Concawe
Environmental Science for European Fuel Manufacturing

Report

Report no. 6/26

Availability Potential of Intermediate Crops in the EU to 2050

ISBN 978-2-87567-213-1

Availability Potential of Intermediate Crops in the EU to 2050

Prepared by:

Berien Elbersen, Michiel van Eupen, Charlotte van Haren, Simone Verzandvoort, Valentina Jara Rios & Igor Staritsky, Wageningen Environmental Research

Efthymia Alexopoulou, Center for Renewable Energy Sources

Under the supervision:

T. Neokosmidis (Concawe Scientific Officer)
A. Ramasary (Concawe Science Executive)

At the request of: Concawe Special Task Force on Sustainable Bio-feedstock Availability (RET/STF-3)

Brussels
May 2026

KEYWORDS

Intermediate crops, cover crops, biomass availability, advanced biofuels, novel crops, oil crops, lignocellulosic crops, fallow land

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.eu)

CONTENTS

EXECUTIVE SUMMARY

Advanced biofuels are recognised as crucial for the decarbonisation of EU hard-to-abate transport segments such as aviation, maritime transport and heavy-duty mobility. Annex IX of the Renewable Energy Directive (RED) lists the sustainable biofeedstocks eligible for advanced biofuel production, and its 2024 revision introduced new feedstocks that can further support EU decarbonisation targets. Among these, intermediate crops, grown during fallow periods within conventional crop rotations, have emerged as a promising new resource attracting strong industry interest. In this context, Concawe, commissioned a study to Wageningen Environmental Research and Center for Renewable Energy Sources (CRES), with the aim to quantify and assess the potential of intermediate crops towards 2050 under evolving climate and land-use conditions across the EU-27.

Among the different intermediate crops, broadly classified as oil or lignocellulosic, the study applied a screening process to prioritise the most promising candidates based on yields, climatic suitability, and environmental criteria. The assessment considered compatibility with EU climate zones, yield data from scientific and field-trial literature, alignment with EU legislation, and environmental impacts related to soil health, biodiversity, and water requirements. This analysis provides guidance on optimal crop selection and management practices.

The results demonstrate that intermediate crop suitability is strongly climate- and region-dependent. Northern and Southern Europe face more extreme weather conditions in winter and summer, respectively, limiting crop flexibility, while Central and Western Europe allow a broader range of options. Oil crops such as Camelina, Crambe and White Mustard show the widest suitability across Europe, while lignocellulosic crops are largely limited to Biomass sorghum cultivated in summer in Central, Western and parts of Northern Europe. Environmentally, intermediate crops generally perform neutrally or positively: they require low water input, improve soil health by reducing erosion and adding soil carbon, and support biodiversity due to their low pesticide needs and provision of floral resources during periods when agricultural flowering is scarce.

To estimate their availability, a spatially explicit crop growth simulation model was applied at regional (NUTS-3) level under rain-fed conditions for the present and for 2030, 2040 and 2050. The model also determines the optimal crop to be deployed in each region based on yield performance. Key factors influencing the potential, such as climate and land-use changes, technological yield improvements, and conventional crop rotation schemes, are included based on available scientific data.

To capture the range of possible developments towards 2050, six scenarios were modelled. These fall into three overarching categories:

1. Current conditions, reflecting today's climate and land-use patterns;
2. A Low Transition scenario, where climate change follows a high-emissions pathway (SSP5-8.5) and land use continues broadly as today; projected warming of ~4.5 °C (range 3.3-5.7 °C) above pre-industrial levels by 2100.
3. A High Transition scenario, aligned with the European Green Deal, combining a lower-emissions climate pathway (SSP1-2.6) with more sustainable agricultural practices and diet-driven land-use changes. SSP1-2.6 is consistent with the Paris Agreement targets and projects a relatively limited global mean temperature increase of ~1.8 °C (range 1.3-2.4 °C) above pre-industrial levels by 2100.

For each of these three cases, two separate simulations were conducted: one assuming the production of only oil crops and one only of lignocellulosic crops.

