and litter (LI)
  - Soil organic carbon (SOC)
  - Harvested wood products (HWP) are 0 under Tier 1

$$\Delta C_{DLUC} = \Delta C_{AGB} + \Delta C_{BGB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SOC} + \Delta C_{HWP}$$

- Additional C flows → Equations 2.27; 11.2; 11.8; 11.10 (IPCC 2006)
  - Non-CO_2 gases (CH_4, N_2O) from burning of AGB, DW and LI
  - N_2O emissions from mineralized N as a result of SOC changes (direct & indirect)

  → Forgone carbon sequestration is excluded

Method for DLUC estimation

- Need to consider spatial **variability in biomass yields, SOC, carbon pools in AGB and BGB, and management practices**
- Two approaches:

1) Scenario-based approach: using default carbon pools and coefficients in IPCC guidelines (2006)

2) Spatially-explicit approach:

- using simulated yields (at 5 arc-minute resolution) by **IIASA-FAO's GAEZv4** https://gaez.fao.org/ considering variability in soil suitability, terrain slopes and land cover consistent with the **Agro-Ecological Zone classification**
- Combined with carbon pools in the **GLOBIOM model: SOC, AGB and BGB** (at 30 arc-minute resolution = 50 x 50 km)

+ Assumptions on crop management in both 1) and 2)

Assumptions for DLUC estimation

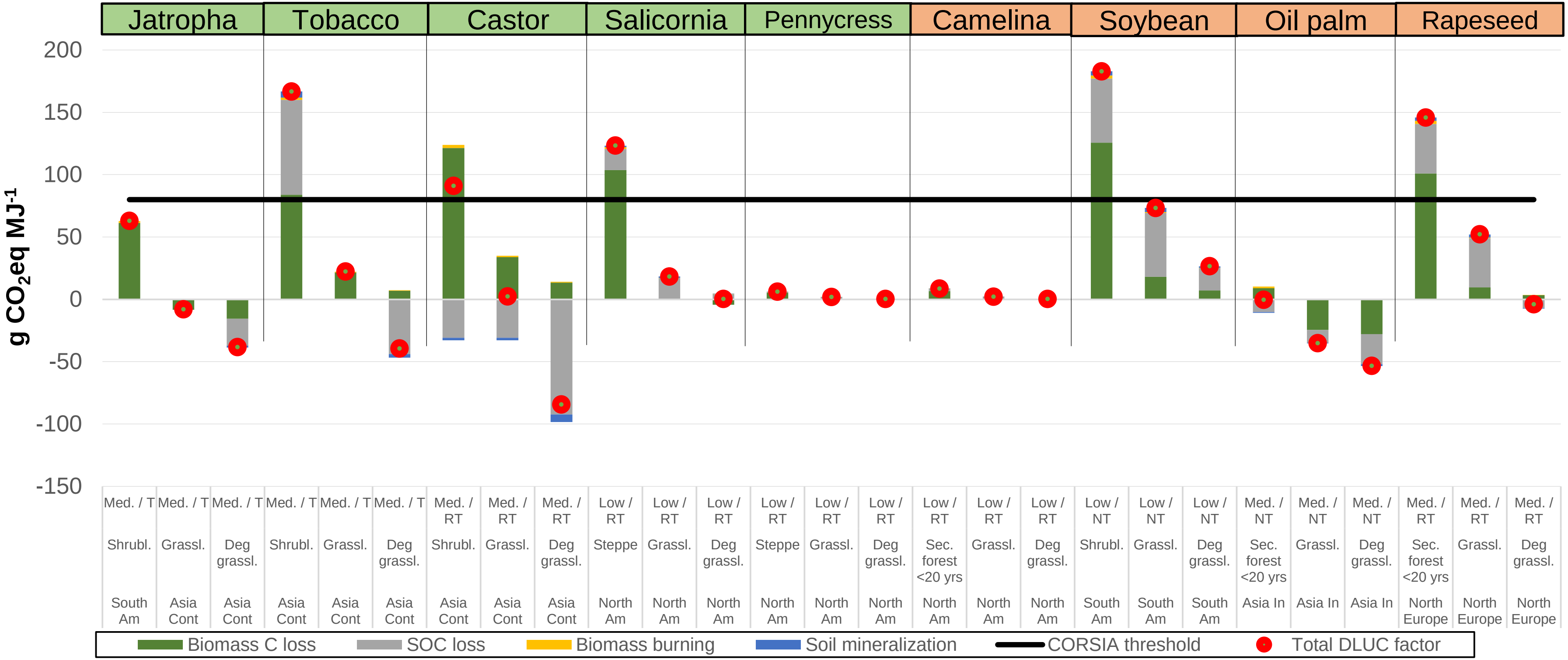
Assumptions needed on:

- Yields (approach 1)
- Oil content in seed (approach 1 & 2)
- Carbon sequestration in agricultural biomass (approach 1 & 2)
- Crop management (approach 1 & 2)
- Fertilizer input intensity (approach 1 & 2)

	Yield (t dm/ha)	**Oil content in seed (%)**	**Crop biomass (t C/ha)**	**Crop management**	**Input intensity**
Camelina	1.9	0.36	1.375	Reduced tillage	Low input
Castor	1.1	0.47	1.29	Reduced tillage	Medium input*
Jatropha	2.5	0.35	12.02	No tillage	Medium input*
Oil palm	18	0.24	37.5	No tillage	Medium input*
Pennycress	1	0.34	1.02	Reduced tillage	Low input
Rapeseed	3.4	0.42	1.47	Tillage	Medium input*
Salicornia	2	0.28	4.2	Reduced tillage	Low input
Soybean	3.2	0.18	1.37	No tillage	Low input
Solaris tobacco	2.1	0.33	2.01	Tillage	Medium input*

* Medium input refers to medium input intensity without manure in all cases.

DLUC emission factors



Asia Cont: Asia continental; Asia In: Asia insular; C. temp: cool temperate; Deg. Grassl.: Degraded grassland; Grassl.: grassland; low: low input intensity; Med.: medium input intensity; NT: No tillage; RT: Reduced tillage; South Am: South America; T: Tillage.

PRELIMINARY RESULTS- PLEASE DO NOT CITE

Land use modelling of jatropha

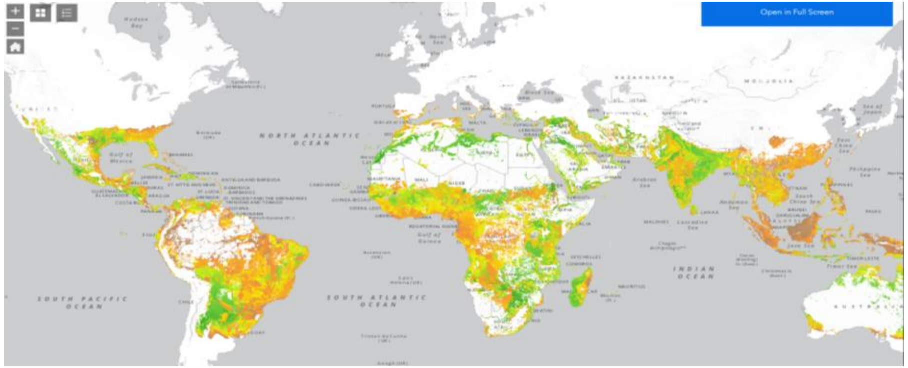
Yield assumptions

- Based on high input irrigated yield maps from GAEZ v4 (FAO-IIASA)
  - World 2.58 t seed/ha
  - India 3.24 t seed/ha
  - USA 2.49 t seed/ha
- Replanting: literature indicates 2 years of very low yield
  - Yields above are adjusted down by 10%

Carbon stock in natural vegetation: Jung et al., 2021

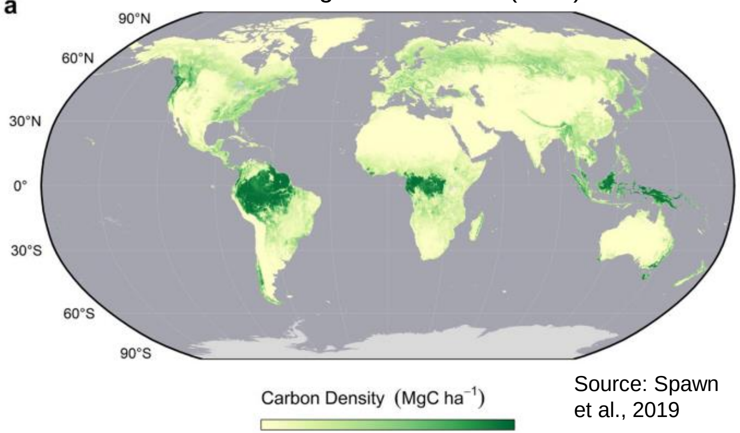
Biomass sequestration: average 20 yrs plantation cycle (above and below ground - ratio: 0.386) - 12.0 t C ha^{-1}

