# Environmental impact of sustainable aviation fuels from the hydroprocessing of oilseed crops: A life cycle assessment approach

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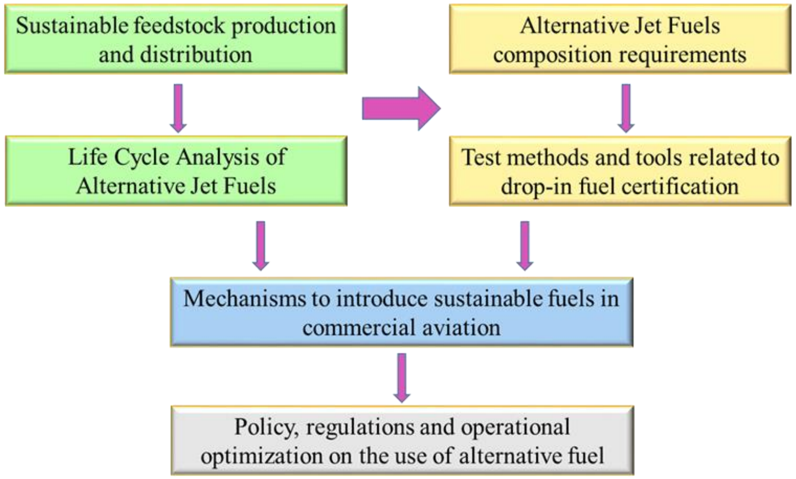
# Objectives

- 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.



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# 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.

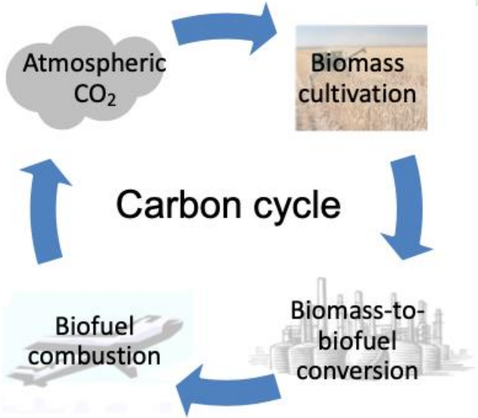
Air Transport Action Group (ATAG) Waypoint 2050 Report, 2020

# 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.

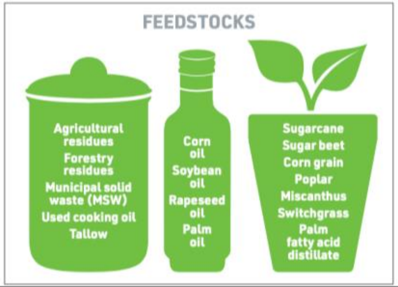
Air Transport Action Group (ATAG) Waypoint 2050 Report, 2020

# 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

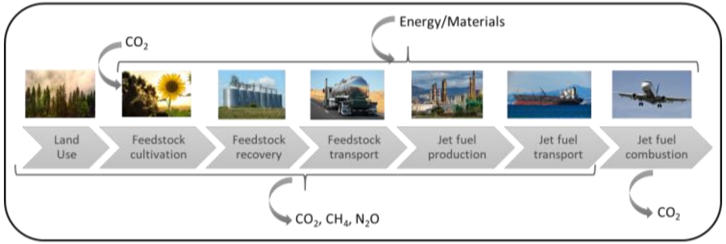
# ASTM Approved Fuel Conversion Pathways

| 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

# Life cycle assessment (LCA)

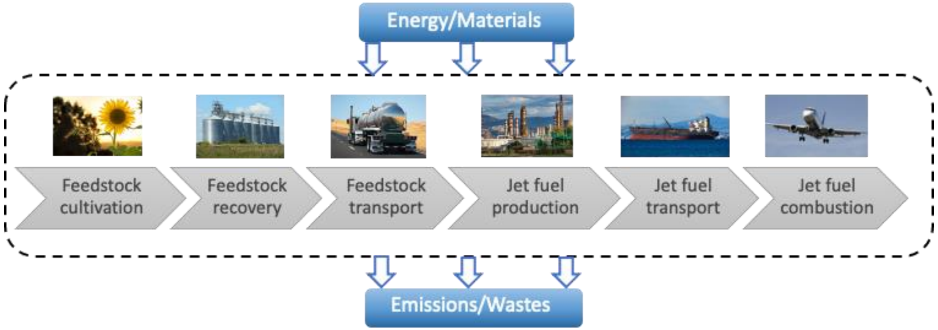
- Methodology used to understand environmental impacts associated with a product, process or service
- Consistency between analysis methodologies is essential for comparisons
- Functional Unit: $gCO_2e$/MJ jet fuel
- System Boundary: emissions from the complete fuel cycle (well-to-wake)




