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Report

# OIL CROPS FOR SUSTAINABLE BIOMATERIALS

## Opportunities for current and future sustainable oil crop production: Exploring **Carinata** and **Coconut**

Günther Fischer, Sylvia Tramberend, Harrij van Velthuizen

July 2025

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## Exploring **Carinata** and **Coconut**

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## About the authors

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**Harrij van Velthuizen** is Guest Senior Research Scholar with the Biodiversity and Natural Resources Program at IIASA. He was member of the working group at the Food and Agriculture Organization of the United Nations (FAO) that developed the Agro-Ecological Zones (AEZ) methodology. Subsequently, he conducted AEZ assessments for regional, national, and sub-national level development planning for agriculture, bioenergy, forestry, and livestock production on behalf of UN agencies and International Research Organizations. At IIASA, he co-developed the global version of agro-ecological zoning methodology and related spatial natural resources databases, and he contributed to global, regional, and national agro-ecological studies covering domains of food security, climate change impact and sustainable biofuel production potentials. (Contact: velt@iiasa.ac.at)

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We thank the persons and institutions who provided highly valuable insight in coconut and carinata production systems, and support for specific steps in the agro-ecological analysis presented.

A core activity in this study has been the development of models for the potential production of plantations with coconut monocropping and coconut intercropping systems, and the production of Brassica carinata as a winter cover crop. The work has, in part, been relying on inputs from several agronomists/ experts with practical field experience.

We thank *Dr U. Surendran,* Principal Scientist at the Indian Council of Agricultural Research (ICAR) for sharing insights and data on coconut production systems in India, *Dr M. N. Eroy,* Senior Science Research Specialist and *Dr W. Mercullo*, Agronomist and Acting Division Chief of Agronomy, Soils and Farming Systems Division, both from the Philippine Coconut Authority - Davao Research Center (PCA-DRC) for sharing data and information on coconut research, including the Philippine National Standard Code of Good Agricultural Practices for Coconut.

Further, we thank *Dr. Rick Bennett*, R&D Leader of the Nuseed carinata breeding program, for an update on Nuseed's research on characteristics and environmental requirements of Carinata cultivars grown as winter cover crops in Argentina and Uruguay. This recent Nuseed carinata research has enabled further development of the AEZ carinata production simulation procedures.

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## Acronyms

| | |
|---|---|
| C | Carbon |
| CN | Carbon Neutral |
| CMIP6 | Coupled Model Intercomparison Project Phase 6 |
| dLUC | Direct land use changes |
| DM | Dry matter |
| FAO | Food and Agriculture Organization of the United Nations |
| FAOSTAT | FAO Statistical Databases |
| GAEZ | Global Agro-ecological Zoning Model |
| GAUL | Global Administrative Unit Layers |
| GCM | General circulation model |
| GHG | Greenhouse gas |
| GLWD | Global Wetland Database |
| GPCC | Global Precipitation Climatology Centre |
| HWSD | Harmonized World Soil Database |
| IPCC | Intergovernmental Panel On Climate Change |
| Mha | Million hectares |
| ms | Marginally suitable land (see Table 12) |
| MS | Moderately suitable land (see Table 12) |
| NS | Not suitable land |
| KBA | Key Biodiversity Areas |
| LCA | Life Cycle Assessment |
| LUT | Land Utilization Type |
| LYD | Lethal Yellowing Disease |
| IIASA | International Institute for Applied Systems Analysis |
| IPCC | International Panel on Climate Change |
| RCP | Representative Concentration Pathway |
| REMAIN | Remaining land once environmental and food sustainability criteria were addressed |
| REMAIN+ | Remaining land once environmental and food sustainability criteria were addressed, due to intercropping with fodder crops additional grass-/shrubland can be considered compared to REMAIN land. |
| RPR | Residue to Produce Ratio |
| RSB | Roundtable on Sustainable Biomaterials |
| S | Suitable land (see Table 12) |
| SDG | Sustainable Development Goal |
| SOC | Soil organic carbon |
| SSP | Shared Socio-economic Pathway |
| VS | Very suitable land (see Table 12) |
| VmS | Very marginally suitable land (see Table 12) |
| WDPA | World Database of Protected Areas |

# Abstract

Sustainable vegetable oil production is key to supplying the bioeconomy with raw material. As it is also a food ingredient, sustainable production options are urgently needed. This study uses the Roundtable on Sustainable Biomaterials (RSB) criteria as a guide to define sustainable production, and soil conservation principles inform the selection of the vegetable oil production systems and explores: i) coconut (as a single crop and in intercropping) in Southeast and South Asia and tropical regions of the Americas; and ii) carinata as a winter cover crop in Europe and the Americas. The RSB sustainability principles were formalized in several analytical steps accounting for land management, environmental protection, GHG emission savings and land quality. The Global Agro-ecological Zones (GAEZ) modelling framework is used to assess the sustainable vegetable oil production potential under current (2001-2020) and future (2050s) climates.

Carinata oil from winter fallow is concentrated in temperate regions. Countries with significant opportunities include Argentina, with an annual production potential of 15.9 Mt, followed by the USA (15.4 Mt), Spain (4.3 Mt), France (3.0 Mt) and Brazil (2.8 Mt), when cultivated on prime and good land under current climate. High prices can make moderately suitable land economically viable. In Argentina, this could increase production to 22.2 Mt, using almost two-thirds (64%) of current cropland. Climate change has a positive impact on carinata winter cover in North America and Western Europe. The acreage in southern USA suitable for growing carinata as a winter fallow could increase vegetable oil production up to 19.6 Mt by 2050s due to warmer temperatures and sufficient rainfall. Climate change has either no or a slight positive effect in South America.

Of the tropical regions examined in this study, the main production areas for coconut that meet sustainability criteria are in South America, Southeast Asia and South Asia. The type of sustainable coconut production strategy chosen depends on current land use patterns. In South America, unprotected grass- and shrubland could be used for coconut monocropping on REMAIN land, i.e., land that remains after environmental and food security criteria have been met. In South America today, up to 18.8 Mt (Tall coconut), 15.3 Mt (Hybrid coconut), or 10.5 Mt (Dwarf coconut) of vegetable oil could be produced annually using only the best quality land. Exploring coconut intercropping with fodder crops (only for Tall and Hybrid varieties), additional unprotected REMAIN land that is currently used for roaming livestock, increases production, in South America up to 22.1 Mt vegetable oil. A high cropland use of 40-60% in Southeast Asia, South Asia and Central America, leaves little room for coconut monocropping and intercropping with fodder crops. Rain-fed coconut intercropping can offer farmers the opportunity to grow coconut alongside cash crops (coffee, cocoa) or staple foods (banana/plantain). In Southeast Asia, intercropping Tall or Hybrid coconut with either of these crops is suitable on up to 13% of cropland, with vegetable oil potentials of between 11.8 Mt (Dwarf coconut) and 14.5 Mt (Tall coconut).

The impact of climate change on coconut production varies and depends on the scenario, location and coconut production system. For the ‘Sustainability’ Scenario, which assumes that global mean temperatures can be kept below 2 degrees Celsius, the impact on coconut production is relatively small. As climate change intensifies, the potential for coconut production drastically decreases. This is particularly noticeable in South America, where in the ‘Fossil-fueled development’ scenario, only 36% of current potentials (6.7 Mt) can be produced from coconut monocropping on REMAIN land, caused primarily by a decline in the Amazonian rainfall. The negative effects of climate change are lower for coconut intercropping systems and when moderate land qualities are also considered. However, intensifying climate change decreases vegetable oils even in intercropping production systems.

This study has compiled a comprehensive database of spatially explicit vegetable oil production potentials that meet strict sustainability criteria. Together with local data, this can serve as a guide for strategies to transform and adapt the vegetable oil sector to meet the demands of the future bioeconomy.

# 1. Introduction

Vegetable oil is used as edible and inedible oil. It is an important food ingredient for heating, cooking or improving flavor or texture. Vegetable oils are also used as an ingredient or component in many manufactured non-food products. The largest use by volume terms is in the production of biodiesel. It is also used in oleochemicals, cosmetics, soaps, perfumes, paints and wood treatment products.

Increase in vegetable oil production was more pronounced compared to many other agricultural commodities. During the past two decades global vegetable oil more than doubled from 112 Mt in 2000 to 246 Mt in 2020 (FAOSTAT, 2022). The main driver was a sharp increase in palm oil because of increasing demand for biodiesel. The bulk of global vegetable oil supply is from palm and soya bean, followed by rapeseed and sunflower (FAO, 2022).

Oil crops have the potential to replace fossil fuels and assist material and fuel suppliers in transitioning their supply chains and services to net-zero, making them a key feedstock of interest for the bioeconomy. The future production potential of oil crops is however dependent on several interrelated factors, such as the land suitability, the impact of climate change on agroclimatic conditions, and direct and indirect competition with land use to produce food, feed and non-food products. To assess the future potential of these crops as vegetable oil sources to meet the growing demand of the bioeconomy, a systems analysis approach is needed that analyses these interrelated factors across specific regions and crops.

This study aims to provide a realistic assessment of the production potential of selected vegetable oils for biomaterials in countries of the Americas, Europe and Southeast Asia. The assessment is based on latest available information and conforms to strict sustainability criteria considering the region's food and environmental safeguard requirements, as well as GHG life cycle assessment results of the considered biomaterials.

The sustainability constraints used for modelling oil crop production potential are operationalized following the criteria of the Roundtable on Sustainable Biomaterials (RSB), which is considered best-in-class in terms of sustainability standards for biomaterial developments (WWF, 2013). In addition, soil conservation principles inform the selection of the vegetable oil production systems. Against this background, the following oil crops and locations were selected for the analysis:

- Coconut (as single crop for monocropping and in intercropping with key cash and food crops) in Southeast Asia and tropical regions of Central and South America
- Carinata as winter cover crop in Europe, South America, and North America

The RSB sustainability principles were formalized in several analytical steps accounting for land management, environmental protection, GHG emission savings and land quality (2nd chapter). The Global Agro-ecological Zones (GAEZ) modelling framework is used for the land suitability assessment to assess the sustainable vegetable oil production potential under current (2001-2020) and future (2050s) climates. The parameterization in GAEZ for both selected oil crops was updated and extended. The novel consolidated land use database provides the backbone for the implementation of land-related sustainability criteria (3rd chapter).

Chapter 4 details the approach and data used for land sustainability considerations. Chapter 5 starts with an introduction of the assessment steps, introduces applied future scenario simulations, and explains details of the database generated. The last section land use balance highlights extents of cropland, shrubland and grassland that could potentially comply with sustainability criteria. The key results of the sustainable vegetable oil potential and required area needs are presented in Chapter 6 for carinata cultivated as winter cover crop and in Chapter 7 for coconut including intercropping. Chapter 8 concludes.

# 2. Sustainability principles

In order to ensure the sustainable potential of vegetable oil production, the study applies the well-recognized principles of the Roundtable on Sustainable Biomaterials in the context of sustainable agricultural production and land management of the selected vegetable oil crops.

## Roundtable on Sustainable Biomaterials (RSB)

The guiding principles for the sustainability assessment in this study are those developed by the Roundtable on Sustainable Biomaterials (RSB). The RSB is an independent and global multi-stakeholder coalition, which works to promote the sustainability of biomaterials, including biomass and biofuels (Box 1).

**Box 1. Roundtable on Sustainable Biomaterials (RSB) Recognition**

Together with the RSB membership community, the RSB has created a robust and credible sustainability framework, which is aligned with the United Nations' Sustainable Development Goals (SDGs). The RSB's sustainability framework has been recognized by NGOs, companies, and regulators including e.g., the WWF, IUCN and the Natural Resources Defense Council. It has been endorsed by the Sustainable Aviation Fuel Users Group for its high level of sustainability assurance and it is increasingly being requested by airlines as an essential part of their biofuel procurement. RSB has also been approved by the European Commission to demonstrate compliance with the sustainability requirements of the Renewable Energy Directive (EU RED). RSB-certified biofuel is therefore eligible for tax incentives and subsidies from EU governments seeking to meet their renewable fuel obligations imposed by the Renewable Energy Directive.

RSB enjoys the endorsement of the international NGO community, UN organizations and key stakeholders in the biofuels, biochemicals and bioplastics industries. For further information please visit https://rsb.org/

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

Specific biomass production projects can apply for and be approved for RSB certification. Obviously, some principles can only be evaluated at the project level of a specific production supply chain. For example, legality, human and labor rights, or land rights, must adhere to country-specific standards and can only be evaluated at the project level.

In contrast, some principles, such as food security (RSB Principle 6), the conservation of biodiversity and ecosystems (RSB Principle 7), the principle on irrigation water use (RSB Principle 9) or the reduction of greenhouse gas emissions (RSB Principle 3), can be applied at broad geographical scales and can be used to constrain estimates of potential crop cultivation to remain within these sustainability domains.

Such principles have been integrated into the vegetable oil assessment carried out in this study by defining the following constraints:

*Principle 3: Greenhouse gas emission saving*

- Exclude soils of high organic matter content from vegetable oil feedstock production

*Principle 6: Local food security*

- Prioritize cropland for food production
- Safeguard biomass from grassland/savannah required for feeding ruminant livestock

*Principle 7: Conservation*

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

*Principle 8: Soils*

- All steep terrain excluded from biomaterial production
- Biomaterial production follows principles of conservation agriculture

*Principle 9: Water regime*

- No irrigated biomaterial production

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

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

## Sustainable agricultural land management

Agricultural landscapes provide essential ecosystem services to a variety of stakeholders, making them crucial socio-ecological systems. Agriculture provides ingredients for food, feed, fiber and other non-food materials. The development of Carbon Neutral (CN) products is gaining momentum, as demonstrated by the World Economic Forum's recent 'Sustainable Development Impact Meeting[1]'. Carbon neutral products are those whose production, use and disposal do not result in additional carbon released into the atmosphere – a process that may require the use of C offsets. For vegetable oils used as ingredients for non-food commodities, CN products may be a comparative advantage in a world striving for sustainability and climate mitigation. Sustainable land management (SLM) will play a central role if agricultural crops are to contribute to CN products.

The World Overview of Conservation Approaches and Technologies (WOCAT[2]) global network defines SLM as the use of land resources - including soil, water, vegetation and animals - to produce goods and provide services to meet human needs, while ensuring the long-term productive potential of these resources and sustaining their environmental functions. Depending on intended agricultural produce and the biophysical context, SLM involves a range of sustainable practices that ultimately aim at the sustainable use of soil and water resources, which is economically feasible for farmers. Permanent soil cover, changing cropping patterns, integration between livestock management and crop systems, carbon sequestration, zero or minimum tillage, are important elements and are advocated by production systems such as multifunctional agriculture, regenerative agriculture, agroecology, or agroforestry. Soil management is central to all approaches, with the aim of preventing land degradation or even restoring degraded land back to fertile soils.

The importance of soils for carbon storage and biodiversity is increasingly being recognized for climate change mitigation and halting land degradation. Of the main land use categories, cropland is the most affected by human-induced land degradation, in particular irrigated cropland (Coppus, 2023). Soil and landscape degradation in agriculture contributes to global warming, decrease in soil productivity and yields for food, feed and non-food materials.

In many regions, soil fertility has been decreasing for decades, and large amounts of fertile soil have been (and continue to be) washed into rivers, lakes and oceans - gone forever, and with it, much carbon, originating from the oxidation of soil organic matter (SOM, commonly known as "humus"), has been released into the atmosphere in the form of $CO_2$, all of these with severe economic implications (UNEP, 2019).

When managing soils in agricultural production, the following principles are suggested for modern Conservation Agriculture systems (Derpsch et al., 2024; FAO, 2024a):

i) no or minimum soil disturbance (no- or reduced tillage)

ii) permanent crop biomass cover on the soil surface

iii) crop biodiversity in crop rotations and/or associations including cover crop mixes

For CN neutral products the soil carbon balance is of importance. The carbon balance of soils results from the rate of carbon supply in the form of crop residues, manure or other organic waste, minus the rate of carbon loss through decomposition. There is significant potential for carbon sequestration in

Cropland soils have a considerable potential for sequestering carbon, especially those with large yield gaps and/or large historic soil organic losses (Amelung et al., 2020). The latter, for example, due to land degradation, soil drainage, or conversion of soils high in organic carbon (histosols). Rewarding farmers with carbon credits

[1] from 18-22 September, 2023, https://www.weforum.org/events/sustainable-development-impact-meetings-2023/
[2] See https://www.wocat.net/en/. The WOCAT network compiles SLM knowledge and technologies.

for practices that increase soil carbon sinks is being discussed (Paustian et al., 2016). Others point out that soil organic carbon sequestration is only one piece in a large puzzle for achieving multiple soil functions (Moinet et al., 2023).

The vegetable oil crops selected in this study adhere to soil conservation principles as follows.

Carinata cultivated as a winter cover avoids otherwise bare soils during the fallow periods and uses existing cropland. Establishing carinata on otherwise fallow land will increase crop biodiversity, generate additional revenue for farmers, and improve conservation of nitrogen and water. Carinata can be planted into minimally tilled soil, or it may be no-till planted in standing stubble (Seepaul et al., 2023). The oil quality profile of carinata brassica includes a high percentage of erucic acid (40–45 %) making it highly desirable as a biofuel and for industrial applications such as production of plastics, lubricants, paints, leather tanning, soaps, and cosmetics (Kumar et al., 2020).

Coconut plantations are assumed to be established in accordance with good agricultural practices for coconut, such as those developed by the Philippine National Standard (BAFS, 2018).

> "*Recommended soil conservation measures such as minimum tillage, contour planting, crop rotation, cover cropping, green manuring, and mulching should be integrated in the coconut production practices to improve or maintain the soil structure and tilth and minimize soil compaction and erosion. Use of crop suitability maps to plan for intercropping and livestock integration is encouraged.*" (BAFS, 2018, p.12)

Although inter- and cover cropping are recommended, we also estimate the vegetable oil potential of coconut monocropping for reference. In compliance with the RSB land sustainability criteria, coconut monocropping will be restricted to land that remains once environmental and food sustainability criteria were addressed (REMAIN land). As a result, REMAIN land comprises of unprotected grass- and shrubland areas that are not used for feed of roaming ruminant livestock. We assume minimum tillage, resulting in low up-front carbon loss, when grasslands and shrublands are converted to coconut plantations.

One point of discussion is the sustainability of the potential use of cropland currently used for non-food crops (e.g., tobacco, natural rubber) for future coconut intercropping or monocropping. Former analysis shows that in 2010 some 12% or 178 Mha of global cropland were cultivated for the non-food sector including specialized industrial crops (e.g., cotton, tobacco, natural rubber), as well as other crops and livestock products intended for industrial use (e.g., biofuels, biopolymers, textiles, leather, and oleo-chemicals) (Tramberend et al., 2019).

Although there is potential for indirect land use change (ILUC), some of the current cropland used for non-food crops (e.g. tobacco) could in principle be used for the non-food vegetable oils considered in this study and still meet the RSB food security criteria. ILUC has been extensively discussed with the introduction of biofuels as it relates to the unintended consequence of releasing more carbon emissions due to land-use changes around the world induced by the expansion of cropland for ethanol or biodiesel production. In general, the greater the amount of land required for the alternative non-food-feed commodity, the more likely it is to induce ILUC. As only relatively small quantities of coconut and carinata oil will be needed to supply the oleochemical industry, we discuss here the potential, limitations and uncertainties of growing non-food vegetable oil on current cropland.

# 3. Methods and Data

## Global Agro-ecological Zones modelling framework

The Global Agro-ecological Zones (GAEZ) modelling framework is used to assess the sustainable vegetable oil production potentials for carinata and coconut under current (2001-2020) and future (2050s) climates (Box 2).

### Box 2. Global Agro-Ecological Zones modelling framework (GAEZ)

The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have implemented the Agro-Ecological Zones (AEZ) modelling framework and databases. This framework describes the agronomically possible upper limit to produce individual feedstocks under given agro-climatic, soil and terrain conditions for specific levels of agricultural inputs and management conditions.

The AEZ methodology was initially implemented in the 1980s to assess the capacity of the world's natural resources to meet the needs for food of a fast-growing global population. Rapid advancements in information technology have led to increasingly detailed and extensive global databases, enabling the first Global AEZ assessment (GAEZ) in 2000. GAEZ assessments have been conducted periodically. Since GAEZ version 3, all results of the assessment are available through publicly accessible Data Portals: (GAEZ v3; GAEZ v4; GAEZ v5)

The GAEZ modeling framework used for the assessment of sustainable vegetable oil feedstock cultivation potentials primarily used the most recent version 5. GAEZ v5 uses 2020 baseline data, including recent land cover, soil and terrain conditions, protected areas, renewable water resources, and livestock numbers. It applies climatic conditions for the historical period 1981–2020 and for a selection of future climate simulations using the latest IPCC AR6 climate model output from five Earth system models (ESMs) from the CMIP6 modelling experiments and for three different scenario pathways. The agro-edaphic soil evaluation uses procedures of GAEZv4.

#### Land suitability assessment

Variants in land quality combined with agronomic management determine crop cultivation potentials. The GAEZ 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. The chosen vegetable oil crops' suitability and production are assessed under baseline conditions and under the effects of climate change.

Figure 1 provides a comprehensive overview of the processing steps and data used in the GAEZ assessments.