Summer intermediate crops potential and constraints:

By 2050, the calculated availability of intermediate crops grown on summer fallow land in the EU-27 ranges from 12.7-13.2 million tonnes of oilseeds, equivalent to ~ 4.0-4.2 Mtoe of advanced biofuel, with white mustard emerging as the most favourable option. This would correspond to around 20-25% of projected EU sustainable aviation fuel (SAF) demand under the ReFuelEU Aviation mandate, based on SAF projections from recent studies, including the *Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels* and the More Molecule scenario of the Concawe and S&P study. If lignocellulosic crops are assumed instead, the potential increases to 27.5-39.9 million tonnes of dry biomass, corresponding to 4.6-6.7 Mtoe, driven by their much higher on-farm productivity (around 10 times higher than oil crops). However, their conversion pathways are typically more costly, while oil-based pathways benefit from higher technology readiness levels (TRL) and could therefore be deployed earlier.

For both crop types, the main limitation across most EU regions is the length of the growing period, which often exceeds the duration of available summer fallow land. In Mediterranean regions, water stress and drought during summer are an additional constraint. As a result, oil intermediate crops could be cultivated on around 25% of summer fallow land, while lignocellulosic crops are limited to about 5-8%.

Winter intermediate crops potential and constraints:

By 2050, the potential for intermediate crops grown during winter is substantially smaller, estimated at 0.7-1.0 Mt of oil seeds, corresponding to 0.3-0.4 Mtoe of advanced biofuel. Their suitability is geographically limited to specific regions in Southern Europe, representing no more than 2% of the total winter fallow land.

The primary constraint on winter intermediate crops is their long growing period, which prevents them from reaching maturity within the limited timeframe available between consecutive conventional crops in many places in EU. As a result, crop rotation constraints limit their winter deployment more strongly than in summer.

Recommendations and potential of wider deployment of intermediate crops:

Recognising the limitations on intermediate crop deployment, particularly during winter, the study evaluated two sensitivities to assess whether additional factors could unlock further potential: (1) Changes in the growing period of conventional crops under climate change (not included in the base scenarios), and (2) Reductions in the growing-day requirements of intermediate crops through targeted breeding.

The results indicate that climate-driven changes in the growth duration of conventional crops lead to only modest increases in the potential for winter oil intermediate crops. At the same time, they slightly reduce the land available for summer intermediate crops, as higher temperatures come with lower water availability and tend to prolong rather than limit the growth period of conventional crops during summer.

In contrast, reducing the growing-day requirements of intermediate crops (assuming no yield penalty) can significantly increase their potential. For winter oil intermediate crops, a 20% reduction in growing-day requirements could increase their potential sevenfold, reaching ~5.5 million tonnes of oilseeds. For summer intermediate crops, the impact of reducing growing-day requirements is marginal for oil crops. However, even small improvements, such as a 5% reduction in the growing-day requirements of lignocellulosic summer intermediate crops, could more or less double their potential. These results highlight the positive role that research and development aimed at shortening crop growing periods could play in unlocking additional feedstock potential and supporting the decarbonisation of the EU transport sector.

1. INTRODUCTION

1.1. OBJECTIVE AND BACKGROUND

Concawe commissioned Wageningen Environmental Research (WENR) together with Center for Renewable Energy Sources (CRES) and International Soil Reference and Information Centre (ISRIC) to conduct this study aimed to explore and quantify the availability potential of intermediate crops and crops grown on severely degraded lands towards 2050. These two biomass types are among the newly added biofeedstocks in the amended RED III Annex IX, and have attracted growing interest from industry for their potential role in advanced biofuel production.

Previous studies, including the one conducted for Concawe by Imperial College Consultants (Panoutsou C & Manatis, 2021), focused on estimating the sustainable availability of feedstocks listed under Annex IX of RED II. With the transition to RED III, new feedstocks have been added to Annex IX, expanding the scope of eligible materials for advanced biofuel production. Among these are intermediate crops and crops grown on severely degraded lands, defined as follows[1]:

- Intermediate crops, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land, and provided the soil organic matter content is maintained, where used for the production of biofuel for the aviation sector;
- Crops grown on severely degraded land, except food and feed crops, where used for the production of biofuel for the aviation sector.