- Baseline: e.g. ICAO Baseline for jet fuel is 89 $gCO_2e$/MJ jet fuel

# Life cycle assessment (LCA)

- 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
- Consequential LCA



# 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]

# 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 is produced at the cost of carbon-rich ecosystems
- IPCC's Tier 1 procedure: GHG emissions from DLUC estimated as **differences in land carbon stocks before and after the land conversion**
  - **25 years amortization period, in line with ICAO**
- **Several scenarios** for land converted to cropland, considering **spatial variability** in yields, **soil organic carbon (SOC),** carbon pools in **above- and below-ground biomass** as well as **management practices** based on revised IPCC guidelines (2019)

➢ CORSIA currently does not have a method for DLUC inclusion

# 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)
  - Foregone carbon sequestration over a 25-year period

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# 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 | | ○ |

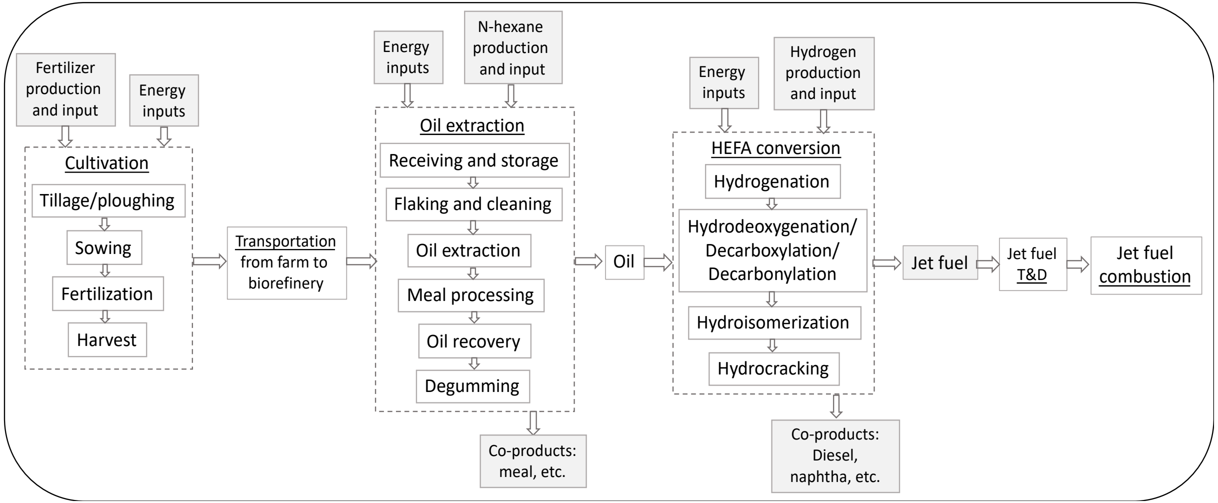
# Oilseed feedstocks

| 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 | 799-3,085 | Meal |
| Castor | India, Brazil, China | 1.1[2] | 47.0 | 398-1,535 | Meal |
| Jatropha | Asia, Africa, S. America | 2.5[3] | 35.0 | 1,185-4,573 | Meal/ husk/shell |
| Palm | Malaysia, Indonesia | 17.9[4] | 22.4 | 10,018-38,666 | Palm kernel meal |
| Pennycress | Eurasia, N. America | 1.0[5] | 34.0 | 456-1,759 | Meal |
| Rapeseed | EU | 3.4[4] | 44.0 | 1,238-4,779 | Meal |
| Salicornia | Africa, Middle East, S. America, China, US | 2.0[3] | 28.2 | 1,169-4,511 | Meal / straw |
| Soybean | N. America, Brazil | 3.2[4] | 19.1 | 2,723-10,511 | Meal |
| Tobacco | China, Brazil, India, US, Greece | 2.1[5] | 38.0 | 925-3,568 | 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