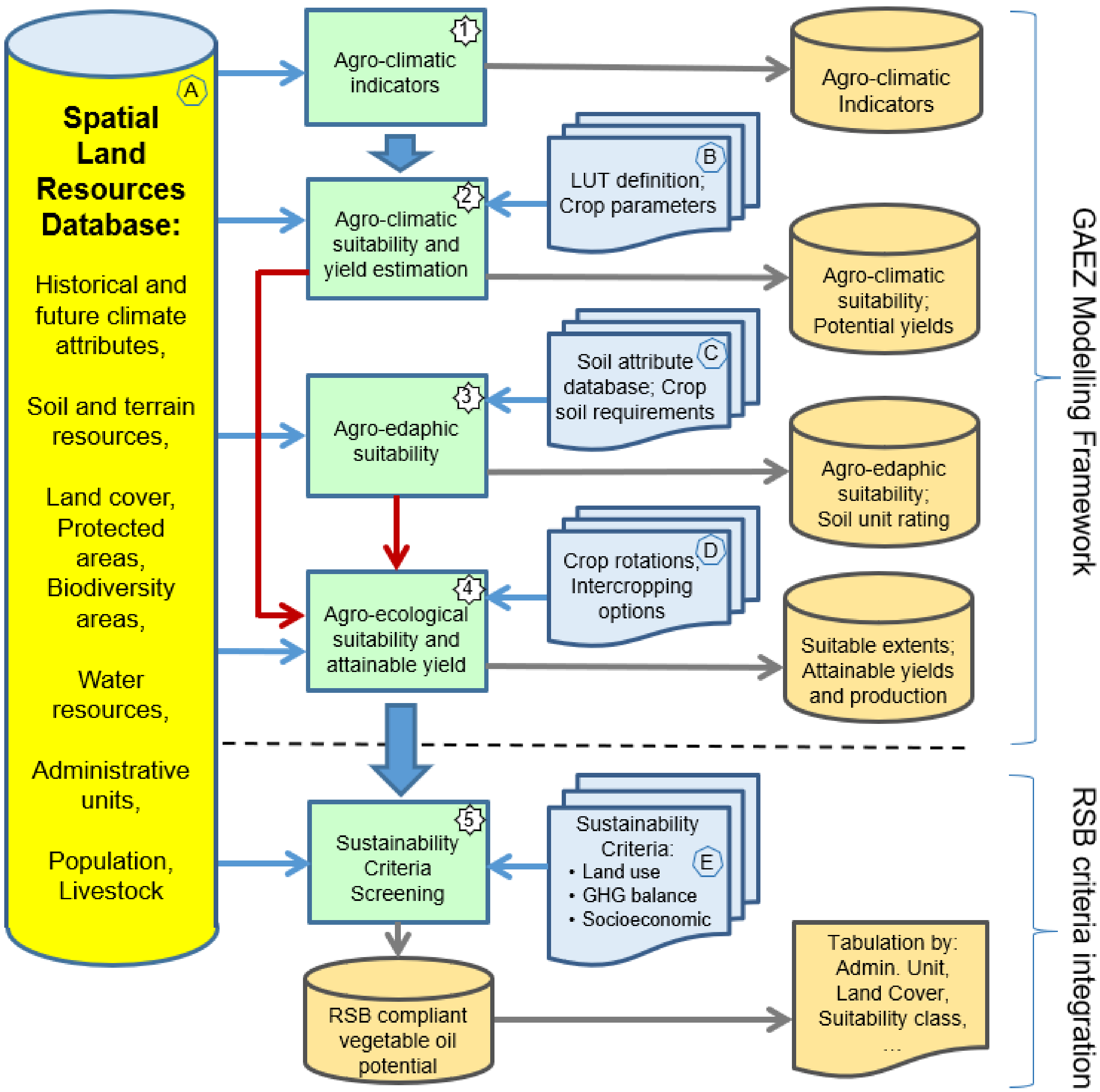
*Land Utilization Types (LUT):* The AEZ procedures have been used to derive potential biomass and yield estimates for rain-fed vegetable oil production by grid-cell. As this study is concerned with economic production at farm level, it assumes a high-level of inputs/advanced management.

High input refers to main socio-economic and agronomic/farm-management components, i.e., the farming system is (1) market oriented; (2) commercial production is a management objective, and (3) production is based on currently known and available cultivars, is mechanized with low labor intensity, and assumes adequate applications of nutrients and pest, disease and weed control.

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

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

*Figure 1. Overview of Agro-Ecological Zones model*



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.

Details of the novel LUTs developed for this study are described in the section below. They include carinata as winter cover crop, coconut monocropping and three types of coconut intercropping systems.

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 location. AEZ combines these two components systematically by successively modifying grid-cell specific agro-climatic potential yields according to assessed soil limitations and location specific terrain characteristics. An overview of the model structure and data integration is shown below.

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.

For the current study, two vegetable oil crops were selected for detailed assessment of their land suitability and production potentials compliant with the RSB sustainability criteria.

### Climate forcing data

GAEZ v5 uses daily data of six climate attributes describing weather conditions for past (1981-2022) and future conditions (2021-2100). The extensive climate database was derived from Copernicus AgERA5 data and the climate scenario data provided by the inter-sectoral impact model intercomparison project (ISI-MIP) (Warszawski et al., 2014).

For the Scenario Model Intercomparison Project (ScenarioMIP), the part of the international Coupled Model Intercomparison Project 6 (CMIP6) of the World Climate Research Programme (WCRP) that comprises scenario runs for the 21st century, a new set of scenarios has been developed. The new scenarios represent combinations of different socio-economic developments as well as different pathways of atmospheric greenhouse gas (GHG) concentrations, the latter is termed representative concentration pathways (RCPs) (Van Vuuren et al., 2011). RCPs are a set of greenhouse gas concentration trajectories developed for the climate modeling community as a basis for long-term and near-term modeling experiments adopted by the International Panel on Climate Change (IPCC).

Using a predefined subset of these scenarios, climate research institutes all over the world have performed climate change simulations for CMIP6 to serve as a basis for the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Masson-Delmotte et al., 2021).

Narratives of socio-economic developments have been developed for the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017). These descriptions of alternative futures of societal development span a range of possible worlds that stretch along two climate-change-related dimensions: mitigation and adaptation challenges. The SSPs reflect five different developments of the world that are characterized by varying levels of global challenges, see (Riahi et al., 2017) for an overview.

Unlike the original RCPs used in CMIP5, the new SSP-based scenarios provide economic and social reasons for the assumed emission pathways and changes in land use. The denomination of individual scenarios comprises the name of the basic socioeconomic pathway followed by two numerals indicating the additional radiative forcing achieved by the year 2100 (in units of tenths of watts), as follows:

*SSP5-RCP8.5*: With an additional radiative forcing of 8.5 W/m² by the year 2100, this scenario represents the upper boundary of the range of scenarios described in the literature. It can be understood as an update of the CMIP5 scenario RCP8.5, now combined with socioeconomic reasons. This scenario has been termed 'Fossil-Fueled Development'.

SSP3-RCP7.0: With 7 W/m² by the year 2100, this scenario is in the upper-middle part of the full range of scenarios. It was newly introduced after the RCP scenarios, closing the gap between RCP6.0 and RCP8.5.

SSP2-RCP4.5: As an update to scenario RCP4.5, SSP245 with an additional radiative forcing of 4.5 W/m² by the year 2100 represents the medium pathway of future greenhouse gas emissions. This scenario assumes that climate protection measures are being taken.

SSP1-RCP2.6: This scenario with 2.6 W/m² by the year 2100 is a remake of the optimistic scenario RCP2.6 and was designed with the aim of simulating a development that is compatible with the 2°C target. This scenario assumes that effective climate protection measures are being taken. SSP1 is referred to as 'Sustainability', and in this study SSP1-RCP2.6 (ssp126) is also referred to as 'Sustainability'.

For GAEZ v5 calculations used in this study, the bias-corrected CMIP6 climate forcing is used provided in ISIMIP3b for historical, SSP1-RCP2.6 (ssp126), SSP3-RCP7.0 (ssp370) and SSP5-RCP8.5 (ssp585) conditions.

Following a performance assessment in the historical period and considering completeness of data provided from climate simulations both for land and ocean, five models were selected as primary input data: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL (Lange, 2019, 2021).

The five climate models are considered a good choice because they are structurally independent in terms of their ocean and atmosphere model components and because their process representation is considered by experts to be fair (IPSL-CM6A-LR, MPI-ESM1-2-HR) to good (GFDL-ESM4, MRI-ESM2-0, UKESM1-0-LL). In terms of climate sensitivity, the five primary models are good representatives of the whole CMIP6 ensemble as they include three models with low climate sensitivity (GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0) and two models with high climate sensitivity (IPSL-CM6A-LR, UKESM1-0-LL).

# Vegetable oil crops

## Brassica carinata

Brassica carinata (Ethiopian or Abyssinian Mustard), referred to as carinata, 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). Carinata was cultivated as a food crop in regions of Africa. The plant is originally cultivated as a leafy vegetable (Ferraris et al. 2019). Carinata vegetable oil is being investigated for the development of aviation fuel. In 2012 a first jet flight was made with biofuel produced from carinata.

Carinata is reported to be successfully grown on relative marginal land, it responds well to added nutrients (nitrogen-sulphur-phosphorous), provided good soil moisture availability prevails. Rotations or combinations with soybean, groundnut, maize, and possibly wheat, barley, peas and lentils are recommended (In Argentina 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 carinata should ideally be grown only every four years in the same field.

**Produce and use of the carinata feedstock**

| Feedstock | Produce | Intermediate product | End product | Potential uses |
|---|---|---|---|---|
| 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 |

Under conventional production a preventative fungicide is applied for pest and disease treatment, mainly for combatting sclerotinia, which is currently the most serious fungal disease threat to reducing yield potential in carinata. Most fields do not require much pesticide application, these are applied as needed to mainly combat harmful insect populations. Under organic production sclerotinia is dealt with through appropriate rotations, improved soil drainage and soil health increasing measures. No pesticide is applied.

*Brassica carinata belongs to C3 plants (including C3 I and C3 II cultivars).*

*C3 I cultivars (spring and winter crops) are characterized with optimum photosynthesis and growth at temperatures between 15 ºC – 20 ºC; maximum growth rates between 20-30 g $m^{-2}day^{-1}$. Operative temperatures range between 5 ºC-30 ºC. C3 I cultivars are adapted to temperate and subtropical winter rainfall zones. Temperatures substantially above 30 ºC lead to lower photosynthesis and heat stress both leading to substantial lower yields.*

*C3 II cultivars (non-hibernating winter crops) are characterized with optimum photosynthesis and growth at temperatures between 15ºC-25ºC with maximum growth rates between 30-35g m-2day -1. Operative temperatures range between 10 ºC-35 ºC. C3 II cultivars are adapted subtropical and tropical zones with cool or moderately cool winter temperatures. Temperatures above 35 ºC lead to lower photosynthesis and heat stress both leading to substantial lower yields.*

NUSEED (https://nuseed.com) 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., 2016). NUSEED confirms these yield levels have also been achieved in Uruguay in small plot testing.

### Carinata Land Utilization Types

Spring carinata is a short to moderate duration annual crop which grows well in temperate and sub-tropical climates. In temperate zones, spring carinata may be grown as soon as mean temperatures exceed 5ºC (Canadian Food Inspection Agency, 2017). In subtropical areas carinata can be grown through the winter, without hibernation with longer growth cycles (Seepaul *et al.,* 2016). Accordingly, we use three different carinata varieties for the analysis, namely: Spring carinata (SP) grown between spring and summer with durations between 105 and 150 days and Sub-tropical varieties, suitable as winter fallow cover crop, growing from autumn to spring, one variety adapted to growing in cool winter temperatures (ST) with longer durations between 165 and 210 days[3], and a 'rabi' variety (RB) adapted to moderately cool winter temperatures with durations between 135 and 150 days.

Ten different 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 (5-15ºC) 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 (5-20ºC) with growth cycles of 135 and 150 days.

For the assessment of suitability and productivity high level inputs* and advanced management are assumed[4].

** 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 while minimum or zero tillage is applied, where possible with low labor intensity and uses strictly controlled applications of nutrients and chemical pest, disease and weed control.*

### 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.

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[3] NUSEED further reports that although plant development slows down during the cool winter periods, hibernating has not been observed. In fact, current carinata varieties are moderately susceptible to frost damage. Therefore, unlike winter rape, hibernating cultivars of carinata have ***not*** been considered in the AEZ analysis.

[4] Requirements and tolerances of 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.

Monoculture practices associated with 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 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 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 carinata cultivation.

## Coconut mono- and intercropping

Conventional production of coconut uses high yielding Tall cultivars, Dwarf cultivars and Hybrids with different rotation lengths and canopy heights. The GAEZ modelling assumes the following rotation periods and canopy height: i) Tall varieties: 80 years rotation growing up to 30 meters; ii) Hybrid: 50 years, up to 20 meters; and iii) Dwarf: 40 years, up to 7 meters.

Coconut plantations have several stages of production, starting with transplanting to flowering, followed by an early, mid and late production stage. Each has different canopy heights and yields, with the most productive being in the middle stages (Table 1). During early-stage light transmission decreases to a minimum, during mid-stage light transmission remains at low levels, and finally during late-stage light transmission increases (about linear) with age due to increasing height, leaf senescence and pruning.

*Table 1. Length and canopy height for different coconut production stages*

| | **Transplanting to Flowering** | | **Early Production Stage** | | **Mid Production Stage** | | **Late Production Stage** | |
|---|---|---|---|---|---|---|---|---|
| | Period (years) | Canopy height | Period (years) | Canopy height | Period (years) | Canopy height | Period (years) | Canopy height |
| **TALL** | 0-5/6 | 1 – 5 m | 5/6 - 15 | 5 – 15 m | 15 – 35 | 15-20 m | 35 - 80 | 20 – 30 m |
| **HYBRID** | 0-5 | 1 – 4 m | 5 - 12 | 4 -10 m | 12 – 25 | 10-15 m | 25 - 50 | 15 – 20 m |
| **DWARF** | 0-4 | 1 – 2 m | 4 - 10 | 2 – 4 m | 10 – 20 | 4 – 6 m | 20 - 40 | 6 – 7 m |

Coconut is suitable for intercropping with fruit crops, vegetable crops, spices, roots and tubers, cereals and legumes. The AEZ assessment includes the following crops, which could be cultivated in intercropping systems: Banana/plantain, citrus, cocoa, cassava, sweet potato, yams, maize, sorghum, millet, groundnut, soybean, pigeon pea, and cowpea. Examples of intercropping systems include:

a) Dwarf coconut intercropped with banana/plantain;

b) Hybrid coconut with as understory robusta coffee, and

c) Tall coconut with as understory cocoa or robusta coffee.

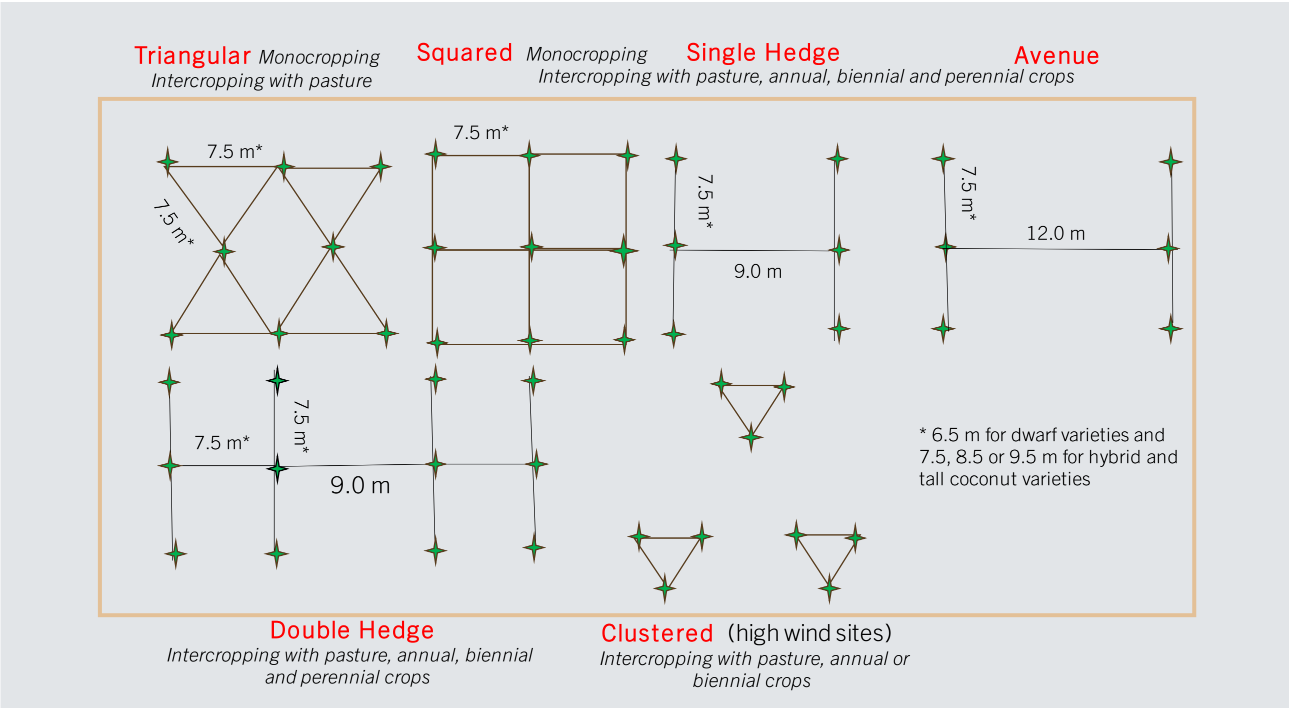
Understory crops must be able to cope with shading. The leaf area of coconut (and available light for understory crops) changes with variety, age and development of coconut canopy.

Coconut plantations, Tall and Hybrid varieties at mature stages, are suitable for introducing understory species for pasture production and livestock grazing. AEZ models are available for: pasture grasses, pasture grasses and pasture legume mix; napier grass, and brachiaria grass. Note, pasture productivity decreases with increasing density and shading of coconut.

The following three coconut varieties—Tall, Hybrid, and Dwarf—with varying plantation designs (6 schemes) and spacing (4 distances) have been taken into consideration:

There is a single plantation spacing for Dwarf coconut of 6.5 m, whereas Tall and Hybrid varieties may have three spacings of 7.5 m, 8.5 m, and 9.5 m. Note, the spacing of rainfed coconut is mainly mandated by the rainfall regime at a location. In areas with annual rainfall below 1600 mm a spacing of 9.5 m is used. In areas with well distributed rainfall exceeding 2000 mm or where irrigation is available, a planting distance of 7.5 m can be used. Plantation schemes of various geometries have been tested and are being applied (Figure 2).

*Figure 2. Layout characteristics for coconut plantations*




The use of different layouts depends on coconut variety, intercropping needs as well as plantation protection and stability need in areas of high winds. Differences in planting distances and plantation layout result in substantial differences in the number of coconut trees per hectares, ranging from 88 trees/ha when using an avenue layout and a spacing of 9.5m to 272 trees/ha for Dwarf coconuts planted in a triangular layout at 6.5 m. About 10 to 12.5 m$^2$ around each palm tree is unavailable for intercropping. Depending on planting density, some 75-90% of the area can be used for intercrops.

## Harvest Index

Number of nuts per palm tree are reported to range between 50 and 200 depending on variety and environmental factors such as amount and distribution of rainfall. Typically, one thousand mature coconuts weigh about 1440 kg and yield about 170 kg of copra (12-17%) from which around 70 liter of coconut oil can be extracted (i.e., 5-7 %). Harvest indexes for copra and vegetable oil needs attention, Hi is to reflect attainable (farm) plantation yields assuming high inputs and advanced management. To be further verified/adjusted by variety with research and extension data.

### Selected coconut intercropping systems

In discussion with the RSB experts, potential coconut intercropping systems include (Table 2).

For the first-order assessment presented in this study, we evaluate

i) Coconut intercropping with fodder crops and

ii) Coconut intercropping with a combination of cash crops and one key staple food, notably banana/plantain as an important staple food.

*Table 2. Examples of coconut intercropping systems agreed with RSB experts*

| | Coconut intercropping with | | |
|---|---|---|---|
| | **Fodder crops** | **Food crops** | **Cash crops** |
| **Selected crops** | Brachiaria grasses, napier grass, pasture grasses & grass legumes | Maize, cassava, sweet potato, banana/plantain, yams | Coffee, cocoa |
| **Selection criteria** | Digestible Energy | Economic (price weight) | Economic (price weight) |
| **Land use considered (RSB compliant)** | Unprotected grass-/shrubland with current livestock | Rainfed cropland | Rainfed cropland with current cash crops |
| **Co-benefit** | Food security, Farm income | Food security, Farm income | Farm income |

## Consolidated land use database

Information on current land use/cover, in particular cropland and forest area, is needed to assess and monitor the sustainability of agriculture at local, regional and planetary scales. Information on cropland area with national or sub-national detail is currently available as:

i) Statistics of agricultural land use, collected from countries by UN-FAO and disseminated in FAOSTAT.

ii) National statistics compiled by individual countries for sub-national (e.g., state or province) administrative units.

iii) High-resolution land cover maps produced from remote sensing.

### High resolution global land use layer

The calibration of a cropland layer for use in GAEZ v5 started from analyzing six global land cover products for circa 2020, which included cropland maps derived from ESRI (Karra et al., 2021), FROM-GLC (Zhao et al., 2021), GLAD-Map (Potapov et al., 2022), GLC-FCS30 (Zhang et al., 2021), GLOBELAND30 (Chen et al., 2015) and WORLDCOVER (Zanaga et al., 2021).

The analysis of the agreement between the six high-resolution maps of cropland was conducted in FAO-ESS (Tubiello et al., 2023) by assigning a value of 1 to pixels containing cropland classes and 0 to non-cropland classes. Individual results were combined by creating pixels with values between 0 (no cropland for all datasets, agreement class AC_0) and 6 (cropland in every dataset, agreement class AC_6).

The extents of each agreement class AC_0 to AC_6 wer then computed by spatial administrative units at country level for comparison with land use statistics from FAOSTAT. Hence, the cropland calibration starts from assembling for each spatial allocation unit *k* (i.e., country) the cropland target value $A^k_{crop}$ as reported in FAOSTAT (FAOSTAT, 2022) and the respective extents of each agreement class $AC^k_j$, j=1,...,6.