Prior to this study, only one study launched by DG-RTD had focused on quantifying the potential of these two feedstocks. This study involved a high-level spatial mapping at country-level and quantification of Annex IX feedstocks for drop-in biofuels (EC, 2024). In light of the previous efforts, Concawe now aims to further explore these two feedstocks in greater depth and conduct a detailed analysis of their availability potential towards 2050 at regional granularity across the EU-27. This study considers a diverse range of crop types, their regional suitability, and the influence of climate and land use changes on future availability.

In this report, the work and results carried out for the first feedstock group, namely the intermediate crops, are reported.

1.2. CONTEXT AND AIM

The overall objective of the study is to quantify the potential availability of intermediate crops and crops grown on severely degraded lands for the EU-27[2] as defined in the RED III - Annex IX, per region (NUTS-3 level) for 2030, 2040 and 2050 under different mobilization scenarios.

[1] Delegated Directive (2024) 1585 final amending Annex IX to Directive (EU) 2018/2001 of the European Parliament and of the Council as regards adding feedstock for the production of biofuels and biogas https://ec.europa.eu/info/law/better-regulation

[2] Countries outside the EU like UK and Norway were not considered due to the lack of recent land use change data towards 2050, a necessary component for modelling intermediate crops potential.

The study is divided into two different phases and in this report the results focusing on the first feedstock category, intermediate crops, are given. The tasks for this phase are structured accordingly:

1. Selection of crops and sustainability and management practices:

A set of potential intermediate crops, both oil and lignocellulosic, are identified and assessed based on key performance indicators (KPIs). These KPIs include climate suitability across different climate zones of Europe, agronomic yields, sustainability benefits and potential environmental impacts and finally technology readiness level. The crops that perform best according to these metrics will be prioritised and ultimately selected for geospatial simulations. The selection process will ensure that crops considered are compatible with existing agricultural systems and meet sustainability criteria relevant for advanced biofuel feedstocks.

2. Scenario development for 2030, 2040 and 2050 and biomass potential calculation:

To estimate future biomass availability, different scenarios were developed to reflect a range of possible outcomes driven by key parameters such as climate change and its impacts on agriculture, the suitability of intermediate crops under future climate conditions, land-use dynamics, and technological progress. Subsequently, the biomass potential of each scenario will be calculated for different scenarios that differ specifically in terms of climate change levels, expected changes in land use in the context of EU and Common Agricultural Policy (CAP) assumptions, and yield improvements due to technological innovations. In this way, the scenarios capture uncertainty related to the major factors that will determine long term availability of agricultural biomass for biofuel production.

3. Crop growth simulation and optimal crop mix for advanced biofuels:

The productivity of the selected crops will be simulated through a dedicated crop yield model, which integrates land characteristics, crop-specific biophysical properties, and climatic variables, including future climate projections. The model is run independently for each crop but also will evaluate different crop mix strategies, such as:

- Scenarios cultivating only oilseed crops - determine the best yield crop in each region
- Scenarios with only lignocellulosic crops- determine the best yield crop in each region

2. CROPS SELECTION: METHODOLOGY AND RESULTS

In this chapter, the methodology developed to screen the different oil and lignocellulosic crops that can be used as intermediate crops in the EU-27 as well as the prioritisation results are presented. For each crop, relevant information is compiled and systematically presented in crop factsheets, included in Appendix 5.

2.1. LIST OF INTERMEDIATE CROPS

In Table 1, the long list of intermediate crops included in the analysis and for which factsheets are generated is given.