Plantation yield



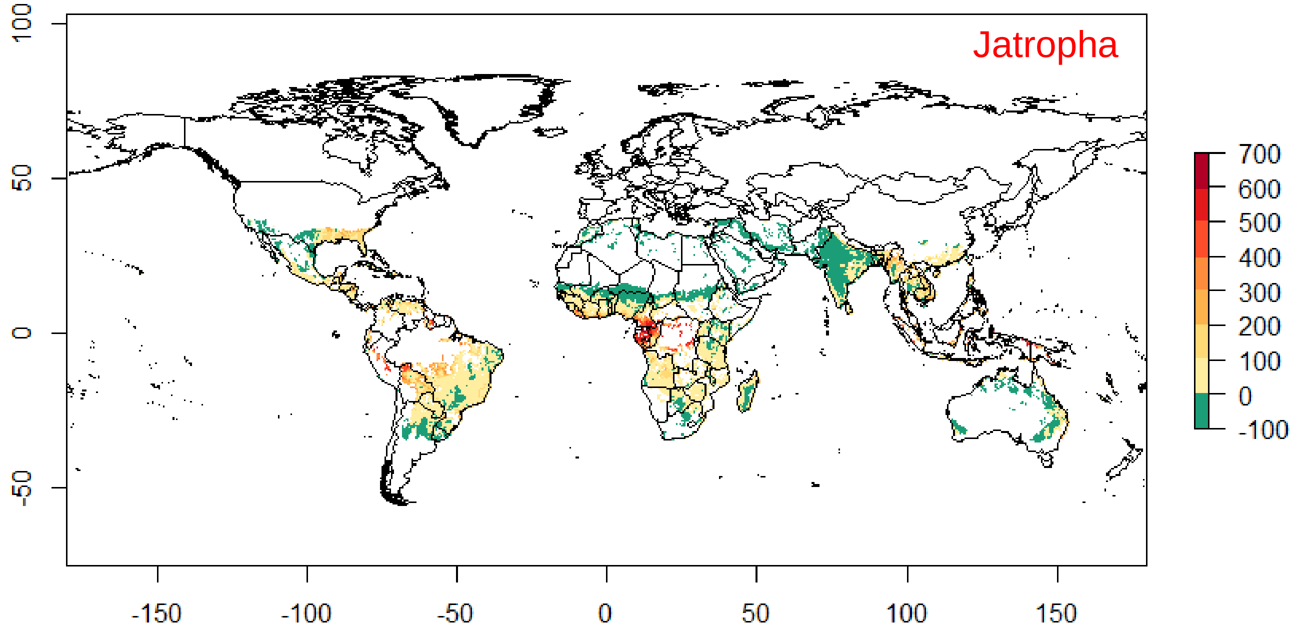
Source: GAEZ v4

Natural vegetation carbon (AGB)



Source: Spawn et al., 2019

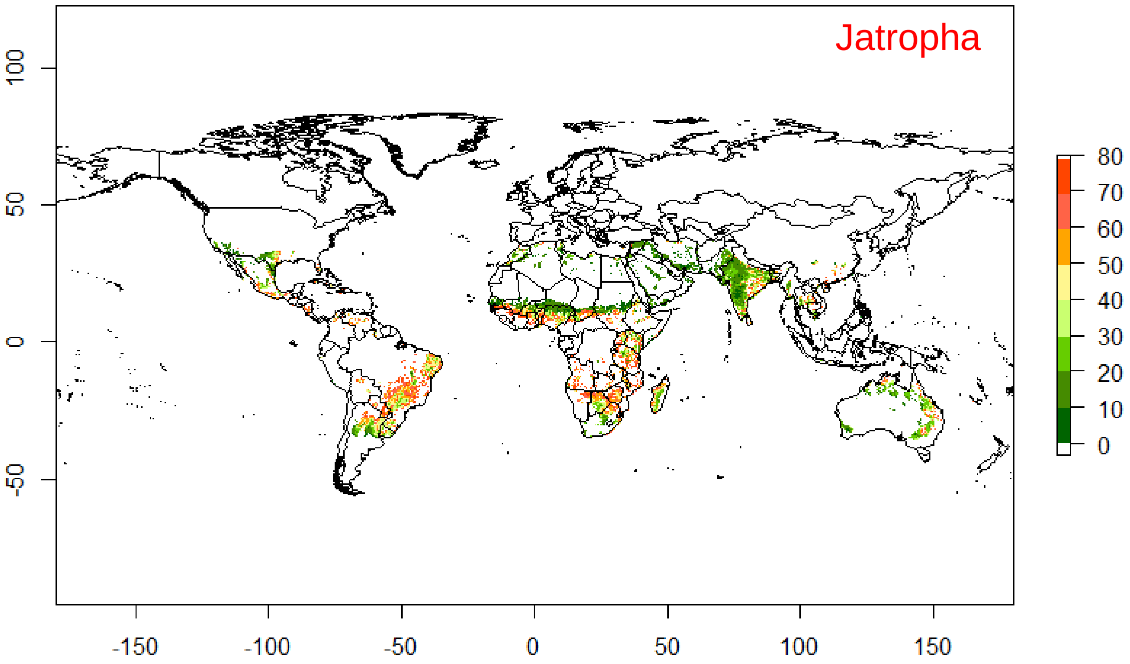
Spatially-explicit DLUC emission factors