Let $p^k$ denote the (unobserved) probability of correctly classifying actual cropland as cropland class in the land cover products and $P^k_j$ the probability that a pixel in class $AC^k_j$ is correctly assigned as cropland, then decay factor z gives the reduction in the probability that a pixel in class $AC^k_{j-1}$ as compared to in class $AC^k_j$. We note that

$z^k = \frac{AC^k_{j-1}}{AC^k_j} = (1-p)/p$ for all j.

We use this relationship among pixels in the different agreement classes to specify a calibration equation for spatial allocation unit k:

$$A^k_{crop} = \sum_{j=1}^{n} c^k_j \, AC^k_j$$

where $c^k_j = (z^k)^{n-j}$ for j=1,...,n (here n=6).

A similar approach was followed to derive a calibrated layer of tree-covered areas from the forest classes provided in the high-resolution land cover datasets. As for cropland, the calibration is performed such that the calibrated raster results in total forest extents to match the average of 2018-2020 reported by the UN Food and Agriculture Organization in FAOSTAT.

A global map of the calibrated cropland and tree-covered layers are shown in Figure 3 and Figure 4.

The consolidated high-resolution land use/cover layers were used to produce distributions of the original data in each 30 arc-second (about 1x1 km) grid-cell for 11 aggregated land use classes (Table 3). Each land cover class is represented as percentage cover in a 30 arc-second grid cell.

*Table 3. Land use/cover classes used in GAEZ v5*

| Major Land use/cover class | Notes |
|---|---|
| **Built-up land, artificial cover** | Urban areas, transportation infrastructure, industrial sites, etc. |
| **Cropland** | Arable land and land under permanent crops, calibrated to national statistics of 2018-2020 |
| **Grassland** | Pastures, rangelands and natural grassland; shrubs/herbaceous cover, regularly flooded |
| **Tree-covered areas** | Calibrated to national forest land statistics of 2018-2020 |
| **Shrubland/Savanna** | Shrub-covered areas |
| **Tree-covered, regularly flooded, saline** | Mangroves, tree-covered areas flooded with saline water |
| **Lichen and mosses** | Natural vegetation, mostly in boreal areas |
| **Bare or sparsely vegetated land** | Bare or sparsely vegetated |
| **Permanent snow, glacier** | Areas of glaciers or permanent snow cover |
| **Water** | Rivers, lakes, reservoirs |

*Figure 3. Spatial distribution of cropland, circa 2020 (% of land)*

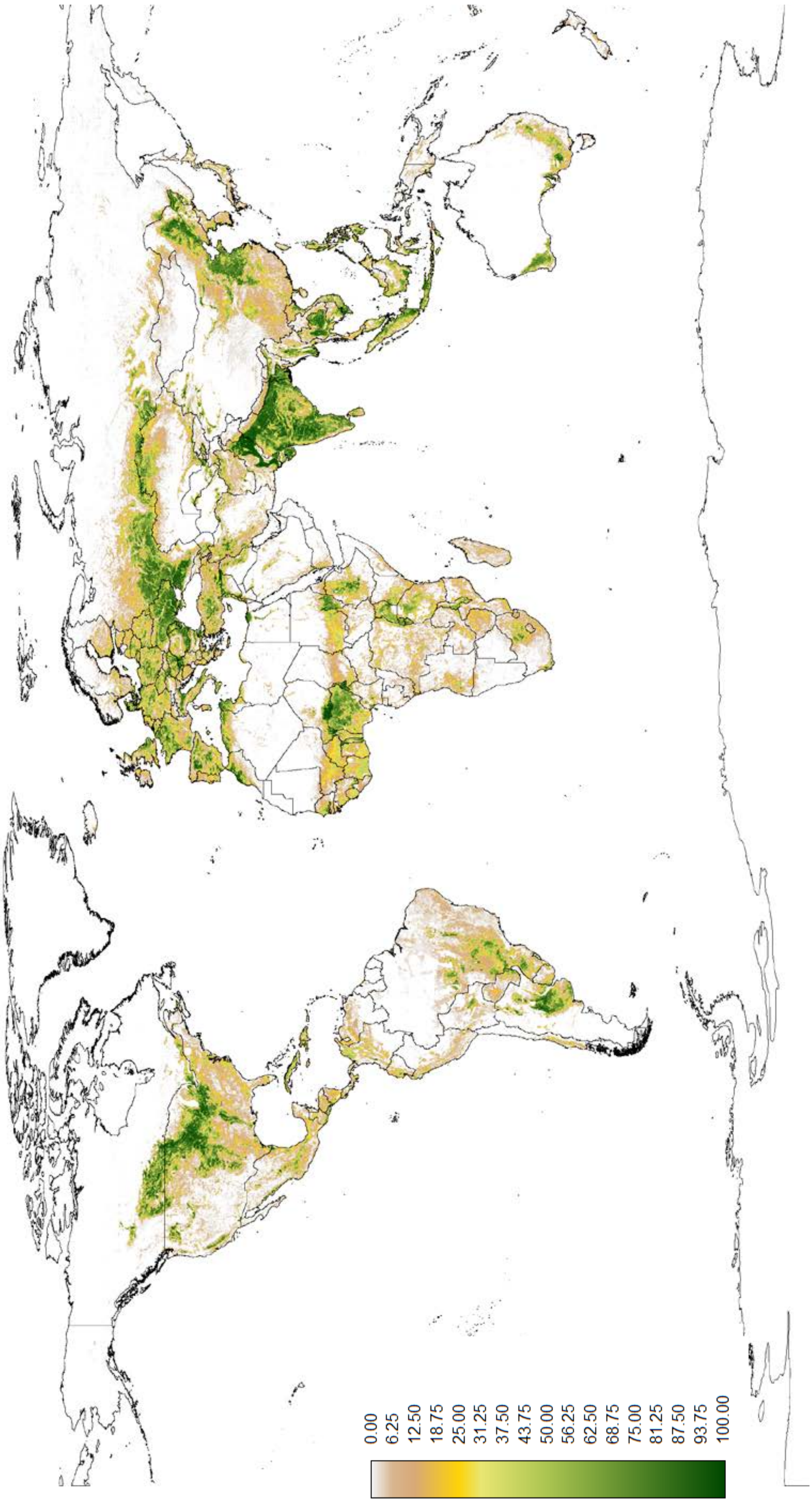
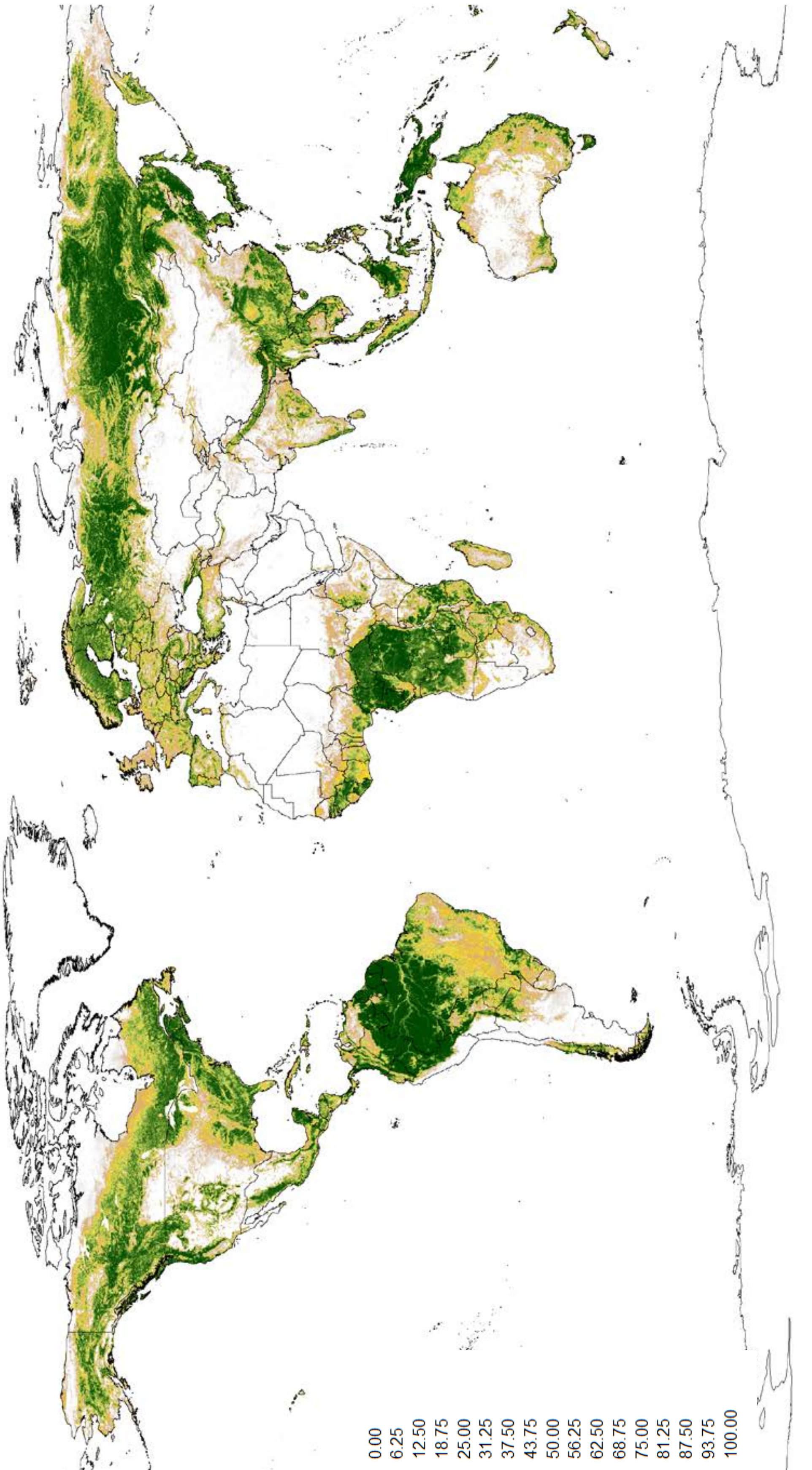


*Figure 4. Spatial distribution of tree-covered land, circa 2020 (% of land)*



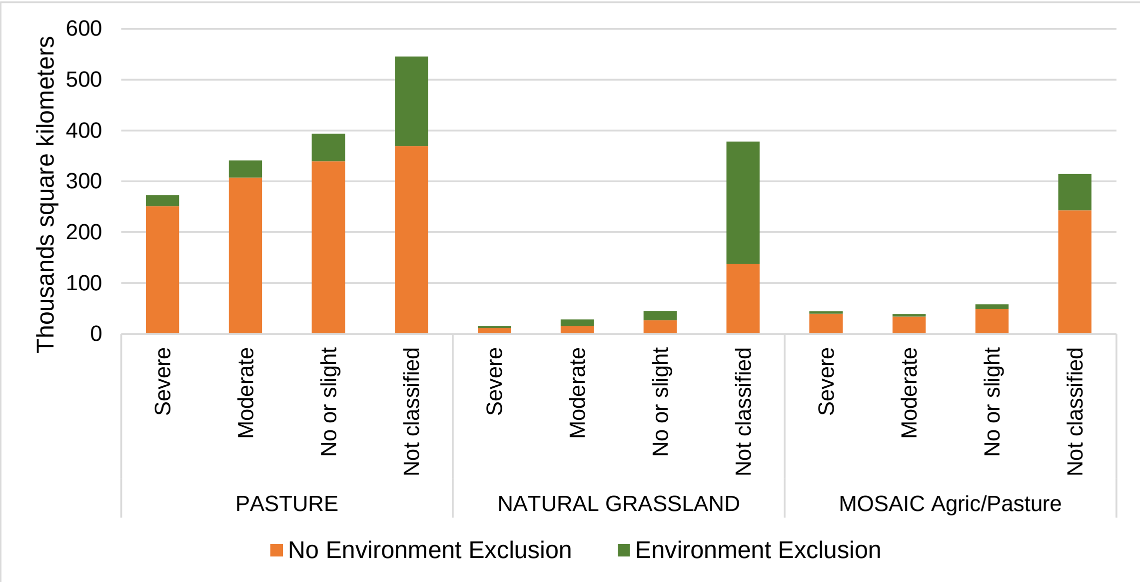
**Brazil – Degraded pastureland**

In the case of Brazil data on degraded pastures are available, which makes it possible to assess the potential cultivation of oil crops by degradation status.

The Mapbiomas pasture quality data[5] 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 into the South America land use database compiled for this study.

Figure 5 shows the distribution of degradation and environment protection for the land use classes potentially considered for oil crop production. 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'.

*Figure 5. Land degradation database of Brazil*




Source: Adapted from Mapbiomas

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 areas were classified as degraded. As expected, 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.

[5] 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/

# 4. Land sustainability considerations

## Excluded ecologically sensitive areas

Protected areas and areas and regions 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[1]) | www.protectplanet.net[1] (IUCN and UNEP-WCMC, 2016) |
| 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 (IUCN, 2016) |
| CIFOR Global Wetlands Map 2016[2] | (Gumbricht et al., 2017) www.cifor.org/global-wetlands/ |
| Global Wetland Database (GLWD) Level 3 (used for areas where CIFOR Wetland is not available) | (Lehner and Döll, 2004) |
| Forest, Mangroves & Wetland is > 50% in 30 arc-second grid cell of land cover/use map | See section land use |

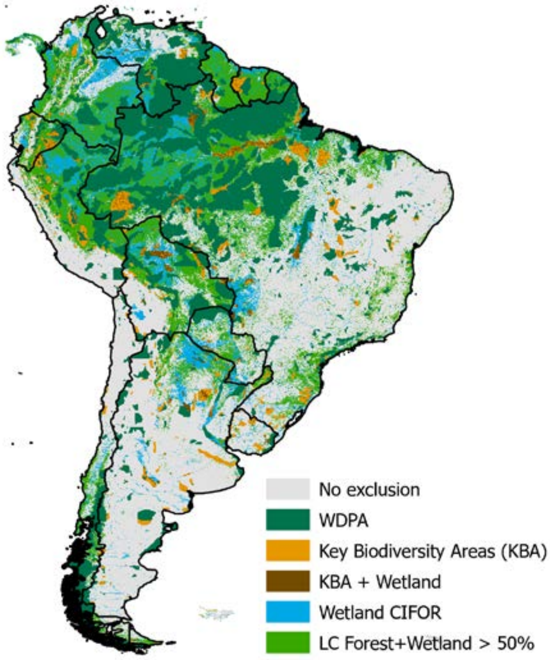
**1** WDPA provides monthly updates. Data access in February 2021; **2** The CIFOR Global Wetlands Map covers the tropics and subtropics regions (40° N to 60° S; 180° E to -180° W), excluding small islands.

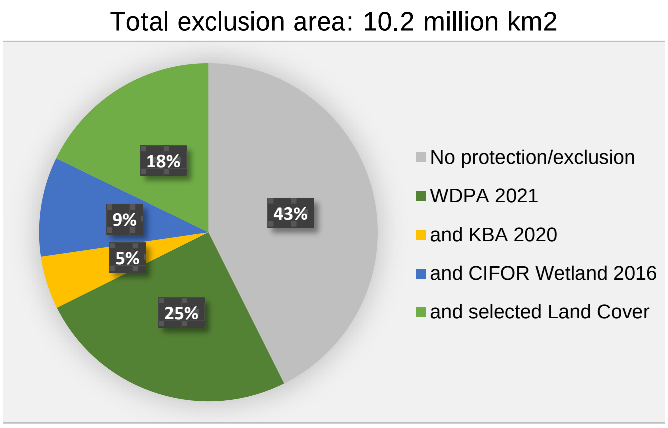
Figure 6 presents the example of South America including a map chart based on the 30-arc second environment exclusion layer. Note, the map has been compiled by sequentially adding data domains as listed in Table 4. The map does not show overlaps of different environmental data domains. Thus, some areas showing WDPA may as well be listed in the KBA data base.

Large areas in South America are of importance for the environment and biodiversity and are therefore not considered here for potential oil crop production. Areas mapped in the World Database of Protected Areas, as Key Biodiversity Areas or in the latest CIFOR wetlands cover 7 mio 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 mio km$^2$ to the environment exclusion layer. In total, at least 10.2 mio km$^2$ (57%) of South America's land is ecologically sensitive and therefore not considered for oil crop production.

Half of the ecologically sensitive aera is in Brazil (4.9 mio 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%) is excluded. In Argentina and Uruguay only 30% and 32% are designated for their environmental importance and therefore excluded.

*Figure 6. South America Environment Exclusion Layer*

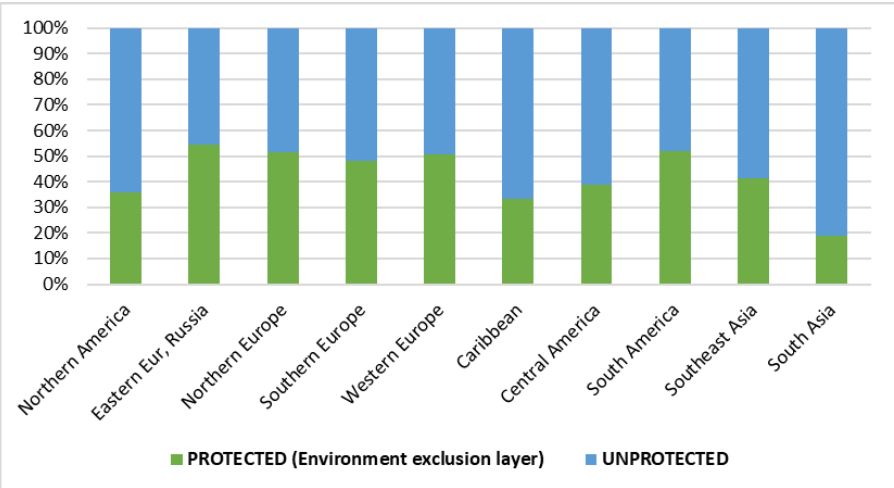



Note, the figures show successive exclusion of different data sources. *WDPA 2021*: Protected area recorded in WDPA 2021; *and KBA 2020*: Exclusion due to presence in KBA 2020, but not in WDPA 2021; *and CIFOR Wetland 2016*: Exclusion due to CIFOR Wetland 2016, but no presence in KBA 2020 and WDPA 2021; *and selected Land Cover*: Exclusion due to 'Forest+Mangrove+Wetland' exceeding 50% of grid cell in LC share, but no presence in KBA 2020 and WDPA 2021

Figure 7 highlights the extents of protected areas in the regions investigated in this study. Forests are the dominant land use class in protected areas. Today, in Europe and South America, just over one half of the land area has some designation for the conservation of the environment and biodiversity. In South Asia only one fifth (19%) of the land has an environment protection designation.

*Figure 7. Distribution of protected and unprotected areas, by major region*



## Ruminant livestock feed and REMAIN land estimation

Complying with the RSB principle (6) to safeguard local food security entails to safeguard 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 are intercropping systems which assume the dual use of land for grazing animals and vegetable oil production (see above section 'Coconut production systems').

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 (GLW3) is a spatial dataset (Gilbert et al., 2018) that shows the global distribution of the major types of livestock (cattle, sheep, goats, pigs, chickens, horses, buffalo, ducks). The methodology followed in the data compilation is described in Gilbert et al., 2018. Original livestock data are reported in heads of cattle, sheep, goats and other animals per grid-cell and have been converted to "Livestock Units" (LU). A measure of the carrying capacity of ruminant livestock, based on the productivity of grassland and shrubland, supplemented by available residues from cropland, was used to estimate the grazing land requirements for livestock.

Details of the calculations applied to determine the share of grassland/shrub land considered unavailable 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:

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

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 (Figure 8) is derived from GLW4 (Gilbert et al., 2022) 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:

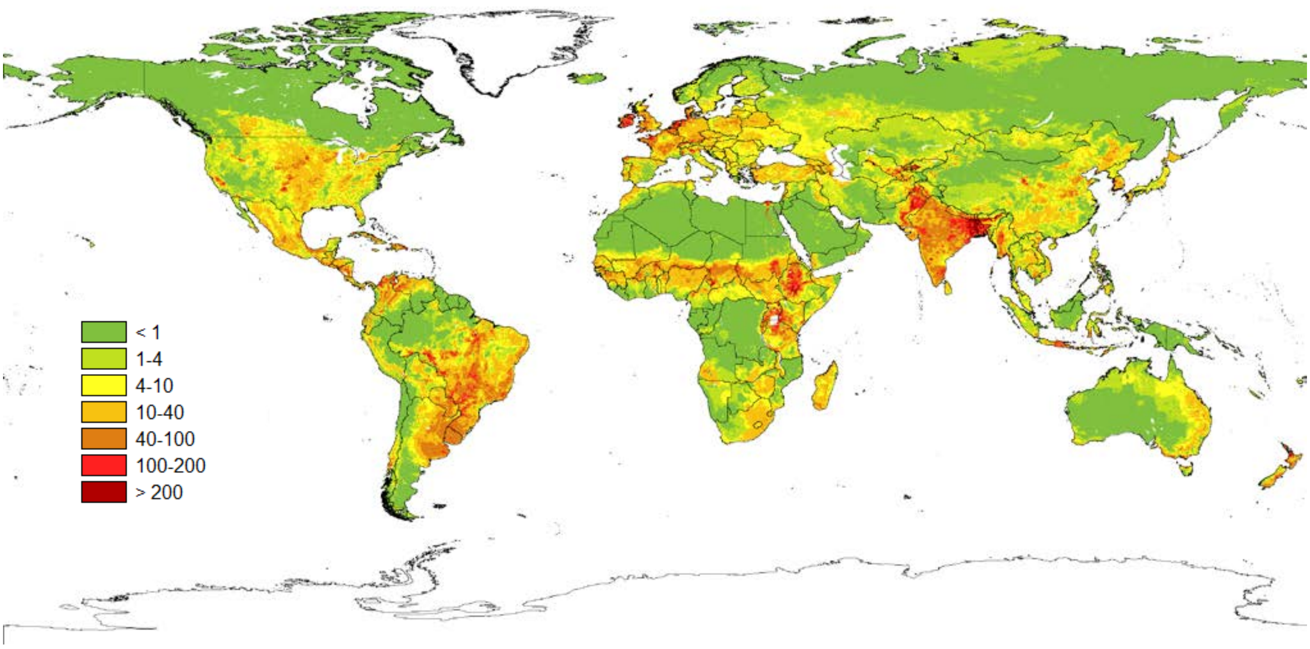
$$F_{sup} = Y_{grass} * f_{util} * A * (s_{Gr} + \alpha * s_{Sh} + \beta * s_{Cr})$$

where

| | |
|---|---|
| $F_{sup}$ | Forage feed supply [tDM] |
| 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] |
| $\alpha$ | forage yield in shrub land relative to potential grass yield [dimensionless] |
| $\beta$ | 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.