Table 1 First overview of crops included in the study

Crop group	Crop
Oil crops - intermediate crops - additional in summer fallow	*Camelina (Camelina sativa)* *Sunflower (Helianthus annuus L)* *Crambe (Crambe abyssinica L.)* *Ethiopian Mustard (Brassica carinata)* *Castor (Ricinus communis L.)* *Safflower (Carthamus tinctorious L.)* *White Mustard (Brassica alba or B. hirta, a.k.a. Sinapis alba))*
Oil crops - intermediate crops - additional in winter fallow	*Camelina (Camelina sativa)* *Crambe (Crambe abyssinica L.)* *Ethiopian Mustard (Brassica carinata)* *Safflower (Carthamus tinctorious L.)*
Lignocellulosic crops - intermediate crops additional in summer fallow	*Biomass Sorghum (Sorghum bicolor L.)* *Sunn hemp (Crotalaria juncea L.)* *Kenaf (Hibiscus cannabinus L.)* *Industrial Hemp (Cannabis sativa L.)*

The information in the factsheets (see Appendix 5) serves as the basis for screening and selecting the most promising crops that will be further evaluated in this study as intermediate crops. Generally, the experience with growing oil and lignocellulosic crops as intermediate crops is still limited in the EU. The information in the factsheets is based on two main information sources:

1. Expert knowledge and field trial experiences derived from former EU projects such as MAGIC, MIDAS, BECOOL, BIKE, CARINA, 4CE-MED, PANACEA, FIBRA, COSMOS, EUROBIOREF (see also project descriptions in Appendix). In all these projects, many field trials were done with the crops listed in Table 1 in a wide range of climatic regions of the EU-27.

2. Published scientific information available and accessible to the consortium members (referenced in the factsheets in Appendix 5).

The factsheets provide a description of each crop, including the origin and an overview of research that has been done for it. They also cover information on the experience with growing the crop in the EU, soil preparation and crop establishment, existing and already tested varieties in EU, diseases, pests risks and management needs in terms of inputs (nutrients, pesticides, water). The factsheets

provide a detailed performance score for the screening criteria based on which the most promising and suitable intermediate crops are selected for the next steps of the study as explained in the next section.

2.2. CRITERIA FOR CROPS SELECTION

Among the various crops considered, a set of evaluation criteria was developed to assess and score their performance. Based on these scores, the highest-performing crops were prioritised for yield simulations and biomass availability calculations. The criteria are the following:

1. Climate suitability to ensure that the selected crops fit to the current and future climate conditions in the EU and to select at least one suitable oil crop and, if possible, one or more suitable lignocellulosic crop per environmental zone in the EU

2. Suitability to become an intermediate crop: the crop should be able to grow and perform its growth cycle within the fallow land periods left in conventional crop rotations on arable land. In this way, it does not cause any additional land demand

3. Attainable yields (t/ha of oil seeds, oil, or biomass)

4. Environmental performance: no negative impact or opportunities for win-win regarding environmental issues for soil health, water quality and quantity and biodiversity

5. Technology readiness level (TRL): The technology readiness of the different crops was evaluated across the main environmental regions of Europe (Northern, Central, and Southern Europe), taking into account current production levels, as well as the availability of propagation material and mechanisation.

Specifically, the final crop selection is based on a scoring on these five aspects described in the crop factsheets (Appendix 5) and summarized in Section 2.3.6. This selection also ensures that there will be at least one oil and, if possible, one lignocellulosic crop suitable in every environmental zone and in every NUTS-3 region. Below, the screening factors for assessing the crops are elaborated.

1) Climate suitability:

For the climate suitability, field trial based expert information and scientifically published information is collected per crop, focusing on the specific climatic factors required for the crop to survive and produce a sufficient yield (less than 75% yield reduction of the attainable yield). These climatic factors are integrated to develop climate suitability maps at each NUTS-3 region in the EU-27. The climate suitability is mapped according to the following factors:

- *Minimum length of growing season*: This refers to the duration (in days) during which temperature is suitable for plant growth (base temperature).
- *Minimum length of growing degree days (GDD)* which is also linked to base temperature: It refers to the accumulated heat required during the growing season, reflecting the warmth a plant needs to reach essential developmental stages.

- *Killing frost (KF)* is the temperature level below zero that crops can cope with. The level to which the crop (above and below ground biomass) can survive is determined by the number of days of mild to heavy frost. The temperature level, but also the number of consecutive days at this frost level are taken into account.
- *Minimum level of precipitation* the crop needs during the growing season.
- *Maximum level of precipitation* a plant can handle during (part of) the growing season (not applicable to all crops).
- *Maximum temperature* at which a crop can still give a sufficient yield (≥ 25% of the attainable yield) (not applicable to all crops).