# 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***

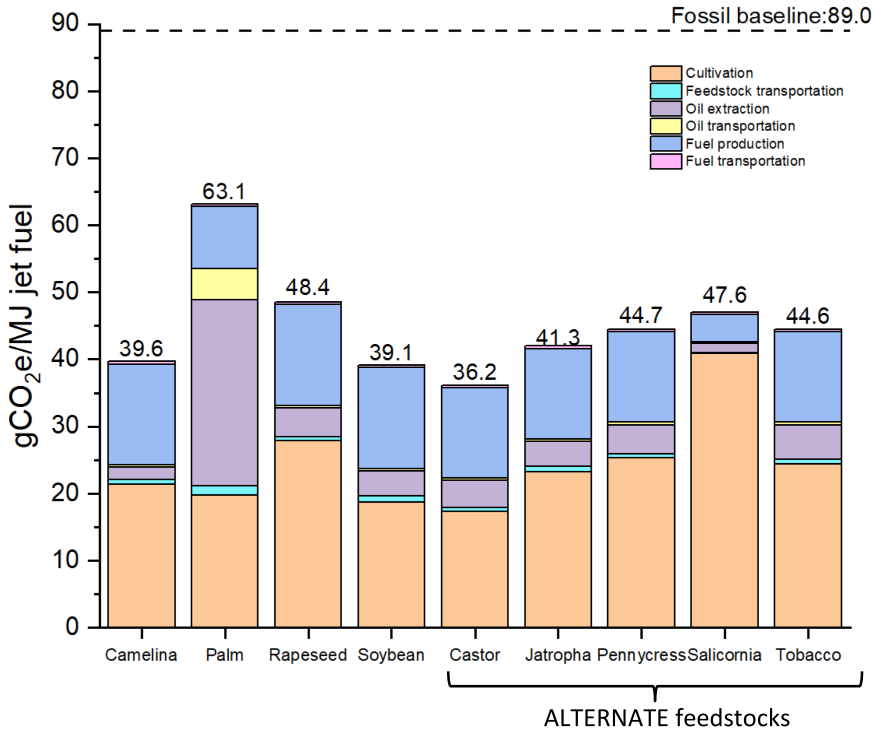
# Assumptions for DLUC estimation

- Assumptions taken to estimate DLUC emission factors per feedstock
- Secondary data on average yields, annual carbon sequestration and root-to-shoot ratios

| | 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 |
| 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.

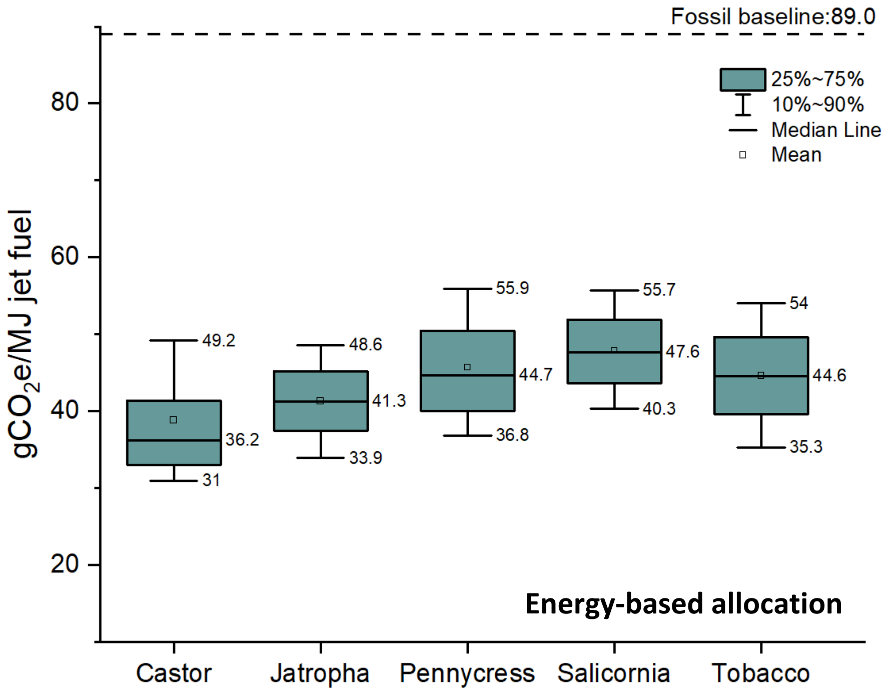
# Attributional results without land-use change




- The attributional LCA results for the ALTERNATE feedstocks show life cycle greenhouse gas emissions below the ICAO fossil-fuel baseline of 89.0 $gCO_2e/MJ$ (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.
- <u>The results show at least ±15 % variability</u>.
- Parameters such as **fertilizer and diesel use** for cultivation are the main reasons for variability.