*Figure 8. Distribution of Cattle in 2015*




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

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 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).

As an example, the map in Figure 9 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 9. Livestock pasture requirement factor in 2010 in South America*

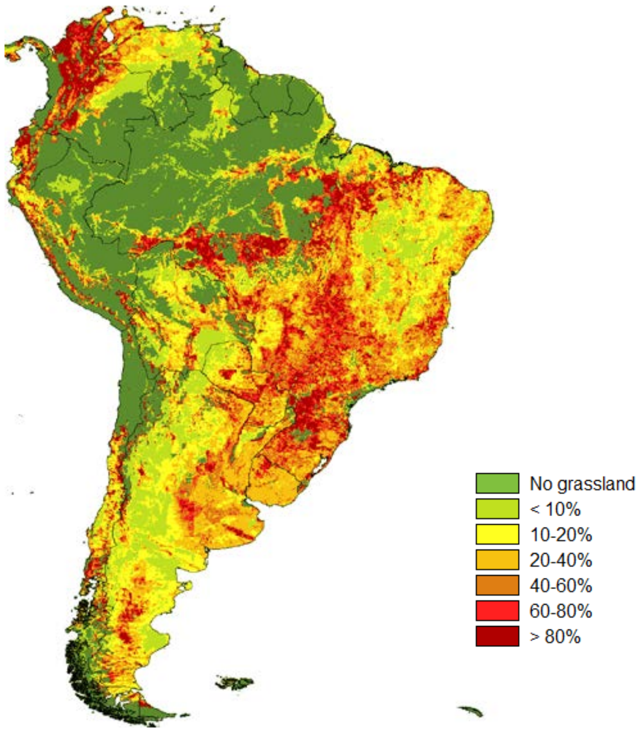


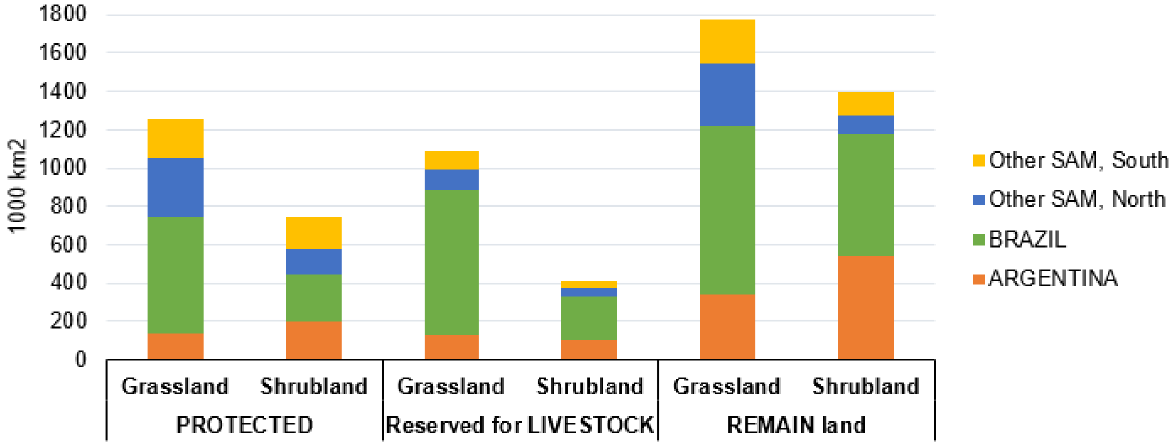

Table 5 and Figure 10 present a land use balance for grass- and shrubland of South America using the methods described above. Almost one third (2.0 mio. km$^2$) of South America's total 6.7 grass-/shrubland mio km$^2$ is protected and therefore not considered for vegetable oil production. Some of it 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, remaining land (termed REMAIN land) of 3.27 mio km$^2$ is explored for potential vegetable oil production.

*Table 5. 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** |

Depending on cropping system, food security 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.

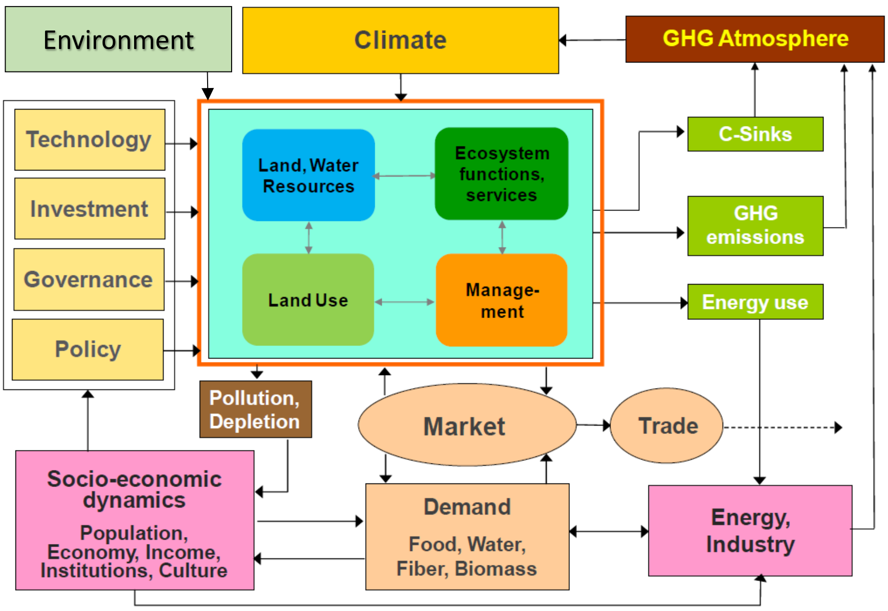
*Figure 10. Grass-/shrubland in South America, protected, reserved for livestock feed and REMAIN land*




## Non-food-feed cropland

As food, feed and energy feedstock markets integrate more closely, both challenges and opportunities arise. Moreover, the agricultural production system is embedded in a dynamic socio-economic, environmental and cultural setting. Understanding the key linkages (Figure 11) within this setting is important for evaluating the possible consequences and indirect effects of alternative policy options for adapting agriculture to changing economic and environmental conditions.

*Figure 11. Key components of agricultural systems in a socio-economic and environmental setting*




*Source: adapted from Fischer, 2011*

The transition to a low-carbon economy with biomass as one of its energy sources will intensify the energy-agriculture linkage and add a new dimension to agricultural systems, heighten resource competition in the food system, and may provide new opportunities for rural communities (Prieler et al., 2013). In the global efforts to reduce human carbon footprints, in addition to the energy sector, there is a need for all industries to source their products from non-fossil materials.

Although cultivated in much smaller quantities than in the food and feed sector, farmers produce a variety of industrial crops (i.e., defined as non-food, non-feed crops). Table 6 lists the global harvested area of non-food industrial crops and the major producing countries. The largest areas of cropland used exclusively for industrial purposes are to produce cotton and natural rubber. Tobacco and fiber crops are other industrial crops reported by FAOSTAT. Together, these industrial crops account for 3.6% (51 Mha) of global harvested areas (1442 Mha) in 2019-2021.

*Table 6. Global harvested areas of non-food industrial crops and main producing countries, 2019-21*

| Industrial Crop | Harvested area | Major producing countries |
|---|---|---|
| Cotton | 33.1 Mha | India (13.2), United States (4.0), China (3.2), Pakistan (2.2), Brazil (1.5), Uzbekistan (1.0), Benin (0.7), Burkina Faso (0.6),…. |
| Natural rubber | 12.8 Mha | Indonesia (3.7), Thailand (3.3), Malaysia (1.1), China (0.7), Vietnam (0.7), Cote d'Ivoire (0.5), Nigeria (0.3), India (0.3), Myanmar (0.3) |
| Tobacco | 3.2 Mha | China (1.0), India (0.43), Brazil (0.35), Indonesia (0.2), Malawi (0.1), …. |
| Jute | 1.3 Mha | Bangladesh (0.7), India (0.6) |
| Other* | 0.9 Mha | |
| Total | **51 Mha** | |

** Here a variety of fiber crops (e.g. Flax, Sisal, Abaca, Kenaf) and pyrethrum flowers is included*

*Source: FAOSTAT*

In addition to specialized industrialized crops, agricultural commodities may be cultivated for the dual or triple purpose of food, feed, and industrial use. For example, today some 16% of global maize production is used for industrial purposes. Significant amounts of vegetable oils are used for non-food purposes, i.e., 53% of palm oil, 46% of soya bean oil, and 52% of rapeseed oil. Sugar cane is another commodity used for food, feed and industry.

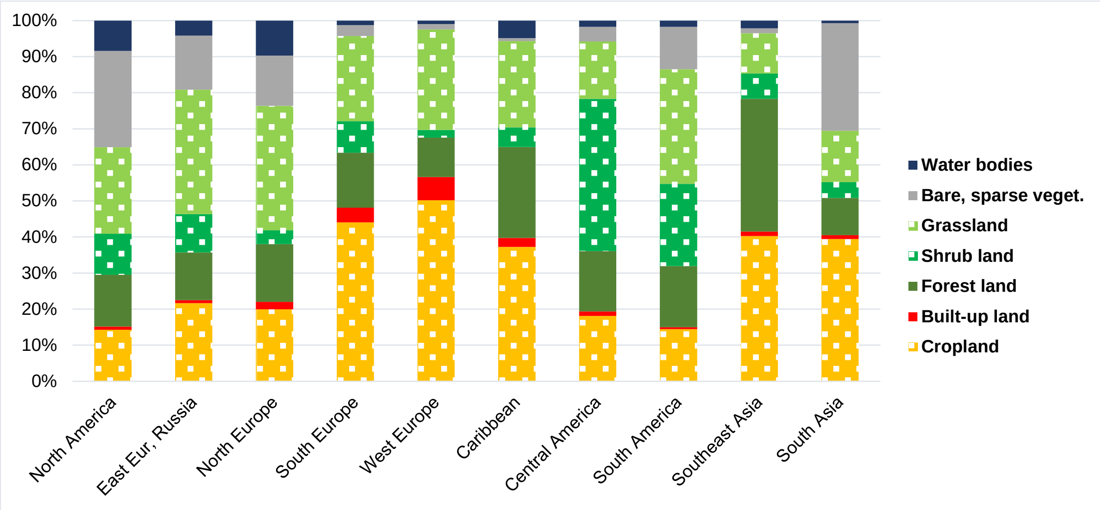
Over the past few decades, the utilization of cropland has shifted towards a greater importance being place on the non-food sector. The utilization of commodities derived from non-food industrial crops grown on cropland varies across regions and has increased over time. Previous analyses suggest that the appropriation of cropland by the non-food sector increased steadily from 132 Mha (8.7% of global cropland) in 1995 to 178 Mha (11.7% of global cropland) by 2010 (Tramberend et al., 2019).

## Land use and permitted production systems

Carinata and Coconut production potentials are tabulated for all GAEZ land use/cover classes (Table 3) and their ecological protection status as defined in the environment exclusion layer (Table 4), the latter termed 'unprotected'.

Figure 12 shows the distribution of unprotected land use classes for the regions explored in this study. In South and Central America and in North and Europe including Russia more than half of total unprotected land is grassland or shrubland. In South and Western Europe and South and Southeast Asia cropland is the dominant land use.

*Figure 12. Distribution of unprotected land use classes explored in this study, by major region*




The authors together with expertise from RSB have selected a sub-set of land use/cover classes for the identification of sustainable production systems (Table 7 and Table 8).

*Table 7. Land considerations for sustainable carinata and coconut production, Part I*

| Land use/cover class | Sustainability considerations |
|---|---|
| Built-up land, artificial cover | Not applicable |
| Cropland | See Table 8 below |
| Grassland, Rangeland | See Table 8 below |
| Tree-covered areas | EXCLUDE |
| Shrubland/Savanna | See Table 8 below |
| Tree-covered, regularly flooded, saline | EXCLUDE |
| Lichen and mosses | EXCLUDE |
| Bare/sparse vegetation | Economic production not possible |
| Permanent snow, glacier | Not applicable |
| Water bodies | Not applicable |

*Table 8. Land considerations for sustainable carinata and coconut production, Part II*

| | Cropland, rainfed | Grassland | Shrubland/Savanna |
|---|---|---|---|
| **Carinata** | as winter fallow crop | EXCLUDE | EXCLUDE |
| **Coconut monocropping** | On current non-food-feed areas[1] | UNPROTECTED REMAIN[1] land | UNPROTECTED REMAIN land |
| **Coconut intercropping**[2] with | | | |
| **Fodder crops** | EXCLUDE | UNPROTECTED | UNPROTECTED |
| **Food crops**[3] | On current non-irrigated cropland | UNPROTECTED REMAIN land | UNPROTECTED REMAIN land |
| **Cash crops**[4] | On current cash-crop areas | UNPROTECTED REMAIN land | UNPROTECTED REMAIN land |

**1** REMAIN land refers to areas that are not needed for the food sector, i.e. areas which are needed for roaming livestock (grazing ruminants) are excluded; **2** Intercrops are described in section above: Tall and Hybrid varieties of coconut plantations are suitable for introducing understory species for pasture production and livestock grazing; **3** Annual staple food crops, e.g. banana/plantain, yams, maize, cassava; **4** Coconut with understory cocoa or robusta coffee.

For compliance with the RSB land-related sustainability criteria, protected areas and all forest land must be excluded. We exclude all tree-covered areas (forests) including regularly flooded areas because these are important carbon sinks and any conversion to agricultural land would contribute to global warming. Lichen and mosses are mostly natural vegetation including areas of high carbon stocks such as swamps and bogs and are therefore excluded.

Built-up land, bare or sparse vegetation and water bodies are not suitable for agricultural production. Thus, unprotected shrubland and grassland could potentially be used for monocropping coconut. Cropland is explored for carinata cultivation as winter cover-crop and defined coconut intercropping systems. In other areas agricultural production is not possible (urban areas, snow, water) or economically feasible (spare vegetation, flooded shrubland. This leaves cropland, grassland and shrubland for further investigation.

Depending on the chosen oil crop management system, different land use restrictions apply. Note, some cropland has a designation status for environment protection in the Environment Exclusion Layer. Because it is already in use for crop production, we include protected cropland areas in the analysis. Table 8 summarizes the defined guidelines and land considerations for different production systems.

Table 9 summarizes extents of cropland, shrub- and grassland by major region. Depending on region between 16% and 53% of shrub- and grassland are protected and therefore safeguarded for environmental reasons. For the remaining unprotected grass-shrubland areas, it is being investigated whether they are needed as fodder for ruminant livestock. Once all the land-related sustainability criteria have been met, these areas are assessed for the quality of the land of the selected crops.

*Table 9. Environment exclusion for cropland, shrubland and grassland, by major region*

| | | CROPLAND | SHRUBLAND | | | GRASSLAND | | |
|---|---|---|---|---|---|---|---|---|
| | *1000 km$^2$* | **Total** | **Protected*** | **Un-protected** | **Total** | **Protected** | **Un-protected** | **Total** |
| **11** | North America | 1,990 | 396 | 1,556 | 1,952 | 757 | 3,264 | 4,021 |
| **21** | East Eur, Russia | 1,973 | 396 | 894 | 1,291 | 1,408 | 2,911 | 4,319 |
| **22** | North Europe | 189 | 12 | 33 | 46 | 156 | 302 | 458 |
| **23** | South Europe | 372 | 47 | 60 | 107 | 122 | 161 | 283 |
| **24** | Western Europe | 347 | 13 | 12 | 25 | 145 | 151 | 296 |
| **31** | Caribbean | 61 | 3 | 8 | 11 | 11 | 37 | 48 |
| **32** | Central America | 301 | 133 | 641 | 773 | 55 | 240 | 295 |
| **41** | South America | 1,322 | 669 | 1,957 | 2,626 | 843 | 2,731 | 3,574 |
| **81** | Southeast Asia | 1,228 | 68 | 186 | 254 | 108 | 294 | 403 |
| **82** | South Asia | 2,396 | 58 | 241 | 299 | 147 | 776 | 923 |

* Extent of areas included in the 'Environment Exclusion Layer' described above (Table 4)

# 5. Results overview and database

## Assessment steps

For the estimation of sustainable vegetable oil potentials, the sustainability principles outlined above were formalized in several analytical steps, summarized in Table 10.

*Table 10. Overview of assessment steps for the estimation of sustainable vegetable oil potentials*

| Step | Perspective / Theme | RSB principle |
|---|---|---|
| | **Land use and management** | |
| 1 | Exclude cropland[1] for food production | 6 Food security |
| 2 | Exclude all forest land | 7 Conservation<br>3 GHG emissions |
| 3 | Exclude areas providing critical ecosystem services and high biodiversity value | 7 Conservation<br>8 Soil<br>9 Water |
| 4 | Exclude built-up, water, bare and sparsely vegetated areas | Not applicable |
| 5 | Exclude areas with soils of high organic matter content | 3 GHG emissions<br>8 Soil |
| 6 | Set aside land for feed requirements of ruminant livestock | 6 Food security |
| 7 | Exclude grid-cells with low remaining land share[2] | Not applicable |
| → | Estimate "REMAIN(ing) land[3]" | |
| 8 | Compile share of cropland used for non-food-feed purposes | 6 Food security |
| → | Estimate national share of non-food-feed cropland | |
| | **Land suitability and production potentials** | |
| 9 | Assess land quality for selected vegetable oil crops using GAEZ | Not applicable |
| → | Vegetable oil potentials:<br>Carinata winter cover, from cropland<br>Coconut monocropping, from REMAIN land<br>Coconut intercropping with food, feed & cash crops | |
| 10 | Umbrella crop for coconut mono- and intercropping | Not applicable |
| → | Vegetable oil potential for coconut | |
| | **GHG savings** | |
| 11 | Estimate direct land use change GHG and agriculture LCA emissions | 3 GHG emissions |

**1** Cropland includes arable land and land under permanent crops cultivated for food and feed crop production. Some cropland areas are already cultivated for non-food crops (e.g., cotton, natural rubber, tobacco). **2** To achieve a viable scale of operation required for economic farm management and commercial feedstock production, we excluded grid-cells where remaining land (after steps 1-6) is less than 10% of the 5x5 arc-minute grid-cell. **3** Land remaining once food and environmental sustainability criteria have been addressed; henceforth termed 'REMAIN land'. **4** An 'Umbrella crop' determines the preferred crop in an area where more than one crop qualify for production, here coconut monocropping and three types of intercropping. Selection criteria is the amount of vegetable oil produced in a grid-cell.

RSB sustainability criteria, notably land related criteria, together with biophysical land quality determine the technical potential for the cultivation of vegetable oils. The RSB land-related criteria suggest that unprotected grassland and shrubland that are not utilized as feed by grazing cattle may be considered to produce vegetable oil. These remaining land areas once environmental and food security criteria were addressed, we term 'REMAIN' land (Step 1-7).

Because the vegetable oils investigated for this study are destined to be used for the non-food sector, we also record cropland currently used for non-food commodities (Step 8). Please refer also to the related discussion at the end of Section 2.

Using the GAEZ modelling framework, we calculate land suitability and production potentials for a geospatial grid with a resolution of 30 arc-seconds (approximately 1 x 1 km). A few variables maintain sub-grid cell distributions, e.g., land use, soil information, and terrain slope. In principle the calculations operate across the entire land areas. However, only areas complying with defined sustainability criteria, as outlined in Step 1-8, represent sustainable vegetable oil production potential.

In the case of coconut monocropping and intercropping, in specific locations, it may be possible to produce more than one of the selected crops. For example, in some sub-tropical regions all selected cash/food crops (robusta coffee, cocoa, banana/plantain) may be suitable for production. The GAEZ uses the concept of an '*umbrella crop*', which determines the preferred crop in areas where more than one crop qualifies for production. The selection criteria could be yield (tons), economic value ($), energy yield (GJ), food calories (cal), or a combination of some of these.

Since the focus of this assessment is to estimate a sustainable vegetable oil potential for biomaterials, we select vegetable oil volume (kg) as the decision criterion where multiple crops are viable in each location. Thus, if more than one coconut land utilization type complies with the sustainability criteria in a specific grid-cell, the one that produces the greatest amount of vegetable oil is selected.

The assessment's results present the extent and quality of land resources for the selected oil crops production potentials that meet the RSB sustainability criteria, notably the land-related criteria. Estimates are presented for current climate conditions (2001-2020 average) and future climates (20-year averages around the 2030s and 2050s).

## Administrative units

This study applies the Global Administrative Unit Layers (GAUL) distributed by the Food and Agricultural Organization of the United Nations. Original GAUL 2014 polygons were converted to a 30 arc-second grid database for aggregation and reporting of data.

For presenting results, we tabulate grid-level data by major regions and country-level administrative units. Table 11 summarizes the administrative units selected for this study in Asia, America, and Europe. For the large countries (Argentina, Brazil, India, Indonesia, Russian Federation, Canada, USA) state or province level results are also tabulated. The study here presents mainly aggregate results by major regions. Specific country-level and sub-regional analysis can be conducted in follow-up studies.