The combined climate factors are then used to produce crop specific zonation maps of Europe, classifying regions as either suitable or unsuitable.

For the annual crops that produce seeds (or other storage organs), the growing season is assessed more strictly as reaching maturing phase is crucial. For lignocellulosic crops, it is acceptable if the minimal level of growth season and GDD are not completely reached, as reaching maturity phase is not necessary for harvesting.

2) Suitability to grow as an intermediate crop

This evaluates whether the crop should be able to be grow in EU-27 regions as a summer or a winter cover crop in rotations of annual crops that are common in the EU and that are mostly aimed at producing food and feed.

3) Attainable yields

A literature review is being conducted to collect information on the yield levels of each crop as reported in published studies. In the factsheets, the yield levels are reported and presented, with the data categorized according to type of farming systems applied (as defined in the former). While the primary focus is on collecting yield data for crops grown specifically as intermediate crops, the scarcity of available data has also necessitated sometimes the inclusion of yield data from instances where these crops were cultivated under other types of management systems.

4) Environmental performance

Among the selection criteria listed above, environmental performance can encompass a wide range aspects and parameters, hence it is further defined here. The environmental performance of each crop, when used as intermediate/cover crop, is scored individually and reported in the respective factsheet based on a qualitative risk and opportunity assessment. The scoring is conducted relative to a scenario where the land would otherwise remain fallow within the rotation, whether during the winter or summer period. Thus, the assessment considers the incremental environmental impacts or benefits of introducing an intermediate crop compared to maintaining a rotational fallow period. Much attention is given to proposing crops and management practices that can deliver environmental win-wins when incorporated in existing conventional cropping systems as intermediate crops.

The scoring of environmental risks and opportunities will be done in relation to 5 aspects:

1) Soil health

2) Water quality

3) Water quantity

4) Biodiversity

5) Technology readiness level - The technology readiness of the different crops was evaluated across the main environmental regions of Europe (Northern, Central, and Southern Europe), taking into account current production levels, as well as the availability of propagation material and mechanisation

The scoring options are as specified in Table 2.

Table 2 Overview of scoring classes and colours.

Color	Scoring
	Very positive effect (as compared to rotational fallow)
	Positive effect (as compared to rotational fallow)
	No effect (as compared to rotational fallow)
	Low to medium adverse effect (as compared to rotational fallow)
	High adverse effect (as compared to rotational fallow)

1) Soil health

Activities such as physical, chemical or hydrological impact or a combination of them can affect the quality and biodiversity status of soil.

Field preparation practices like ploughing, tilling, disking, typically involve strong disturbance of the soil, and have an impact on soil structure. However, the extent of soil modification and damage during field preparation, plant management and harvesting strongly depends on the type of soil, soil moisture and timing. Generally, poorly structured soils (e.g., sandy soils and sandy loam soils) have a higher risk for mechanical damage and loss of soil via erosion. Wet soils (e.g., because they are poorly drained) are more susceptible to compaction, as wheelings from tractor tires tend to penetrate deeper and tramlines are more likely to develop (Johannsen & Armitage, 2010). Compaction makes the soil difficult to work with and negatively affects plants growth due to the difficulty of the roots to deeply penetrate the soil and access nutrients. In addition, it adversely affects soil biodiversity. Compaction resulting from the formation of plough layers also affects the water balance in soil, potentially leading to water logging (Johannssen & Armitage, 2010).

To what extent tilling and other physical soil activities will affect the build-up or decrease the soil carbon is debated and depends on the type of soil and weather conditions. It has been suggested that under no-till conditions, sequestration of soil carbon will be enhanced but such observations are not generally valid and the relation between soil physical handling and the degree of carbon sequestration seems to be highly conditional, depending on the combination of soil type, form of carbon in soil and obviously the type of tillage techniques applied (Ogle, et al., 2019) . However, what cannot be denied is that farming activities involving physical handling of soil can increase mineralisation of C, thus reducing the soil carbon stock. Furthermore, any cropping activity always entails soil disturbance and therefore a higher risk for soil erosion and loss of nutrients and carbon (Verheijen, et al., 2009). The removal of plants and/or plant residues leaves the soil bare and makes it immediately susceptible to erosion by wind or water. The use of cover and catch crops minimizes the time the soil is left bare and reduces the risks.