PRELIMINARY RESULTS- PLEASE DO NOT CITE

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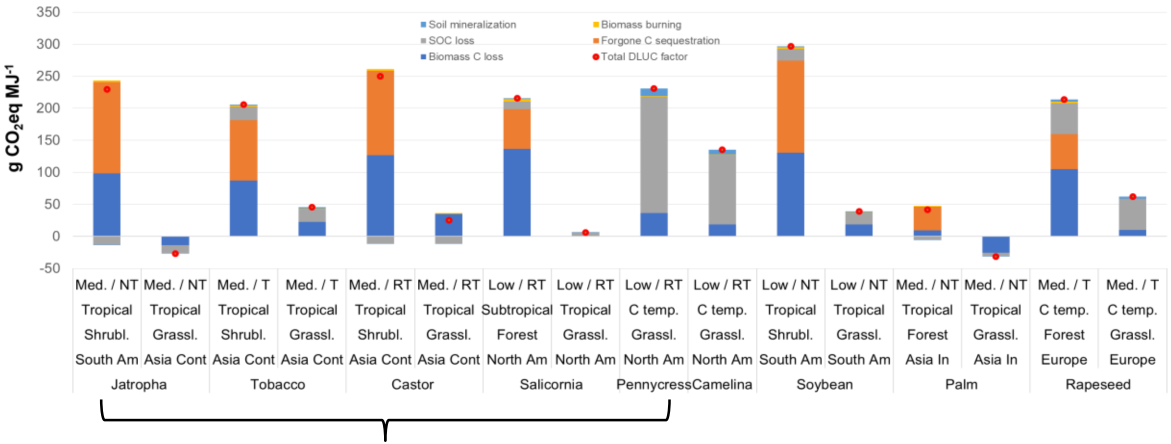
# Estimations of DLUC



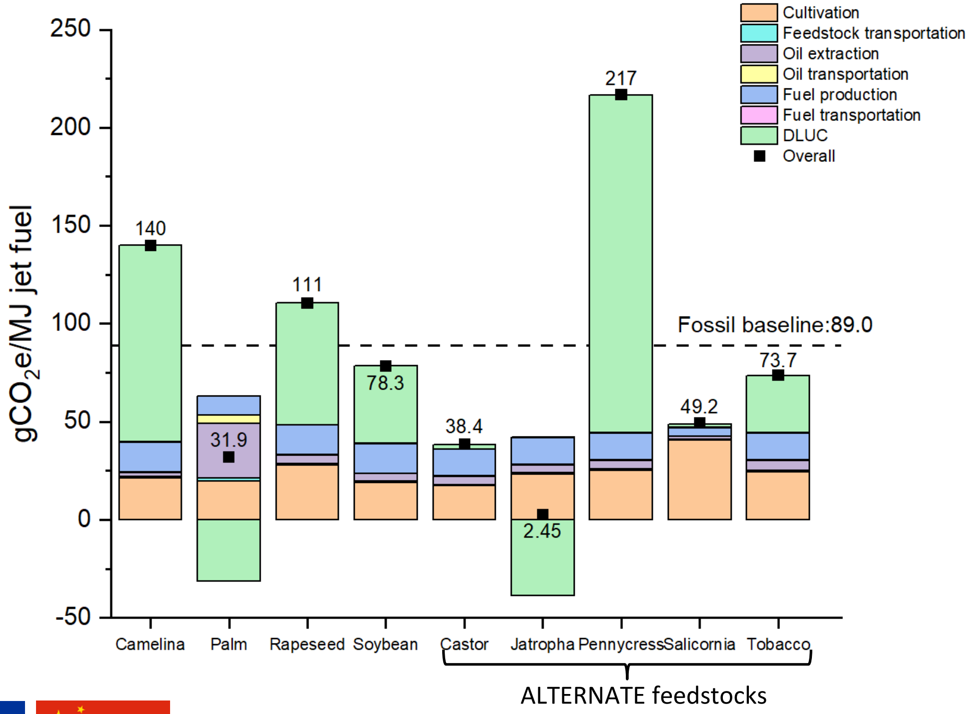

ALTERNATE feedstocks

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

- Scenario-specific DLUC emission factors for ALTERNATE feedstocks vs. reference CORSIA feedstocks are shown, taking 25 years as amortization time.
- Results show the emission differences from DLUC when different types of land are converted for the cultivation of crops for SAF production.
- <u>DLUC emission factors are high if forest or shrubland is converted for cultivation.</u>
- <u>Grassland and degraded grassland yield the lowest DLUC emission factors if they are converted into cropland.</u>

**PRELIMINARY RESULTS- PLEASE DO NOT CITE**

# Attributional results with DLUC




- Emissions including the impact from direct land use change are shown when **grassland or degraded grassland** is **used for the cultivation** of crops.
- **High DLUC emission factors** are due to **low seed yields** from the corresponding crops.
- Most of the ALTERNATE feedstocks are below the fossil baseline even when the land use change is factored in. At least 17% emissions savings are provided.
- **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 17% emissions savings.
- Monte-Carlo sampling displayed the extent of uncertainty within the results: at least ±15% variability and 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
- The importance of emissions from land use change is clearly visible in the overall results: Conversion of grassland/degraded grassland into cropland was shown to keep the overall emissions lower in most cases.
- The oil from most of the new crops investigated within this work are non-edible: No competition for food/feed sources.
- 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.

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