*Table 11. Administrative units selected for tabulation of results*

| Major Region | # | **Country,** in brackets number of **province/states sub-units** where available |
|---|---|---|
| **ASIA** | | |
| Southeast Asia | 81 | Brunei Darussalam, Cambodia, **Indonesia** (33 states), Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Thailand, Timor-Leste, Viet Nam |
| South Asia | 82 | Afghanistan, Bangladesh, Bhutan, **India** (34 states), Iran (Islamic Republic of), Nepal, Pakistan, Sri Lanka |
| **EUROPE** | | |
| East Europe and North Asia | 21 | Belarus, Bulgaria, Czech Republic, Hungary, Moldova Rep., Poland, Romania, **Russian Federation** (90 oblast), Slovak Republic, Ukraine |
| North Europe | 22 | Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, UK |
| South Europe | 23 | Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Montenegro, North Macedonia, Portugal, Serbia, Slovenia, Spain |
| Western Europe | 24 | Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland |
| **AMERICAS** | | |
| North America | 11 | **Canada** (13 states), **United States of America** (50 states) |
| Caribbean | 31 | Antigua and Barbuda, Bahamas, Barbados, Cuba, Dominica, Dominican Republic, Guadeloupe, Haiti, Jamaica, Martinique (Fr.), Puerto Rico, Saint Lucia, Trinidad and Tobago, Turks and Caicos Isl (UK) |
| Central America | 32 | Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama |
| South America | 41 | **Argentina** [Province-level data (24 provinces[1])]; **Brazil** [Province-level (27 provinces[2])], Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname, French Guiana, Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname, French Guiana |

**1** Provinces of ARGENTINA: 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** States of BRAZIL: 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

## Climate forcing

The main results are presented for current (2001-2020) and future climates. Suitability and yield impacts of the climate forcing levels of the RCPs selected for the scenarios were analyzed based on spatial data from the IPCC's AR6 CMIP6 process, data bias-corrected and downscaled to 0.5 degree in the Inter-sectoral Impact Model Inter-comparison Project (ISIMIP3).

Outputs from five Earth System Models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) and for three Scenarios (SSP126, SSP370 and SSP585) – a total of 15 GCM/Scenario combinations of respectively RCPs and climate models – were employed to compile daily climate data for use as input in GAEZ v5, for year-by-year analysis and for average conditions in the 2030s (2021-2040), 2050s (2041-2060), the 2070s (2061-2080) and the end of this century (2081-2100).

RSB compliant scenarios are being assessed for current and future 20-year average climatic conditions. GAEZ was forced with historic (average 2001-2020) and future (average 2021-2040, 2041-2060) climate scenarios represented by the level of radiative forcing of the climate system as characterized by the selected scenarios.

SSP126 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. SSP126 is often referred to as the 'Sustainability' scenario. Two other scenarios, SSP370 ('Regional Rivalry') and SSP585 ('Fossil-fueled development') represent increasingly stronger climatic change. SSP585 represents the 'worst case' upper boundary of scenarios described in the literature.

Although climate variability and extremes can have a significant impact on vegetable oil production in individual years, this study aims to explore aggregate trends and therefore generally forces the modelling system with 20-year average climate conditions taken from the bias-corrected CMIP6 climate model projections available from the ISIMIP3 process (Lange, 2021).

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). In the scenarios crop yields are generally quantified with and without $CO_2$ 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 2041-2060) amount to 443 ppm compared to 540 ppm for RCP8.5 and 390 ppm in 2010. Because the plant stimulating $CO_2$ fertilization effect is uncertain, we here only present results without $CO_2$ fertilization effect.

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 vegetable oils 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.

## Land suitability and productivity

GAEZ reports the distribution of land quality for various crop cultivation expressed in terms of agronomically attainable crop yields and grouped in five suitability classes.

Farm economics depend on the relationship between input costs for labour and agro-inputs (seeds, fertilizer, pest, disease and weeds control and energy for mechanized field operations and investment costs) and achievable crop yields and prices. Experience has shown that economic production is feasible on prime and good land where achievable yields are respectively 80-100% and 60-80% of maximum attainable yields. Moderately suitable land, where 40-60% of the best yields can be achieved, is often not economically viable for commercial production. However, it may become so in the case of high commodity demand, which results in 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 12 summarizes the land quality classification used in GAEZ.

From a farm-economic perspective, very suitable (VS) and suitable (S) land is well suited for commercial feedstock production. Economic production conditions on moderately suitable land (MS) may be risky and would likely depend on product prices being high. Henceforth we use the term 'prime and good land' for VS and S land, and 'moderate land' for MS extents. Also, note that the designation of suitability is not an attribute of physical land per se but always applies to a combination of land and land utilization type (LUT; crop cultivated under a certain management assumption).

Because of farm economics, this study considers mainly prime and good land, i.e., very suitable (VS) and suitable (S) land qualities for vegetable oil production. To give an indication, in case of higher demand and increasing prices, in addition moderate suitable land (MS) may become viable for production.

*Table 12. Land suitability classes reported in GAEZ*

| Acronym | Suitability description | Farm economics |
|---|---|---|
| **VS** | Very suitable land<br>(80-100 % of maximum achievable yield around the world) | Prime land offering the 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 is 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 land | Production not possible |

# 6. Carinata winter fallow

When cultivated as a winter cover, carinata develops on existing cropland and prevents otherwise bare soils during the fallow periods. Planting carinata on fallow land will improve nitrogen and water conservation, boost crop biodiversity, and generate additional income for farmers. No- or minimum tillage practices are suggested for soil fertility management.

## Suitability and production, current climate

In the region studied, the main production potential for carinata oil from winter fallow is in South America (22.7 Mt), followed by North America (15.4 Mt) and South Europe (9.9 Mt). These quantities could be produced using 16% (South America), 7% (North America) and 26% (South Europe) of the respective cropland in the region. Additional production could be sourced from land of moderate suitability amounting to 38 Mt for South America, 16 Mt for North America and 11 Mt for Europe (Table 13). Economic production on moderate land qualities requires higher crop prices.

*Table 13. Carinate winter cover, land suitability and production potential, current climate*

| | Cropland, rainfed | Prime and good land (VS+S) | | | Prime, good and moderate land (VS+S+MS) | | |
|---|---|---|---|---|---|---|---|
| Historic climate (2001-2020) | | Area [1000 $km^2$] | %* | Production [Mt veg oil] | Area | % | Production [Mt veg oil] |
| **North America** | 1,764 | 129.5 | 7% | 15.4 | 144.6 | 8% | 16.4 |
| **Caribbean** | 50 | 0.9 | 2% | 0.1 | 2.4 | 5% | 0.1 |
| **Central America** | 242 | 8.5 | 4% | 0.8 | 29.0 | 12% | 2.0 |
| **South America** | 1,230 | 198.9 | 16% | 22.7 | 437.6 | 36% | 38.5 |
| **East Europe, Russia** | 1,887 | 0.0 | | 0.0 | 0.0 | | 0.0 |
| **North Europe** | 181 | 1.6 | 0.9% | 0.2 | 3.9 | 2% | 0.3 |
| **South Europe** | 279 | 73.2 | 26% | 8.9 | 98.5 | 35% | 10.9 |
| **Western Europe** | 313 | 26.8 | 9% | 3.0 | 45.0 | 14% | 4.5 |
| **Southeast Asia** | 1,026 | 0.2 | | 0.0 | 10.6 | 1% | 0.5 |
| **South Asia** | 1,423 | 21.5 | 2% | 2.1 | 54.1 | 4% | 4.0 |

* Share in total rainfed cropland

Production potentials are concentrated in a few countries including Argentina, Brazil and Uruguay in South America, USA in North America, and Spain, France, Turkey and Italy in Europe (Table 14).

*Table 14. Selected countries for carinata winter cover crop production*

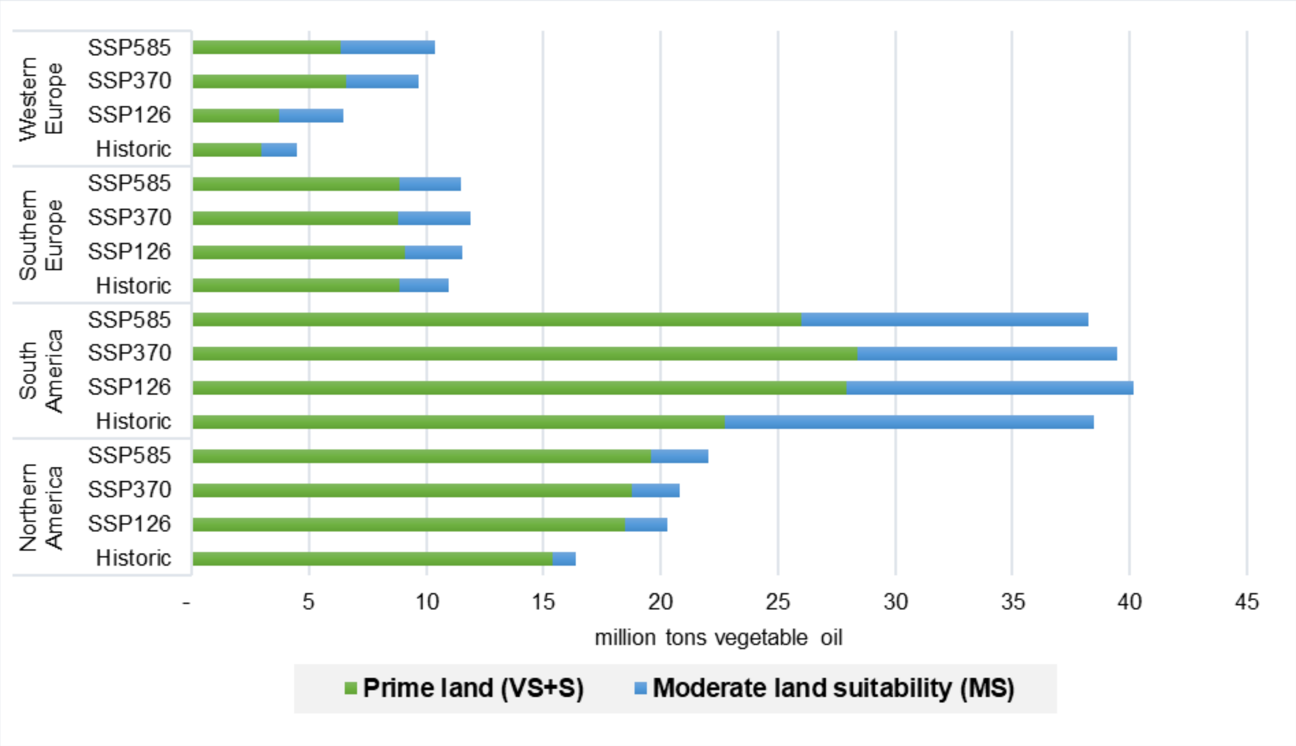
| | Cropland, rainfed | Prime and good land (VS+S) | | | Prime, good and moderate land (VS+S+MS) | | |
|---|---|---|---|---|---|---|---|
| Historic climate (2001-2020) | | Area [1000 $km^2$] | %* | Production [Mt veg oil] | Area | % | Production [Mt veg oil] |
| **Argentina** | 327 | 126.6 | 39% | 15.9 | 210.4 | 64% | 22.2 |
| **USA** | 1,385 | 129.5 | 9% | 15.4 | 144.6 | 10% | 16.4 |
| **Spain** | 133 | 35.9 | 27% | 4.3 | 52.8 | 40% | 5.6 |
| **France** | 167 | 26.8 | 16% | 3.0 | 45.0 | 27% | 4.5 |
| **Brazil** | 598 | 34.4 | 6% | 2.8 | 157.6 | 26% | 10.4 |
| **Turkey** | 185 | 21.1 | 11% | 2.7 | 24.4 | 13% | 2.9 |
| **Uruguay** | 21 | 20.2 | 99% | 2.5 | 20.3 | 99% | 2.5 |
| **Italy** | 57 | 19.5 | 34% | 2.4 | 24.4 | 43% | 2.8 |

## Climate change impacts

Climate change has a positive impact on carinata winter cover production in most of the regions investigated in this study. Compared to today's climate (2001-2020), by the 2050s more areas become suitable for carinata as winter cover crops. This is especially true for North America, where in southern USA more croplands become of prime suitability for carinata cultivated as winter cover crop. The current vegetable oil potential in the USA is 15.4 Mt, which is expected to increase by more than one fourth (27%) to 19.6 Mt (Ensemble) by the 2050s under scenario SSP585. The minimum and maximum of this future ensemble mean is 18.0 and 21.7 Mt.

Also, in South America, extents of prime production conditions increase resulting in higher vegetable potential compared to historic climate. The highest relative increase occurs in Western Europe for vegetable oil production from both prime and moderate land qualities. (Figure 13).

*Figure 13. Climate change impacts on vegetable oil production for carinata winter cover crops*




The figure shows vegetable oil production for historic climate (2001-2020) conditions and for the 2050s (2041-2060) under climate ensemble means of three scenarios (SSP126, SSP370, SSP585).

*Table 15. Carinate winter cover, land suitability and production potential, 2041-2060, by scenario*

a) Scenario 'Sustainability' SSP126, Climate Ensemble[1] average

| Region | Cropland[2] | VS+S land | | | VS+S+MS land[3] | | |
|---|---|---|---|---|---|---|---|
| | Area [1000 km$^2$] | Area [1000 km$^2$] | % | Production [Mt veg oil] | Area | % | Production [Mt veg oil] |
| **North America** | 1,764 | 167.3 | 9% | 18.5 | 192.7 | 11% | 20.3 |
| **Caribbean** | 50 | 0.4 | 1% | 0.0 | 0.9 | 2% | 0.1 |
| **Central America** | 242 | 6.1 | 3% | 0.6 | 19.4 | 8% | 1.3 |
| **South America** | 1,230 | 240.1 | 20% | 27.9 | 441.8 | 36% | 40.2 |
| **East Europe, Russia** | 1,887 | 0.1 | 0% | 0.0 | 0.2 | 0% | 0.0 |
| **North Europe** | 181 | 2.5 | 1% | 0.3 | 7.8 | 4% | 0.7 |
| **South Europe** | 279 | 76.8 | 28% | 9.1 | 107.8 | 39% | 11.6 |
| **Western Europe** | 313 | 33.3 | 11% | 3.7 | 66.8 | 21% | 6.5 |
| **Southeast Asia** | 1,026 | 0.1 | 0% | 0.0 | 4.7 | 0% | 0.2 |
| **South Asia** | 1,423 | 19.5 | 1% | 1.7 | 55.2 | 4% | 3.8 |

**1** Climate ensemble represents the average of five climate circulation models: *GFDL, IPSL, MPI, MRI, UKESM;* **2** Rainfed cropland; Share in total rainfed cropland; **3** Prime (very suitable VS), good (suitable S), moderate (moderately suitable MS) land;

b) Scenario 'Regional Rivalry' SSP370, Climate Ensemble average

| Region | Cropland | VS+S land | | | VS+S+MS land | | |
|---|---|---|---|---|---|---|---|
| | Area [1000 km$^2$] | Area [1000 km$^2$] | % | Production [Mt veg oil] | Area | % | Production [Mt veg oil] |
| **North America** | 1,764 | 174.9 | 10% | 18.8 | 203.6 | 12% | 20.8 |
| **Caribbean** | 50 | 0.3 | 1% | 0.0 | 0.6 | 1% | 0.0 |
| **Central America** | 242 | 3.9 | 2% | 0.4 | 15.5 | 6% | 1.1 |
| **South America** | 1,230 | 247.3 | 20% | 28.4 | 429.2 | 35% | 39.5 |
| **East Europe, Russia** | 1,887 | 2.2 | 0% | 0.2 | 2.5 | 0% | 0.3 |
| **North Europe** | 181 | 5.2 | 3% | 0.5 | 15.7 | 9% | 1.4 |
| **South Europe** | 279 | 77.4 | 28% | 8.8 | 116.4 | 42% | 11.9 |
| **Western Europe** | 313 | 58.2 | 19% | 6.6 | 94.6 | 30% | 9.7 |
| **Southeast Asia** | 1,026 | 0.1 | 0% | 0.0 | 3.9 | 0% | 0.2 |
| **South Asia** | 1,423 | 24.6 | 2% | 2.1 | 93.9 | 7% | 5.9 |

Scenario 'Fossil Fuel Development' SSP585, Climate Ensemble average

| Region | Cropland | VS+S land | | | VS+S+MS land | | |
|---|---|---|---|---|---|---|---|
| | Area [1000 km2] | Area [1000 km2] | % | Production [Mt veg oil] | Area | % | Production [Mt veg oil] |
| **North America** | 1,764 | 183.4 | 10% | 19.6 | 217.9 | 12% | 22.0 |
| **Caribbean** | 50 | 0.2 | 0% | 0.0 | 0.5 | 1% | 0.0 |
| **Central America** | 242 | 4.0 | 2% | 0.4 | 12.8 | 5% | 0.9 |
| **South America** | 1,230 | 228.9 | 19% | 26.0 | 428.7 | 35% | 38.2 |
| **East Europe, Russia** | 1,887 | 5.6 | 0% | 0.7 | 9.1 | 0% | 0.9 |
| **North Europe** | 181 | 6.3 | 3% | 0.7 | 17.3 | 10% | 1.5 |
| **South Europe** | 279 | 77.6 | 28% | 8.9 | 112.2 | 40% | 11.5 |
| **Western Europe** | 313 | 56.5 | 18% | 6.3 | 104.9 | 34% | 10.4 |
| **Southeast Asia** | 1,026 | 0.3 | 0% | 0.0 | 3.5 | 0% | 0.2 |
| **South Asia** | 1,423 | 17.8 | 1% | 1.6 | 56.4 | 4% | 3.7 |

# 7. Coconut

## World coconut production and utilization

Today some 62 million tons (Mt) of coconuts are being produced globally. Production is concentrated in Indonesia (17 Mt or 27%), Philippines (24%) and India (22%). Other producers with over 1 Mt include Brazil, Sri Lanka, Vietnam, Myanmar, Papa New Guinea, and Mexico (FAO, 2024b). These countries accounted for 90% of world coconut production in 2020-2022. Even though coconut could be produced throughout the tropical belt as shown in Annex I (Figure 16, Table 30, Table 31), coconut production is concentrated in a few countries only.

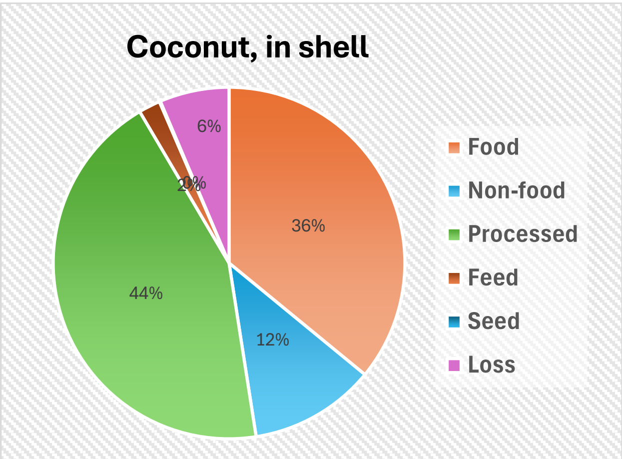
Coconut is the dominant crop in the Philippines in terms of harvested areas, often produced by smallholders. Cropland statistics distinguish between arable land (for annual crop production) and permanent crops. In the Philippines, coconut harvested area (3.6 Mha in 2019-2022) represents one-third of total cropland (11.2 Mha) and two-thirds of permanent crops (5.6 Mha). In Indonesia, coconut accounts for 10% (2.7 Mha) of the area under permanent crops.

Only 1.6 Mt or 2.5 % of coconuts enter cross-country trade. Thus, by far most coconuts are used in countries of production, for further processing (44%), direct food consumption (36%), or non-food use (12%) (Figure 14a). When processed, most coconuts are taken to the oil mills where they are ground into coconut oil. Smaller amounts are processed into desiccated coconuts.

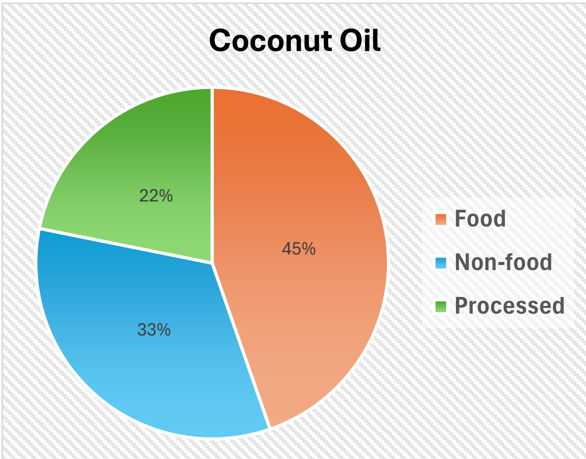
Indonesia, Philippines and India are main producers of coconut oil, together accounting for some 70% of global production. In contrast to raw coconuts, more than 80% of world coconut oil production enter international trade. Globally, almost half of all 2.8 Mt coconut oil is used for food (45%), a third (33%) for non-food purposes and the rest is further processed (Figure 14b).

*Figure 14. Utilization of coconut (a) and coconut oil (b), World, 2020-2022*

a) Coconut, total utilization = 62.5 Mt




b) Coconut oil, total = 2.8 Mt




Source: FAOSTAT Supply Utilization Accounts and Production statistics

Below we present major results for coconut monocropping and two intercropping systems by major region. As an example, Annex III highlights the Philippines in terms of land use balance and suitability for Tall coconut production.