- Spatially-explicit **DLUC emission factors of jatropha production (g CO_2e/MJ)**
- Potential for net carbon gain in locations with **relatively high yields and relatively low carbon stocks**
- Very high **DLUC factors in tropical locations** with very high land carbon stocks

PRELIMINARY RESULTS- PLEASE DO NOT CITE

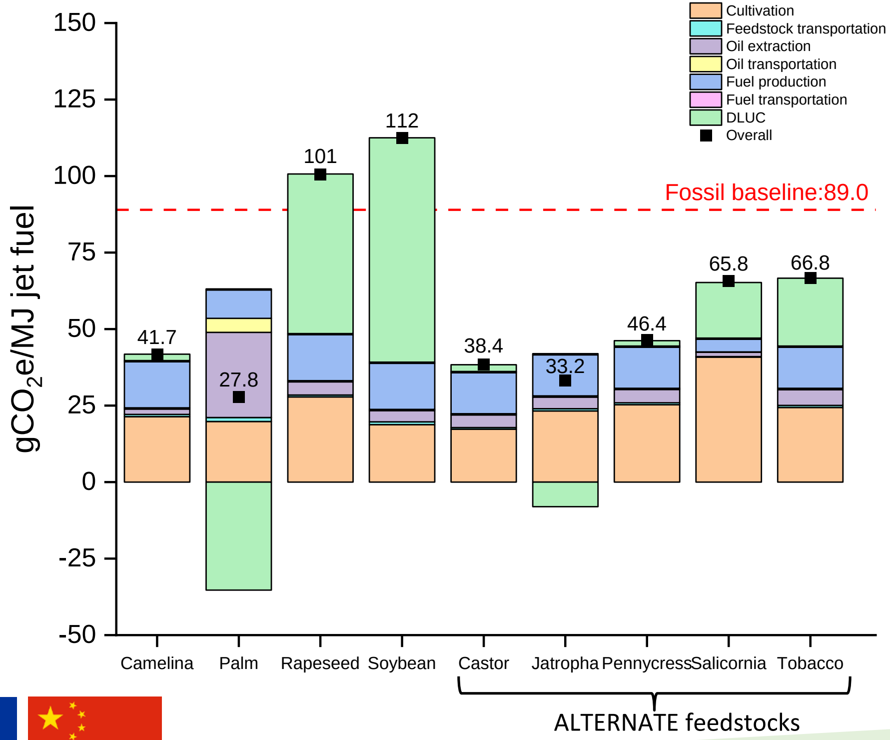
Total GHG emissions (g CO_2e/MJ)



- Total life cycle GHG emissions: **DLUC factors + core-LCA emissions** (41.3 gCO_2e/MJ) for jatropha.
- Potential for net GHG savings relative to the fossil reference fuel in locations with **relatively high yields and relatively low carbon stocks:**
- India, USA, Sub-Saharan Africa, Southern Brazil and Argentina and Oceania

PRELIMINARY RESULTS- PLEASE DO NOT CITE

Attributional results with DLUC



- Emissions including the impact from direct land use change are shown when **grassland** is **used for the cultivation** of crops.
- **High DLUC emission factors are due to soil organic carbon loss. Low seed/oil yields** from the corresponding crops also contribute to high DLUC factors.
- All of the ALTERNATE feedstocks are below the fossil baseline even when the land use change is factored in. At least 25 % emissions savings are provided (max 63 % savings).
- **Next step: Consequential LCA** that will factor in **induced land use change** and the changes to the market.

PRELIMINARY RESULTS- PLEASE DO NOT CITE

Summary

- Attributional LCA of GHG emissions from HEFA-jet fuels have been presented and the results show at least 25 % emissions savings, when suitable land types are targeted (grassland).
- Monte-Carlo sampling for ALTERNATE feedstocks displayed the extent of uncertainty within the results: at least ±15 % variability (up to 35 %).
- Treatment of co-products and allocation methods was shown to have an impact on results: energy-based allocation was used for baseline
- Sensitivity analysis was performed: higher sensitivity to nitrogen use and hydrogen production technology
- The importance of emissions from land use change is clearly visible in the overall results: Conversion of grassland/degraded grassland into cropland keep the overall emissions low, but conversion of other land types may lead to emissions higher than fossil fuel.
- Most of the new crops presented are not domesticated, and they have been cultivated in small fields. Their domestication will improve the oil yields, and as a result have a positive impact on their life cycle emissions. On the other hand, their deployment could generate additional emissions through indirect land use changes, not captured here.

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