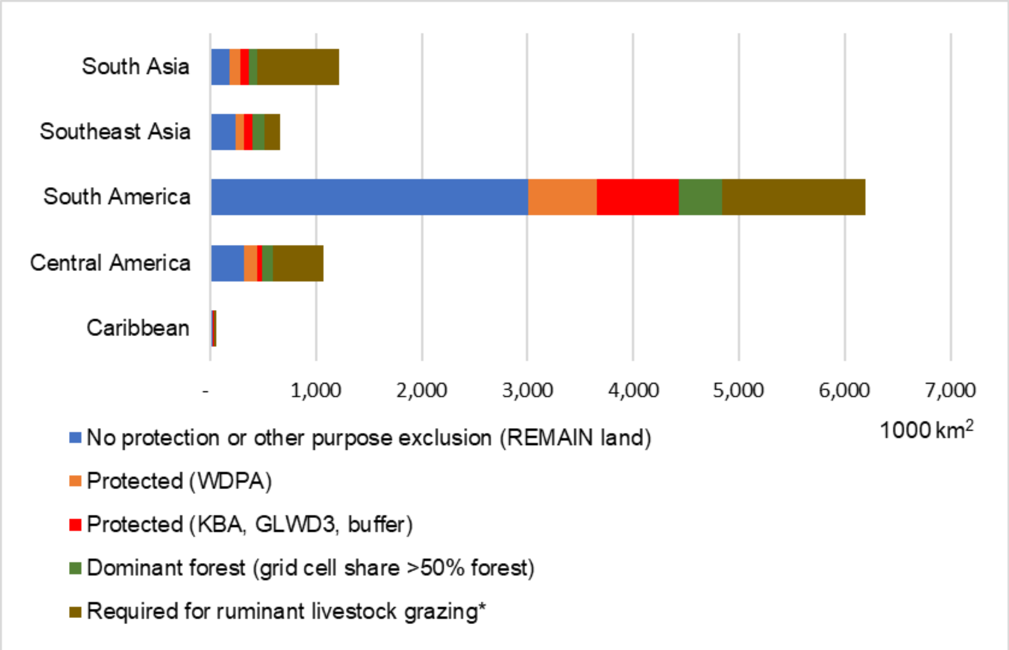
## Coconut monocropping

We applied the GAEZ v5 system to estimate suitability and attainable yields of different coconut types (Tall, Hybrid and Dwarf coconut types) while assuming for monocropping non-productive, not competing under growth for preventing top-soil erosion. Current climate is represented by using historic (averages of 2001-2020) daily weather data to force the AEZ modelling system.

Adhering to the RSB land use criteria, only REMAIN land is considered for coconut monocropping. REMAIN land represents grass- and shrubland after excluding protected areas and areas designated for its high importance for biodiversity. It also excludes areas that are reserved for ruminant livestock feeding and areas where soils have a high-organic carbon content. Figure 15 shows the exclusion status of the combined grass- and shrubland by major region. Because cropland has already been excluded for monocropping coconut, the blue area 'No protection or environment exclusion' in Figure 15 highlights the regional extents of REMAIN land.

It is interesting to note that in South Asia and Central America a large share of grass- and shrubland is excluded, foremost reserved for ruminant livestock feeding. In Southeast Asia there are many protected grass- and shrubland areas.

*Figure 15. Grassland and shrubland extents, by exclusion status*




* Includes also smaller areas of the exclusion category 'Soils with high organic carbon content'

### Tall coconut

Owing to its vast land resources and large extents of REMAIN land, South America has a very substantial spare potential to produce coconut oil, i.e., up to 18.8 Mt today for Tall coconut in prime quality REMAIN land alone (Table 16). Most of this potential could be sourced from Brazil. There is also some potential in Central America (1.9 Mt) and Southeast Asia (1.5 Mt).

However, climate change impacts negatively on production potentials of Tall coconut in all regions. Impacts attributed to Sustainability Scenario are reducing extents and production of prime quality REMAIN land substantially and are strongly negative when considering the Fossil-fueled development scenario (Table 17).

Reduced rainfall and associated lower relative humidity are the main causes for the significant reduction. In South America, the potential production capacity of vegetable oil from Tall coconut in prime quality REMAIN land decreases to 16.2 Mt in Sustainability scenario (-14%) and to 9.9 Mt in Fossil-fueled development scenario (-48%).

*Table 16. Tall coconut (monocropping) from REMAIN land, current climate*

| TALL COCONUT | Caribbean | Central Amer. | South Amer. | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Historic climate** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 2.6 | 19.4 | 3.4 | 0.4 |
| VS+S REMAIN Grassland | 0.1 | 12.0 | 124.1 | 7.4 | 0.6 |
| Total | **0.1** | **14.6** | **143.6** | **10.9** | **1.0** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 2 | 348 | 2,601 | 460 | 50 |
| VS+S REMAIN Grassland | 7 | 1,630 | 16,199 | 1,005 | 84 |
| Total | **9** | **1,978** | **18,801** | **1,465** | **135** |

*Table 17.Tall coconut (monocropping) from REMAIN land under climate change (2041-2060)*

| TALL COCONUT | Caribbean | Central Amer. | South Amer. | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Climate Scenario SSP126** (Sustainability) | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 1.9 | 17.4 | 3.2 | 0.3 |
| VS+S REMAIN Grassland | 0.0 | 9.6 | 107.6 | 6.5 | 0.5 |
| Total | **0.0** | **11.5** | **125.1** | **9.7** | **0.9** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 1 | 254 | 2,279 | 432 | 45 |
| VS+S REMAIN Grassland | 3 | 1,288 | 13,889 | 873 | 71 |
| Total | **3** | **1,542** | **16,168** | **1,305** | **116** |
| Change relative to historic | -67% | -22% | -14% | -11% | -14% |
| **Climate Scenario SSP585** ('Fossil-fueled development') | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 1.5 | 11.9 | 3.0 | 0.4 |
| VS+S REMAIN Grassland | 0.0 | 7.3 | 66.6 | 6.0 | 0.5 |
| Total | **0.0** | **8.7** | **78.5** | **9.0** | **0.9** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 0 | 191 | 1,519 | 397 | 45 |
| VS+S REMAIN Grassland | 2 | 972 | 8,350 | 788 | 69 |
| Total | **2** | **1,163** | **9,869** | **1,185** | **114** |
| Change relative to historic | -78% | -41% | -48% | -19% | -16% |

## Hybrid coconut

The results for Hybrid coconut are like those of Tall coconut. However, per tree and hectare yields are generally smaller compared to Tall coconuts, thus the quantities of copra and the vegetable oils obtained are lower. While prime and good land extents in REMAIN land are similar to those of Tall coconut, Hybrid coconut oil production potential due to mainly lower yield is 15.3 Mt (Table 18) compared to 18.8 Mt (Table 16), for Tall coconut.

*Table 18. Hybrid coconut (monocropping) from REMAIN land, current climate*

| HYBRID COCONUT | Caribbean | Central Amer. | South Amer | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Historic climate** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 2.7 | 19.6 | 3.5 | 0.4 |
| VS+S REMAIN Grassland | 0.1 | 12.2 | 125.3 | 7.5 | 0.6 |
| Total | **0.1** | **14.8** | **144.8** | **11.1** | **1.0** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 2 | 286 | 2,111 | 378 | 41 |
| VS+S REMAIN Grassland | 6 | 1,335 | 13,181 | 824 | 69 |
| Total | **7** | **1,621** | **15,292** | **1,203** | **110** |

Climate change has a negative impact as for Tall coconuts but less pronounced. For South America, production potentials of coconut oil from prime and good REMAIN land areas drops from 15.3 Mt under current climate to 8.2 Mt under Fossil-fueled development by 2050s (Table 19). Impacts are more substantial in Central America (-41%) and South America (-46%) as compared to Southeast Asia (-18%) and South Asia (-15%). The difference can be attributed to a relatively large decline of prime and good quality REMAIN land in Central and South America with climate change assuming Fossil-fueled development scenario for 2041-2060.

*Table 19. Hybrid coconut (monocropping) from REMAIN land under climate change (2041-2060)*

| HYBRID COCONUT | Caribbean | Central Amer. | South Amer. | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Climate Scenario SSP126** (Sustainability) | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 2.0 | 17.7 | 3.3 | 0.4 |
| VS+S REMAIN Grassland | 0.0 | 9.8 | 110.1 | 6.7 | 0.6 |
| Total | **0.0** | **11.8** | **127.8** | **10.0** | **0.9** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 1 | 221 | 1,957 | 372 | 39 |
| VS+S REMAIN Grassland | 2 | 1,108 | 11,977 | 749 | 61 |
| Total | **3** | **1,329** | **13,934** | **1,121** | **100** |
| Change relative to historic | -57% | -18% | -9% | -7% | -9% |
| **Climate Scenario SSP585** (‘Fossil-fueled development’) | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 1.5 | 12.3 | 3.1 | 0.4 |
| VS+S REMAIN Grassland | 0.0 | 7.4 | 69.4 | 6.2 | 0.5 |
| Total | **0.0** | **8.9** | **81.6** | **9.3** | **0.9** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 0 | 156 | 1,255 | 333 | 37 |
| VS+S REMAIN Grassland | 1 | 800 | 6,993 | 655 | 57 |
| Total | **2** | **956** | **8,248** | **987** | **94** |
| Change relative to historic | -71% | -41% | -46% | -18% | -15% |

For Hybrid coconut, we also highlight the impact of considering moderately suitable land (MS) in addition to prime land of very suitable (VS) and suitable (S) quality. Taking also into account the MS areas, the suitable areas in South and Central America almost double and more than triple in Southeast Asia. Accordingly, vegetable oil production increases by 35% (Central America, from 1.6 Mt for VS+S to 2.2 Mt for VS+S+MS), 63 % (South America), and 150 % (Southeast Asia) (Table 20).

*Table 20. Hybrid Coconut (monocropping) from REMAIN land for VS+S land (a) and VS+S+MS land (b), current climate (2001-2020)*

| HYBRID COCONUT | Caribbean | Central Amer. | South Amer. | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **a. Prime and good land (VS+S)** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 2.7 | 19.6 | 3.5 | 0.4 |
| VS+S REMAIN Grassland | 0.1 | 12.2 | 125.3 | 7.5 | 0.6 |
| Total | **0.1** | **14.8** | **144.8** | **11.1** | **1.0** |
| **Vegetable oil** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 2 | 286 | 2,111 | 378 | 41 |
| VS+S REMAIN Grassland | 6 | 1,335 | 13,181 | 824 | 69 |
| Total | **7** | **1,621** | **15,292** | **1,203** | **110** |
| **b. Prime, good and moderate land (VS+S+MS)** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S+MS REMAIN Shrubland | 0.1 | 4.3 | 43.0 | 13.1 | 0.9 |
| VS+S+MS REMAIN Grassland | 0.5 | 18.1 | 229.4 | 22.6 | 1.2 |
| Total | **0.6** | **22.4** | **272.4** | **35.7** | **2.1** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S+MS REMAIN Shrubland | 9 | 414 | 3,866 | 1,072 | 79 |
| VS+S+MS REMAIN Grassland | 40 | 1,777 | 21,073 | 1,930 | 114 |
| Total | **50** | **2,191** | **24,939** | **3,002** | **193** |

*Table 21. Climate change impact (2041-2060) on Hybrid coconut (monocropping) from REMAIN land*

| HYBRID COCONUT | Caribbean | Central Amer. | South Amer. | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Extents** from prime, good and moderate REMAIN land (VS+S+MS) [1000 km$^2$] | | | | | |
| Historic (2001-2020) | 0.6 | 22.4 | 272.4 | 35.7 | 2.1 |
| Climate Ensemble (2041-2060) | | | | | |
| SSP126 (Sustainability) | 0.3 | 22.1 | 279.3 | 35.4 | 2.3 |
| SSP585 (Fossil-fueled) | 0.2 | 20.3 | 242.5 | 34.5 | 2.5 |
| **Vegetable oil production** from prime, good and moderate REMAIN land (VS+S+MS) [1000 tons] | | | | | |
| Historic (2001-2020) | 50 | 2,191 | 24,939 | 3,002 | 193 |
| Climate Ensemble (2041-2060) | | | | | |
| SSP126 (Sustainability) | 26 | 2,175 | 25,914 | 3,089 | 208 |
| Relative change to historic | -48% | -1% | 4% | 3% | 8% |
| SSP585 (Fossil-fueled) | 16 | 1,839 | 20,474 | 2,862 | 212 |
| Relative change to historic | -68% | -16% | -18% | -5% | 10% |

Table 21 shows the climate change impact of the high-end ‘fossil-fueled development’ scenario, again separate by land quality, on the one hand for prime land only (VS+S) and on the other hand for prime and moderate land (VS+S+MS). Obviously, climate change causes a shift in production opportunities from prime land to moderately suitable land (except South Asia). The production decrease is less pronounced if prime and moderate land is considered compared to only considering prime land. For example, in South America, for the SSP585 scenario, production capacities from VS+S land decrease by -46% when considering VS+S land (from 15.9 Mt historic climate to 8.2 Mt by the 2050s) compared to -18% when considering VS+S+MS land (from 24.9 Mt to 20.5 Mt) (see Table 19 and Table 21). Climate change impact is mostly related to changes in relative humidity and the precipitation regime, of key importance for rain-fed production systems.

## Dwarf coconut

Dwarfs are distinguished from Tall and Hybrid coconut primarily by short height, early setting of nuts, and relative short rotation period (up to 40 years). Dwarf coconuts generally yield less coconut oil than Tall and Hybrid varieties because of lower nut yield per hectare and smaller nut size with relatively lower copra content. Also, copra from Dwarf coconuts generally has a lower oil content compared to that of Tall and Hybrid varieties. Commercial cultivation is mainly for the sweet and flavorful tender nut water rather than for copra production

Dwarf coconuts are bred primarily for qualities like early bearing, shorter stature, and ease of harvesting. They are usually cultivated close to human settlements. Commercial cultivation is mainly for the harvest of sweet and flavorful tender nut water rather than for copra production. Several Dwarf varieties exhibit resistance to diseases like lethal yellowing, making them valuable in areas prone to specific coconut diseases. On the other hand, Dwarf varieties are slightly less tolerant of certain adverse conditions, such as water stress or lower soil nutrient availability, compared to Hybrid and Tall varieties.

Albeit the acreage of prime and good land qualities is in many regions like Tall coconut, less vegetable oil quantities can be harvested from Dwarf coconut. For example, for South America, under current climate, we find some 144 thousand km$^2$ prime land suitability for both coconut varieties, but vegetable oil production is 10.5 Mt versus 18.8 Mt for Dwarf (Table 22) and Tall (Table 16) coconut respectively. This difference is less pronounced in Central America and Southeast Asia mainly because larger areas qualify as prime production for Dwarf compared to Tall coconut.

In South America, under current climate, we find some 144.7 thousand km$^2$ prime and good quality (VS+S) REMAIN land for Dwarf coconut quite similar Tall coconut (143.6 thousand km$^2$). Differences in coconut oil production are quite pronounced. Coconut oil production potential is 10.5 Mt for Dwarf coconut (Table 22) and 18.8 Mt for Tall coconut (Table 16); Dwarf coconut produces about 44 % less.

However, the impact of climate change on Dwarf coconut is less pronounced than on Tall coconut, suggesting that Dwarf varieties are more resilient. Coconut oil production remains almost unchanged in the SSP126 scenario ('Sustainability', in line with Paris Agreement). In South America and Southeast and South Asia small increases are observed due to larger areas falling into the prime land area quality under future climate. For the SSP585 scenario ('Fossil-fueled development'), the production potential in South America decreases to 7.4 Mt (-30% compared to historical), For Tall and Hybrid coconut production deceases will be more dramatic namely respectively 45% and 46%. (See Tables 22 and 23 for Dwarf, Tables 16 and 17 for Tall and Tables 18 and 19 for Hybrid coconuts).

In summary, while Tall coconut produces higher yields of vegetable oil compared to Dwarf coconut under historic climate, this effect becomes smaller as climate change becomes more severe. For example, in South America Tall and Dwarf coconuts produce 18.8 Mt and 10.5 Mt of vegetable oil, respectively, under current climate. Thus, production under Dwarf is 44% lower than Tall. By the 2050s, under SSP585, Tall and Dwarf produce 9.8 Mt and 7.4 Mt respectively, so Dwarf's production potential is only 25% lower.

*Table 22. Dwarf coconut (monocropping) from REMAIN land, VS+S land, current climate*

| DWARF COCONUT | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Historic climate** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0.0 | 3.1 | 20.8 | 5.5 | 0.5 |
| VS+S REMAIN Grassland | 0.1 | 13.4 | 123.9 | 9.4 | 0.6 |
| Total | **0.1** | **16.5** | **144.7** | **14.9** | **1.1** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 1 | 220 | 1,537 | 397 | 34 |
| VS+S REMAIN Grassland | 3 | 978 | 8,982 | 683 | 48 |
| Total | **5** | **1,198** | **10,519** | **1,079** | **82** |

*Table 23. Climate change impact (2041-2060) on Dwarf coconut (monocropping) from REMAIN land*

| Dwarf COCONUT | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Climate Scenario SSP126** (Sustainability) | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0 | 2.4 | 21.0 | 6.4 | 0.6 |
| VS+S REMAIN Grassland | 0 | 11.3 | 131.7 | 10.0 | 0.7 |
| Total | **0** | **13.6** | **152.7** | **16.4** | **1.3** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 0 | 170 | 1,479 | 456 | 39 |
| VS+S REMAIN Grassland | 2 | 809 | 9,267 | 712 | 50 |
| Total | **2** | **979** | **10,747** | **1,168** | **89** |
| Change relative to historic | -60% | -18% | 2% | 8% | 9% |
| **Climate Scenario SSP585** (Fossil-fueled development) | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN Shrubland | 0 | 1.7 | 15.3 | 6.0 | 0.5 |
| VS+S REMAIN Grassland | 0 | 8.3 | 93.1 | 9.3 | 0.7 |
| Total | **0** | **10.1** | **108.4** | **15.3** | **1.2** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN Shrubland | 0 | 122 | 1,049 | 419 | 36 |
| VS+S REMAIN Grassland | 1 | 592 | 6,365 | 651 | 47 |
| Total | **1** | **714** | **7,413** | **1,070** | **83** |
| Change relative to historic | -80% | -40% | -30% | -1% | 1% |

## Coconut intercropping systems

Coconut intercropping systems may increase the potential areas for sustainable production systems. We present two options, one for intercropping on shrub- and grassland areas and one for cropland.

### Intercropping with fodder crops on shrub/grassland

Coconut intercropping with fodder crops adopts a joint utilization of unprotected shrubland and grassland for livestock feed from pasture crops and coconut production (see Table 2). In contrast to monoculture cultivation, intercropping coconut with fodder crops allows the utilization of land that is currently used for feeding ruminants. Therefore, if land suitability is favorable, additional areas are considered for coconut intercropping.

Note, that the forage provided by intercropping with fodder crops may exceed the biomass of natural pastures, which is the current management practice, as the intercropping system proposed here assumes improved pastures cultivated with specific fodder crops. Brachiaria grasses, napier grass, and a range of pasture grasses and pasture legumes have been selected and at each site the forage with the highest biomass is selected (see the concept of 'umbrella crops' described in 'Assessment steps' – Section 5).

The spacing of coconut trees is set in relation to the estimated feed requirements of current ruminant livestock extents (i.e., within a grid-cell). Thus, the spacing depends on the calculated pasture feed requirement factor, i.e. the Total Livestock Unit requirement (TLUreq) factor as follows:

If more than 95% of the grass- or shrubland in a grid cell is required for animal feed (i.e., TLUreq > 0.95), then all the land is reserved for livestock feed and intercropping is not considered. If TLUreq is between 0.80 and 0.95, avenue planting (9.5 x 12 m) with 88 trees/ha is assumed. For TLUreq between 0.6 and 0.8, we assume squared planting (7.5 x 12 m) with 111 trees/ha; when TLUreq is 0.4-0.6, we assume single hedge planting (7.5 x 9 m) with 148 trees/ha; for TLUreq between 0.1-0.4, we assume double hedge planting (7.5 x 7.5/7.5/9 m) with 163 trees/ha. Finally, for TLUreq < 0.1, i.e., ruminants require less than 10% of the grid cell forage, we assume squared planting (7.5 x 7.5 m) with 178 trees/ha, as for coconut monocultures. In this way, the REMAIN land is extended but still meets RSB's food security criteria (REMAIN+ land).

As expected, in all regions, coconut intercropping with fodder crops produces more vegetable oil than monocropping, due to the larger areas considered. For example, under current climate, in South America, coconut intercropping with fodder crops can produce 18% more vegetable oil at 22.1 Mt (Table 24) compared to monocropping at 18.8 Mt (Table 16).

The impact of climate change for Tall coconut intercropping with fodder crops is less pronounced compared to Tall coconut monocropping. In South America and Southeast Asia climate change appears beneficial considering the sustainability scenario (SSP126). In case of fossil fueled development scenario (SSP585) only in Southeast Asia climate change is slightly beneficial. This is revealed by a comparing Table 16 and Table 17 for Tall coconut monocropping with Table 24 and Table 25 for Tall coconut intercropping with fodder crops.

The sustainability scenario (SSP126) for Tall coconut intercropping with fodder crops results in higher vegetable oil potential from VS+S REMAIN+ land in South America (+13%) and Southeast Asia (+15%) by the 2050s. The other regions show a declining vegetable oil potential in SSP126. The high-end scenario 'Fossil-fueled development' decreases production potentials in almost all explored regions. A notable exception is South-East Asia, where at the aggregate regional level a small increase (+6%) in vegetable oil potential is found.

*Table 24. Tall coconut intercropping with fodder crops from REMAIN+ land, for VS+S land, rainfed production, current climate*

| Tall coconut intercropping with fodder crops | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Historic climate (2001-2020)** | | | | | |
| **Extents** [1000 km²] | | | | | |
| VS+S REMAIN+ Shrubland | 0.0 | 3.3 | 23.1 | 4.2 | 0.6 |
| VS+S REMAIN+ Grassland | 0.2 | 15.3 | 145.6 | 9.3 | 0.9 |
| Total | **0.2** | **18.7** | **168.8** | **13.5** | **1.5** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN+ Shrubland | 5 | 444 | 3,089 | 562 | 77 |
| VS+S REMAIN+ Grassland | 22 | 2,071 | 19,030 | 1,252 | 128 |
| Total | **27** | **2,515** | **22,119** | **1,814** | **205** |

*Table 25. Tall coconut intercropping with fodder crops from REMAIN+ land, for VS+S land, rainfed production, under climate change Scenario SSP126 and SSP585*

| Tall coconut intercropping with fodder crops | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **Climate Scenario SSP126 (Sustainability)** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN+ Shrubland | 0.0 | 3.0 | 27.2 | 5.1 | 0.6 |
| VS+S REMAIN+ Grassland | 0.1 | 14.7 | 167.1 | 10.4 | 0.9 |
| Total | **0.1** | **17.7** | **194.3** | **15.5** | **1.5** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN+ Shrubland | 3 | 397 | 3,541 | 682 | 76 |
| VS+S REMAIN+ Grassland | 12 | 1,975 | 21,522 | 1,399 | 121 |
| Total | **14** | **2,372** | **25,063** | **2,081** | **197** |
| Change relative to historic % | -47% | -6% | 13% | 15% | -3% |
| **Climate Scenario SSP585 (Fossil-fueled development)** | | | | | |
| **Extents** [1000 km$^2$] | | | | | |
| VS+S REMAIN+ Shrubland | 0.0 | 2.3 | 18.7 | 4.9 | 0.6 |
| VS+S REMAIN+ Grassland | 0.1 | 11.3 | 105.1 | 9.7 | 0.9 |
| Total | **0.1** | **13.6** | **123.8** | **14.6** | **1.6** |
| **Vegetable oil production** [1000 tons] | | | | | |
| VS+S REMAIN+ Shrubland | 2 | 300 | 2,380 | 640 | 79 |
| VS+S REMAIN+ Grassland | 8 | 1,497 | 13,191 | 1,275 | 121 |
| Total | **9** | **1,797** | **15,571** | **1,915** | **200** |
| Change relative to historic % | -65% | -29% | -30% | 6% | -2% |

## Intercropping with cash and food crops on cropland

In the Caribbean, Southeast Asia and South Asia more than one fourth of total land is cropland (Table 27). Significant extents of cropland in South and Southeast Asia regions are already cultivated to produce permanent crops, mainly oil palm, natural rubber, fruits, and coconut. Several countries are characterized by a strong concentration of the production of individual permanent crops. For example, Malaysia and Indonesia are dominated by oil palm production, Thailand by natural rubber, and the Philippines by coconut.

*Table 26. Cropland extents, circa 2020, by region*

| Cropland extents | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| Rain-fed cropland (1000 km$^2$) | 50 | 242 | 1,230 | 1,026 | 1,423 |
| Irrigated cropland (1000 km$^2$) | 11 | 59 | 91 | 202 | 973 |
| Total cropland (1000 km$^2$) | 61 | 301 | 1,321 | 1,228 | 2,396 |
| Cropland share in total land use | 26% | 12% | 7% | 27% | 36% |

Coconut-based intercropping systems have been proposed as a viable option for enhancing economic, energy, and environmental benefits, and if well-designed can significantly enhance farm productivity and profitability compared to coconut monocropping (Arunachalam et al., 2025). Rain-fed coconut intercropping offers farmers the opportunity to grow coconut alongside cash crops or staple food. For cash crops, we have selected coffee and cocoa, and for staples, banana/plantain, an important food security crop in many parts of the world. As these are all perennial permanent crops, they do not require annual ploughing and are well suited for intercropping with Tall and Hybrid coconut[6].

Hybrid coconut has a moderately tall but open canopy, allowing more filtered sunlight to reach the understory. This provides the ideal light conditions (30–50% shade) needed by cocoa and Robusta coffee, which are shade-tolerant but not deep-shade species.

We have constructed an 'umbrella' using robusta coffee, cocoa and banana/plantain. When more than one crop in the umbrella qualifies, the one with higher agro-ecological suitability was selected. If both are of similar suitability, the crop with the higher output value (i.e., yield multiplied by an international price weight for the commodity) was chosen. The multiple uses per unit of cropland are defined as follows: Tall coconut (single hedge cultivation) uses 45% and Hybrid coconut 52% of cropland. This leaves a balance of 55% (Tall c.) and 48% (Hybrid c.) for the intercropped perennial cash/food crop.

Table 27 shows regional cropland extents, followed by extents and vegetable oil potentials for Tall and Hybrid coconut intercropping with perennials, i.e., the selected 'umbrella' crop. In contrast to monocropping coconut on REMAIN grass- and shrubland, the key production areas for intercropping on cropland are in Southeast Asia. Half of total rainfed cropland in Southeast Asia is suitable for Tall or Hybrid coconut intercropping with perennials.

*Table 27. Coconut intercropping with cash/food crop umbrella (robusta coffee, cocoa, banana/plantain) on rainfed cropland, current climate (2001-2020)*

| | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **TALL coconut intercropping with perennials** | | | | | |
| **Extents** | | | | | |
| VS+S rain-fed cropland (1000 km$^2$) | 1.5 | 26.8 | 61.8 | 132.6 | 7.3 |
| VS+S share in rain-fed cropland (%) | 3.0% | 11.1% | 5.0% | 12.9% | 0.5% |
| VS+S+MS rain-fed cropland (1000 km$^2$) | 5.2 | 56.4 | 134.0 | 522.1 | 39.3 |
| VS+S+MS share in rain-fed cropland (%) | 10.5% | 23.3% | 10.9% | 50.9% | 2.8% |
| **Vegetable oil production** | | | | | |
| VS+S rain-fed cropland (1000 tons) | 162 | 2,948 | 6,735 | 14,462 | 785 |
| VS+S+MS rain-fed cropland (1000 tons) | 434 | 5,213 | 12,108 | 43,305 | 3,261 |

| | | | | | |
|---|---|---|---|---|---|
| **HYBRID coconut intercropping with perennials** | | | | | |
| **Extents** | | | | | |
| VS+S rain-fed cropland (1000 km$^2$) | 1.5 | 27.2 | 62.5 | 135.0 | 7.6 |
| VS+S share in rain-fed cropland (%) | 3.1% | 11.2% | 5.1% | 13.2% | 0.5% |
| VS+S+MS rain-fed cropland (1000 km$^2$) | 4.9 | 56.2 | 133.8 | 522.5 | 38.9 |
| VS+S+MS share in rain-fed cropland (%) | 9.8% | 23.3% | 10.9% | 50.9% | 2.7% |
| **Vegetable oil production** | | | | | |
| VS+S rain-fed cropland (1000 tons) | 132 | 2,408 | 5,488 | 11,849 | 651 |
| VS+S+MS rain-fed cropland (1000 tons) | 332 | 4,194 | 9,745 | 34,934 | 2,607 |

[6] Dwarf coconut is only suited for intercropping with banana/plantain. Due to several ecological and agronomic factors, including light and root competition, allelopathy, and space limitations, coffee and cocoa cannot be grown effectively under dwarf coconut. Therefore, Dwarf coconut intercropping with the here examined cash/food crop umbrella is not possible.

In Southeast Asia, being the most productive region, some 13% of the total rainfed cropland is prime land (VS+S) for rain-fed Tall or Hybrid coconut perennial intercropping systems (using robusta coffee, cocoa and banana/plantain). If moderate suitable land is included, over 50% of rainfed cropland in Southeast Asia is suitable for Tall or Hybrid coconut intercropping with perennials.

If suitable cropland is used for coconut intercropping with perennials, depending on variety, significant amounts of vegetable oil could be produced. For example, in Southeast Asia some 11.8 Mt vegetable oil could be produced from prime land (VS+S) from Hybrid coconut intercropping with cash/food crop perennials. This could increase to 43.3 Mt, if moderate land is included (VS+S+MS) and used for cultivating Tall coconut intercropping with the here proposed cash/food crop perennials, thereby using 51% of current cropland (Table 27).

Although vegetable oil production potentials are lower for Hybrid compared to Tall coconut, Lethal Yellowing Disease (LYD) tends to affect Tall coconut varieties more severely than Hybrid Coconut varieties. Cocoa, coffee, and other shade-loving intercrops are less likely to be harmed by abrupt exposure to full sunshine since most hybrid cultivars are resistant to LYD.

The impact of climate change varies across regions, scenario, and land quality. Table 28 and Table 29 summarize results for the 'sustainability' scenario SSP126 and 'Fossil Fueled' Scenario SSP585 respectively.

*Table 28. Coconut intercropping with cash/food crop umbrella (robusta coffee, cocoa, banana/plantain) on rainfed cropland, ENSEMBLE mean under climate change (2041-2060) for Scenario SSP126*

| | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **TALL coconut intercropping with perennials** | | | | | |
| **Extents** | | | | | |
| VS+S rain-fed cropland (1000 km$^2$) | 1.0 | 24.5 | 72.2 | 141.1 | 9.7 |
| VS+S share in rain-fed cropland (%) | 1.9% | 10.1% | 5.9% | 13.8% | 0.7% |
| VS+S+MS rain-fed cropland (1000 km$^2$) | 4.6 | 52.8 | 203.9 | 522.4 | 63.0 |
| VS+S+MS share in rain-fed cropland (%) | 9.2% | 21.8% | 16.6% | 50.9% | 4.4% |
| **Vegetable oil production** | | | | | |
| VS+S rain-fed cropland (1000 tons) | 104 | 2,690 | 7,657 | 15,386 | 1,005 |
| Relative to historic (2001-2021) | -36% | -9% | 14% | 6% | 28% |
| VS+S+MS rain-fed cropland (1000 tons) | 374 | 4,889 | 17,540 | 43,853 | 5,139 |
| Relative to historic (2001-2021) | -14% | -6% | 45% | 1% | 58% |
| **HYBRID coconut intercropping with perennials** | | | | | |
| **Extents** | | | | | |
| VS+S rain-fed cropland (1000 km$^2$) | 1.0 | 24.9 | 74.1 | 144.9 | 10.4 |
| VS+S share in rain-fed cropland (%) | 2.0% | 10.3% | 6.0% | 14.1% | 0.7% |
| VS+S+MS rain-fed cropland (1000 km$^2$) | 4.5 | 52.7 | 203.4 | 525.2 | 63.2 |
| VS+S+MS share in rain-fed cropland (%) | 9.0% | 21.8% | 16.5% | 51.2% | 4.4% |
| **Vegetable oil production** | | | | | |
| VS+S rain-fed cropland (1000 tons) | 86 | 2,195 | 6,325 | 12,705 | 864 |
| Relative to historic (2001-2021) | -47% | -26% | -6% | -12% | 10% |
| VS+S+MS rain-fed cropland (1000 tons) | 294 | 3,930 | 14,108 | 35,513 | 4,157 |
| Relative to historic (2001-2021) | -32% | -25% | 17% | -18% | 27% |

In Southeast Asia, the impact of climate change is small or slightly negative (up to -19% compared to current climate). By the 2050s, the region remains the main potential production area for coconut intercropping with perennials among those investigated in this study. Production capacities of vegetable oil are between 12 and 43 Mt, similar compared to potentials under current climate.

In South Asia, there is a positive impact of climate change on the potential for vegetable oil production from coconut intercropping. This is due to a doubling of area extents suitable for rainfed production. However, the overall potential in the region (0.8 to 4.5 Mt vegetable oil) is small compared to Southeast Asia and South America.

In South America, climate change increases the vegetable oil production potential for SSP126 and but has a negative impact for the prime land qualities in SSP585. Only when considering prime and moderate land qualities (VS+S+MS), there is no or a positive impact of climate change.

For the Caribbean and Central America, both climate models reveal a negative impact of climate change for coconut intercropping with perennials. However, both regions are further from the tropical belt and have much lower production potentials compared to the large region of South America and Southeast Asia.

*Table 29. Coconut intercropping with cash/food crop umbrella (robusta coffee, cocoa, banana/plantain) on rainfed cropland, ENSEMBLE mean under climate change (2041-2060) for Scenario SSP585*

| | Caribbean | Central America | South America | Southeast Asia | South Asia |
|---|---|---|---|---|---|
| **TALL coconut intercropping with perennials** | | | | | |
| **Extents** | | | | | |
| VS+S rain-fed cropland (1000 $km^2$) | 0.6 | 20.5 | 53.6 | 141.7 | 12.6 |
| VS+S share in rain-fed cropland (%) | 1.3% | 8.5% | 4.4% | 13.8% | 0.9% |
| VS+S+MS rain-fed cropland (1000 $km^2$) | 3.4 | 47.6 | 178.7 | 512.6 | 67.5 |
| VS+S+MS share in rain-fed cropland (%) | 6.9% | 19.7% | 14.5% | 50.0% | 4.7% |
| **Vegetable oil production** | | | | | |
| VS+S rain-fed cropland (1000 tons) | 70 | 2,210 | 5,601 | 15,239 | 1,284 |
| Relative to historic (2001-2021) | -57% | -25% | -17% | 5% | 64% |
| VS+S+MS rain-fed cropland (1000 tons) | 275 | 4,314 | 15,084 | 43,201 | 5,583 |
| Relative to historic (2001-2021) | -37% | -17% | 25% | 0% | 71% |

| | | | | | |
|---|---|---|---|---|---|
| **HYBRID coconut intercropping with perennials** | | | | | |
| **Extents** | | | | | |
| VS+S rain-fed cropland (1000 $km^2$) | 0.6 | 20.9 | 55.4 | 146.3 | 13.4 |
| VS+S share in rain-fed cropland (%) | 1.3% | 8.6% | 4.5% | 14.3% | 0.9% |
| VS+S+MS rain-fed cropland (1000 $km^2$) | 3.3 | 47.6 | 179.2 | 517.7 | 67.5 |
| VS+S+MS share in rain-fed cropland (%) | 6.5% | 19.7% | 14.6% | 50.5% | 4.7% |
| **Vegetable oil production** | | | | | |
| VS+S rain-fed cropland (1000 tons) | 57 | 1,809 | 4,171 | 12,647 | 1,098 |
| Relative to historic (2001-2021) | -65% | -39% | -38% | -13% | 40% |
| VS+S+MS rain-fed cropland (1000 tons) | 213 | 3,473 | 12,177 | 35,107 | 4,504 |
| Relative to historic (2001-2021) | -51% | -33% | 1% | -19% | 38% |

# 8. Conclusions

Vegetable oils are of key interest to the bioeconomy, which is urgently needed to combat climate change and its impacts. They have attracted considerable attention for the biofuel sector, but are also needed to supply other non-food products, such as oleochemicals, detergents or cosmetics. The production of sustainable vegetable oils depends on several interrelated factors, including direct and indirect competition with land use for food, feed and other non-food products, availability and ecological suitability of land, and the impacts of climate change on land and water resources. A systems analysis approach is needed to analyze these interrelated factors for specific regions and crops.

In the quest for sustainable production and towards carbon neutral products, this study selects two promising vegetable oils, produced from carinata and coconut. These crops, which differ in their agro-ecological niches and agronomic management options, allow to explore different solution strategies for sustainable vegetable oil production. Carinata was selected for cultivation on cropland as a winter cover crop. Coconut can be grown as monoculture or together with suitable food or forage crops in intercropping systems. Winter cover and intercropping support key soil conservation principles such as permanent crop biomass cover on soil surface, no or minimum tillage, and enhanced crop biodiversity through crop rotation and mixed cropping systems. The sustainability assessment here is guided by criteria developed by the Roundtable on Sustainable Biomaterials. The Global Agro-ecological Zones (GAEZ) modelling framework is used to evaluate with great spatial detail the sustainable production of carinata and coconut vegetable oils in Europe, the Americas, and Southeast Asia under current and future climate conditions. Below we summarize the main conclusions of this first-order assessment.

The largest production potentials for carinata oil from winter fallow is found in South America (22.7 Mt), followed by North America (15.4 Mt) and South Europe (9.9 Mt). These quantities could be produced using 16% (South America), 7% (North America) and 26% (South Europe) of the respective cropland in the region. Climate change is expected to have a positive impact on carinata winter cover production in North America and Western Europe. For instance, in the southern USA, as frost occurrence will move northwards due to higher temperatures and with sufficient winter rainfall, more cropland acreage will become of prime quality for carinata as a winter cover crop, increasing from 15.4 Mt today to 19.6 Mt in the 2050s. In South America the climate change impact on carinata winter cover cropping is less pronounced. Climate change has a small positive or no impact, depending on climate scenario.

Compared to carinata, sustainability considerations and climate change impacts differ for coconut production. Of the tropical regions examined in this study, the main production areas of coconut production that meet sustainability criteria are in South America, Southeast Asia and South Asia. Current distribution of land use determines the type of sustainable coconut production system that can be considered.

In South America, there are still vast areas of unprotected grass- and shrubland which could be used for coconut monocropping on REMAIN land, i.e., the areas that remain once environmental and food security criteria have been addressed. Depending on coconut variety, some 18.8 Mt (Tall coconut), 15.3 Mt (Hybrid coconut) and 10.5 Mt (Dwarf coconut) of vegetable oil could be produced annually in South America today using only areas of prime land quality. While in the case of coconut monocropping, shrub- and grassland used by ruminant livestock must be reserved for food security, the coconut intercropping with fodder crops could tap into additional unprotected grass- and shrubland. As a result of intercropping coconut with fodder crops, the production potential for coconut increases in all regions, e.g., in South America for Tall coconut to 22.1 Mt vegetable oil.

Availability of only limited REMAIN grass- and shrubland resources in Southeast Asia, South Asia and Central America restricts sustainable coconut monocropping in these regions. Coconut intercropping with fodder crops on pastures also produces much lower levels than in South America. To achieve comparable volumes of vegetable oil as is possible in South America, coconut intercropping on ample cropland could be considered in Asia. In many countries in Southeast and South Asia, 40 to 60% of the total land area is today used as cropland. The intercropping of coconut with cash or food crops can offer sustainable production opportunities for vegetable oils with beneficial environmental outcomes, reduced economic risks due to diversification and likely more stable and increased incomes for farmers.

Coconut intercropping on rain-fed cropland can offer farmers the opportunity to grow coconut alongside cash crops or staple foods. For cash crops, we have selected coffee and cocoa, and for staples, banana/plantain, an important food security crop in many parts of the world. Selecting the best of these cash/food crops in a particular location ('Umbrella crop' concept), under current climate (2001-2020) in Southeast Asia up to 13% of rainfed cropland are of prime quality for Tall or Hybrid coconut intercropping with coffee, cocoa, or banana/plantain. Associated vegetable oil potentials are 14.4 Mt (Tall coconut) and 11.8 Mt (Hybrid coconut). If vegetable oil prices are sufficiently high, land of moderate suitability may also be used for production, increasing oil production volumes to 43.3 Mt (Tall) and 34.0 Mt (Hybrid).

The impact of climate change on coconut production depends on the scenario, location and coconut production system. For the 'Sustainability' Scenario, which assumes that global mean temperatures can on average be kept below 2 degrees Celsius, as for example envisaged in the Paris agreement, the impact on coconut production is relatively small. In the main producing regions 80% to 90% of current production potentials are still achievable under the 'Sustainability' Scenario.

Coconut monocropping production potential is expected to drop dramatically with higher levels of climate change. This is especially pronounced in the main production area for coconut monocropping production on REMAIN land in South America. Under the 'Fossil-fueled development' scenario, only 36% (6.7 Mt) of current production (18.8 Mt) is possible. The main reason is the drying of land and shortening of moisture growing periods due to a decrease in rainfall in the Amazonas, occurring in all five Earth system models used in this study and especially pronounced in one of the models included in the here reported ensemble means.

The negative effects of climate change are less pronounced for coconut intercropping systems. Under the 'Sustainability' scenario, there is even a modest increase in vegetable oil production potential in South America and Southeast Asia for coconut intercropping with fodder crops. Climate change impacts depend on location and due to intercropping additional pasture areas with less severe, sometimes even positive, climate change impacts on coconut productivity are included in the analysis.

In the 'Fossil-fueled development' scenario, on the other hand, the quantities of vegetable oils decease almost everywhere, even in intercropping production systems. The exception is Southeast Asia, where the climate change impacts on coconut productivity remain low and may even lead to a slight increase in production potential in some areas. Coconut requires a fairly humid, lowland tropical environment with warm temperatures and stable relative humidity throughout the year, which are expected to prevail under climate change.

This regional overview study illustrates the complexity of outcomes and underlines the importance of a spatially explicit analysis, the inclusion of climate change impacts and the consideration of different vegetable oil production systems for medium- to long-term strategies for the procurement of sustainable vegetable oils. As the calculations presented here are based on a high spatial resolution on a gridded database at 5 arc-minutes (about 9 x 9 km at equator), the results can be analyzed for individual countries or regions in more detail. Production conditions of individual countries are diverse, often dominated by only a few crops, and will experience quite different impacts of future climatic conditions.

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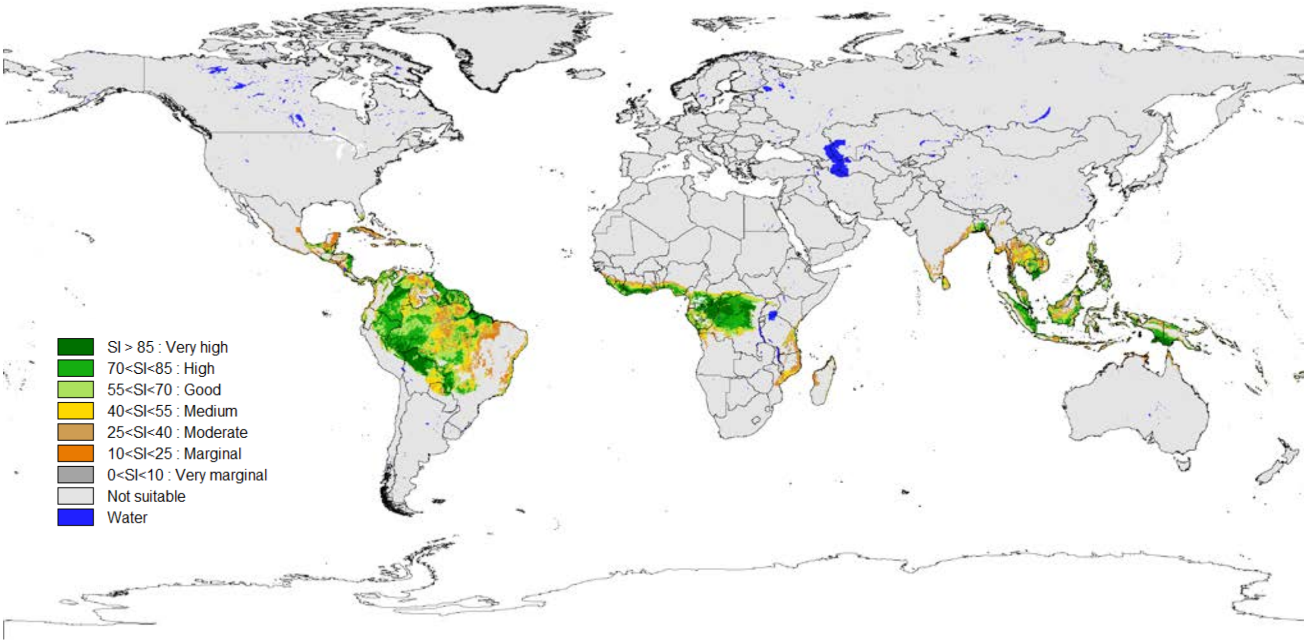
# ANNEX

## Annex I. Global land suitability for coconut mono-cropping

For reference, we also present global suitability results for coconut mono-cropping, exemplified by Tall and Dwarf coconut. Figure 16 shows a global map mono-cropped Dwarf Coconut and Figure 17 highlights attainable copra yields in South and Southeast Asia.

*Figure 16. Agro-ecological suitability of mono-cropped rain-fed Dwarf Coconut in 2001-2020*




The map shows agro-ecological suitability of rain-fed Dwarf Coconut mapped in classes of a normalized suitability index SI in the range of 0 (not suitable) to 100 (all land very suitable). Source: GAEZ v5

*Figure 17. Attainable yield (kg copra/ha) of mono-cropped rain-fed Dwarf Coconut in 2001-2020*


Source: GAEZ v5

Table 30 and Table 31 present extents of prime land qualities and vegetable oil potentials for Tall and Dwarf coconut respectively. Note, unlike in the main report (Section 7), here we do not show REMAIN land extents but all cropland, shrubland and grassland.

*Table 30. Rain-fed Tall Coconut production potential on VS+S land, average climate 2001-2020, by region and land use*

| | **Prime land (VS+S), unprotected [km$^2$]** | | | | **Vegetable oil* [million tons]** | | | |
|---|---|---|---|---|---|---|---|---|
| | Cropland | Shrubland | Grassland | Total | Cropland | Shrubland | Grassland | Total |
| **Caribbean** | 1,833 | 98 | 353 | 2,284 | 0.4 | 0.0 | 0.1 | 0.4 |
| **Central America** | 24,325 | 3,471 | 15,679 | 43,474 | 4.9 | 0.7 | 3.3 | 8.9 |
| **South America** | 60,379 | 23,982 | 151,954 | 236,315 | 12.1 | 4.9 | 30.5 | 47.5 |
| **Micronesia, Polyn.** | 2,102 | 1,302 | 2,097 | 5,500 | 0.4 | 0.3 | 0.4 | 1.1 |
| **East Africa** | 2,902 | 1,337 | 1,829 | 6,068 | 0.5 | 0.3 | 0.3 | 1.2 |
| **Middle Africa** | 28,107 | 7,626 | 11,263 | 46,996 | 5.4 | 1.5 | 2.2 | 9.1 |
| **Gulf of Guinea** | 32,439 | 6,356 | 9,262 | 48,057 | 6.5 | 1.3 | 1.9 | 9.7 |
| **Southeast Asia** | 159,473 | 5,931 | 13,901 | 179,304 | 32.2 | 1.2 | 2.9 | 36.3 |
| **South Asia** | 8,367 | 850 | 1,243 | 10,459 | 1.7 | 0.2 | 0.3 | 2.1 |
| **East Asia** | 1,735 | 237 | 513 | 2,484 | 0.3 | 0.0 | 0.1 | 0.5 |
| | | | | | | | | |
| **WORLD** | 321,890 | 51,205 | 208,145 | 581,239 | 65 | 10 | 42 | **117** |

* Note, production reflects yields of mature coconut plantations. Annual yields over the full lifespan are 65% based on a weighted average over the three coconut production stages: i) Early: from year of first harvest to full cover; 2) Mid: Full cover; 3) Late: Full cover to end rotation).

*Table 31. Rain-fed Dwarf Coconut production potential on VS+S land, average climate 2001-2020, by region and land use*

| | **Prime land (VS+S), unprotected [km$^2$]** | | | | **Vegetable oil* [1000 million tons]** | | | |
|---|---|---|---|---|---|---|---|---|
| | Cropland | Shrubland | Grassland | Total | Cropland | Shrubland | Grassland | Total |
| **Caribbean** | 1,857 | 109 | 377 | 2,342 | 0.2 | 0.0 | 0.0 | 0.3 |
| **Central America** | 29,016 | 4,113 | 17,551 | 50,681 | 3.3 | 0.5 | 2.0 | 5.9 |
| **South America** | 66,073 | 26,040 | 152,882 | 244,995 | 7.6 | 3.0 | 17.7 | 28.3 |
| **Micronesia, Polyn.** | 3,267 | 1,832 | 3,576 | 8,675 | 0.4 | 0.2 | 0.4 | 1.0 |
| **East Africa** | 3,798 | 2,279 | 2,825 | 8,902 | 0.4 | 0.3 | 0.3 | 1.0 |
| **Middle Africa** | 38,664 | 7,892 | 12,559 | 59,114 | 4.3 | 0.9 | 1.4 | 6.5 |
| **Gulf of Guinea** | 43,300 | 8,178 | 11,950 | 63,428 | 4.8 | 0.9 | 1.3 | 7.1 |
| **Southeast Asia** | 298,212 | 11,254 | 19,640 | 329,106 | 34.0 | 1.3 | 2.3 | 37.5 |
| **South Asia** | 8,319 | 951 | 1,275 | 10,545 | 0.9 | 0.1 | 0.1 | 1.2 |
| **East Asia** | 1,051 | 89 | 252 | 1,392 | 0.1 | 0.0 | 0.0 | 0.1 |
| | | | | | | | | |
| **WORLD** | 493,809 | 62,785 | 223,007 | 779,601 | 56.0 | 7.2 | 25.7 | **88.9** |

* Note, production reflects yields of mature coconut plantations. Annual yields over the full lifespan are 62.5% based on a weighted average over the three coconut production stages: i) Early: from year of first harvest to full cover; 2) Mid: Full cover; 3) Late: Full cover to end rotation).

## Annex II. Global land suitability for Carinata

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.

Figure 18 and Figure 19 show agro-ecological suitability of B. carinata for respectively all types simulated in GAEZ v5 and for winter types only, i.e., crop types which can be cultivated without hibernation in the cool season in regions with sub-tropical climate conditions.

*Figure 18. Agro-climatic potential yield of rain-fed B. carinata, all types*

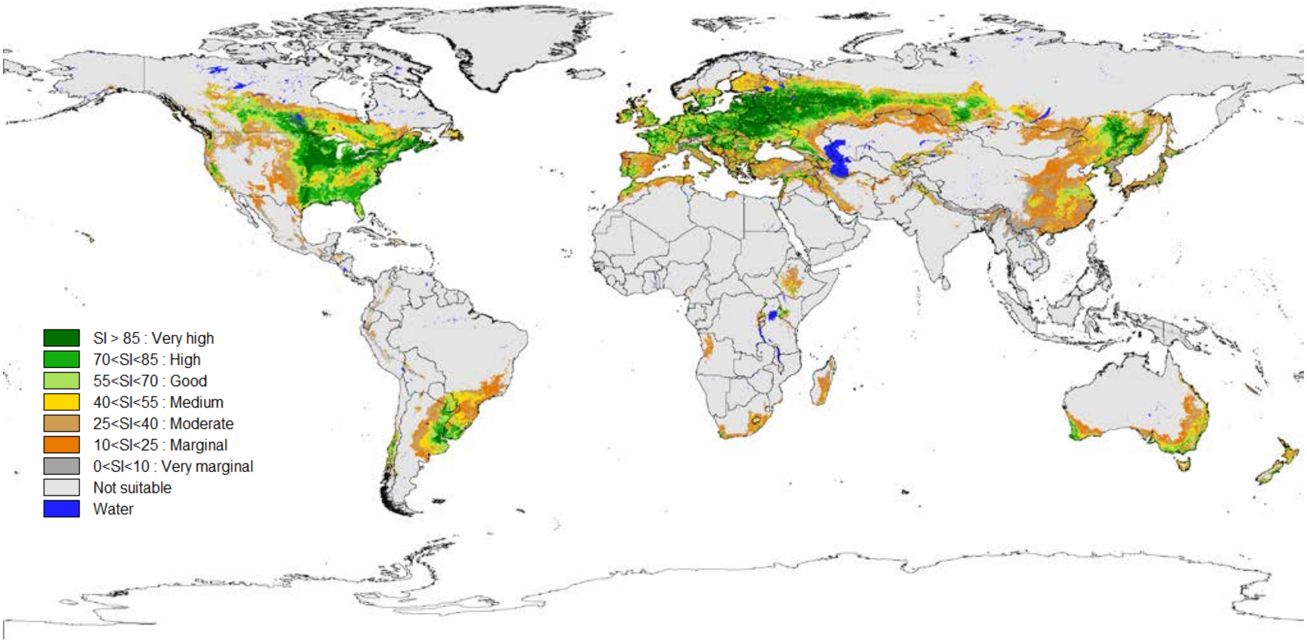
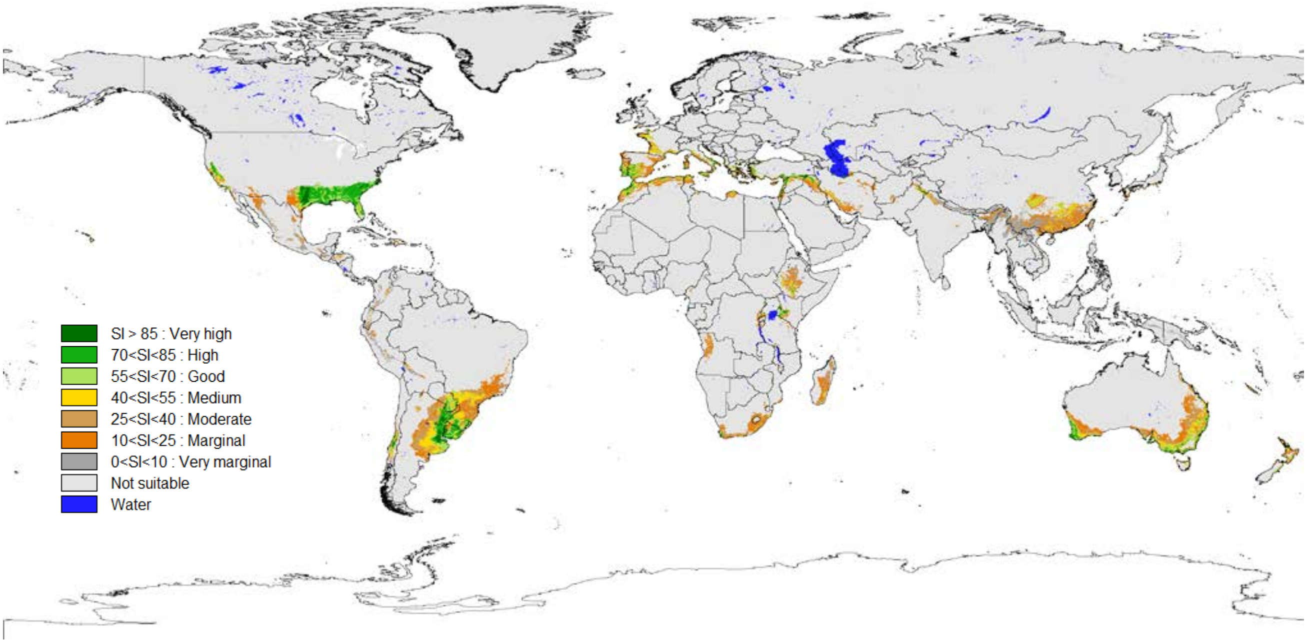



*Figure 19. Agro-ecological suitability of rain-fed B. carinata, winter types*



As is evident from these maps and summarized below in Table 32, much larger suitable cropland areas are found in the temperate region where spring types can be grown but cultivation of B. carinata as winter fallow is not possible due to low temperatures.

The results in Table 32 indicate that about a quarter of global cropland is very suitable or suitable for B. carinata cultivation. When only considering winter B. carinata types, then only about 5% of cropland is very suitable or suitable.

*Table 32. Suitability of rain-fed B. carinata in current cropland*

| 1000 hectares | **Cropland** | **All B. carinata types** | | **B. carinata winter types** | |
|---|---|---|---|---|---|
| | **Total** | **VS+S** | **MS** | **VS+S** | **MS** |
| North America | 199,028 | 120,402 | 30,675 | 15,202 | 1,964 |
| Europe and North Asia | 288,154 | 170,264 | 58,085 | 10,863 | 6,733 |
| Central America and Caribbean | 36,225 | 159 | 434 | 158 | 433 |
| South America | 132,150 | 17,343 | 24,051 | 14,841 | 25,147 |
| Oceania | 33,054 | 6,581 | 6,348 | 6,209 | 6,622 |
| Sub-Saharan Africa | 228,929 | 6,315 | 5,291 | 5,907 | 5,031 |
| North Africa and Western Asia | 93,873 | 22,503 | 13,912 | 14,731 | 7,040 |
| Asia, excl. Western Asia | 546,545 | 36,082 | 59,871 | 6,480 | 15,875 |
| **World, total** | **1,557,958** | **379,650** | **198,666** | **74,392** | **68,844** |

# Annex III. Focus country: Philippines

Agriculture is an important sector to the Philippine economy, the country being the second largest producer of coconut in shell (23% of global production or 14.8 Mt). As much as 36.6 thousand km$^2$ are used for coconut plantations, the largest of all countries and account for 33% of global harvested areas of coconuts (FAOSTAT, 2023). One third of the total land area is cropland with coconut, rice and maize being the most important crops. Although the percentage share of agriculture in GDP is slowly declining (to 8% in 2020), it is still a very important sector for employment with about one quarter of Filipinos depending on agriculture for their income.

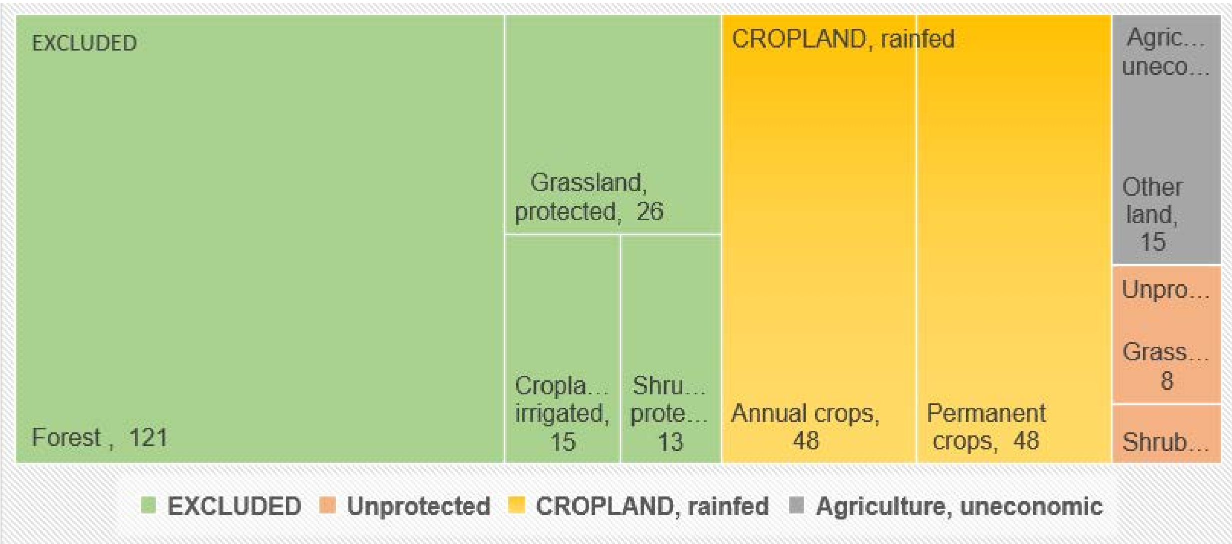
Table 33 and Figure 20 present the land balance of the Philippines in the context of the RSB sustainability criteria. From the total land extents (298 thousand km$^2$), over half (59 %) is excluded and not considered for coconut production because of land and water conservation, biodiversity and carbon protection. Another 5% is not relevant for agricultural production including bare and sparsely vegetated areas, built-up areas and inland water bodies. This leaves a balance of 96 thousand km$^2$ cropland and 12 thousand km$^2$ unprotected shrub- and grassland. Following the land considerations for sustainable non-food coconut production, the land suitability of these areas for coconut production is further investigated for potential coconut inter- or monocropping systems.

*Table 33. Land balance of Philippines, Analysis steps by land use and protection status*

| Analysis step | Land use / Protection | **Area** 1000 km$^2$ | Share |
|---|---|---|---|
| **EXCLUDED** | Forest | 121 | 41% |
| | Shrubland, protected | 13 | 4% |
| | Grassland, protected | 26 | 9% |
| | Cropland, irrigated | 15 | 5% |
| **Other land (not for agriculture)** | Bare/spare veg., built-up, water | 15 | 5% |
| **Coconut land quality assessment conducted for** | | | |
| Shrub/Grassland | Shrubland, unprotected | 4 | 1% |
| | Grassland, unprotected | 8 | 3% |
| CROPLAND, rainfed | Annual crops | 48 | 16% |
| | Permanent crops | 48 | 16% |
| **Total area** | | **298** | 100 % |

*Source: GAEZ and FAOSTAT*

*Figure 20. Land balance of Philippines, 2019-20*

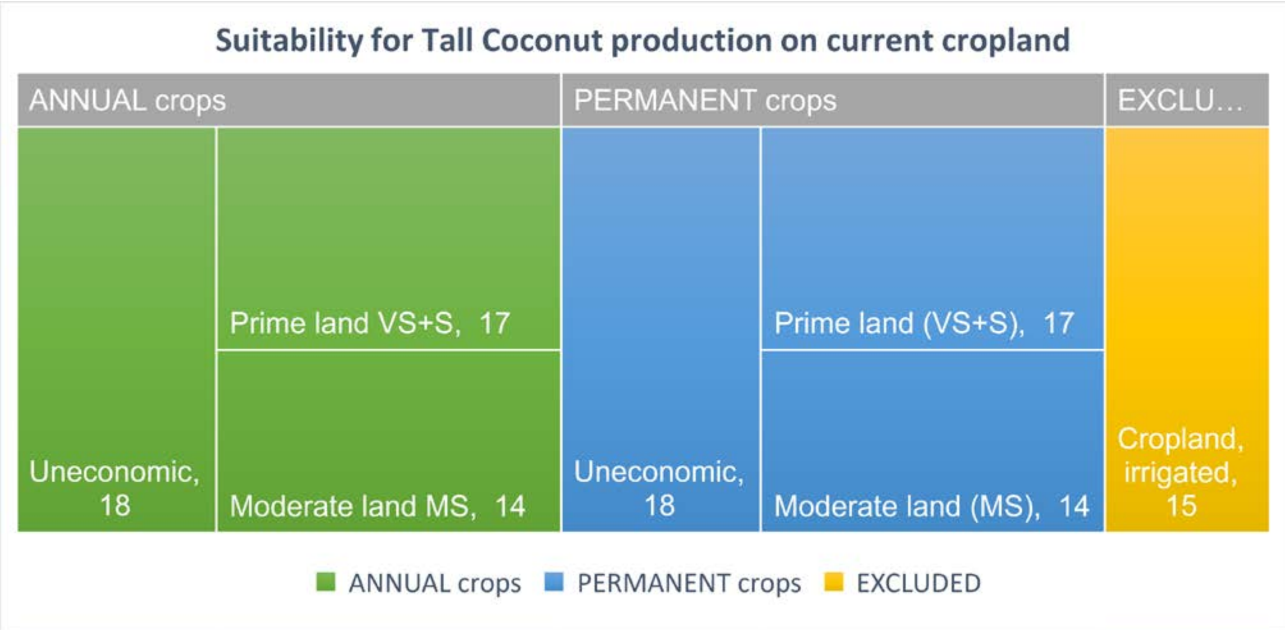


Only some 12 thousand km$^2$ (4% or total land) are unprotected grass- and shrubland, some of which may be used for roaming livestock.

Almost one third of land is rain-fed cropland today. To give an indication, Figure 21 shows suitability estimates for the production of Tall coconut on Philippines cropland. Note, spatial land use data do not differentiate between cropland for annual crops and for perennials. Therefore, the assessment assumes that the suitability estimated in GAEZ occurs in the same ratio as the FAOSTAT reported land use data for Annual and Permanent crops. GAEZ includes the land use category cropland but does not differentiate between cropland for annual crops (arable land) and for permanent crops.

From the total rainfed cropland (96 thousand km$^2$), more than one third (34 thousand km$^2$) is of prime quality to produce Tall coconut. Another 28 thousand km$^2$ are of moderate land quality, still permitting economic production when prices are high. This compares to 36 thousand km$^2$ of coconuts harvested in the Philippines today. While much of the permanent cropland of prime and moderate land quality is likely already used for coconut production, prime land qualities on cropland used today for annual crops offers the possibility for coconut intercropping with Tall or Hybrid coconut.

*Figure 21. Philippines, cropland balance for Tall coconut production*




Source: IIASA, GAEZ calculations and FAOSTAT.