With permanent crops (perennials), once established, disturbance is less frequent than with rotational annual crops, including annual cover or intermediate crops, which require additional mechanized field management activities per year. When compared to annual crops, perennial crops are more effective in building up soil organic carbon (SOC), but also in enhancing soil structure, improving the water holding capacity and reducing erosion (Lewandowski, 2015), (Pancaldi & Trindade, 2020), (McCalmont, et al., 2017). The main reasons for this are the lower levels of mechanisation (and thus soil disturbance), the year-round soil coverage of perennial crops, and their deeper and more well-branched rooting (Pancaldi & Trindade, 2020), (McCalmont, et al., 2017), (Cossel, et al., 2020).

Fertilisers used, whether artificial fertilisers, manure, or biosolids such as sludge and compost, can have an impact on the load of unwanted substances in the soil such as (heavy) metals (e.g., cadmium (Cd), copper (Cu) and zinc (Zn) and, less commonly, uranium (U)) which may have a negative impact on soil biodiversity. Application of pesticides and herbicides may also lead to accumulation of toxic elements that adversely affect soil biodiversity. Any imbalanced fertiliser application, either mineral or organic has an impact on the nutrients balance in the soil. However, this has a relatively small impact on soil quality itself, but it poses broader environmental risks, specifically for air and water. Over-fertilisation for example can lead to increased GHG emissions (N_2O) and transfer of nutrients to ground and surface waters (leaching/run-off). In addition, certain fertilisers may contain heavy metals such as cadmium.

Summarizing, the three sub categories according to which the environmental performance of the crop on soil health needs to be evaluated are:

1a) Soil structure - needs to be maintained as much as possible. This implies minimizing activities that disturb the soil, lead to compaction which negatively affects the water balance in the soil.

1b) Soil organic carbon - SOC needs to be maintained or even increased as much as possible. This implies that losses of carbon through physical handling, increased erosion because of leaving the soil bare (especially in winter) or unbalanced removal (or even burning) of plant residues from and in the soil, need to be limited.

1c) Soil biodiversity -needs to be maintained as much as possible. This implies that application of toxic elements through pesticides, herbicides or fertilisers containing toxic elements such as heavy metals, should be avoided.

2) Water quality

All field preparations, crop treatments and harvesting activities that involve strong disturbance of the soil (e.g., ploughing, tilling, disking) or leave the soil bare for a short or long time, may enhance turnover of nutrients and thereby increase the potential risk of losing nitrogenous and phosphorus compounds into water resources through surface runoff and soil erosion (Vries, et al., 2021). This may lead to eutrophication of ground and surface water resources.

The choice of crops or rotation will have an effect on water quality. However, considering the existing range of crop-specific practices (which can vary depending on the agro-ecological zone), there is no generic 'impact' to be allocated to a specific crop. Clearly, crops with high annual fertiliser input demands (e.g., potato) or crops commonly used for the disposal of animal manure (forage maize) are more prone to impact water quality compared to those requiring low inputs or less intensive soil management (Vries, et al., 2021), (Wei, et al., 2024). Of course, the

level of input losses to surface water depends on a combination of factors such as water balance, soil type, crop type, slope, and ploughing directions. In general, the impact of agronomic practices on ground and surface waters is greatest in the areas with both highly intensive agricultural systems, and moderate to high rainfall which results in nearby surface water systems or high groundwater tables (Wei et al., 2024).

Traditional tillage practices completely expose the soil surface, leaving it very susceptible to erosion. Conservation tillage, however, involves soil management practices that minimise the disruption of soil, thereby reduces the erosion and degradation of soil and the adverse impacts upon waterbodies (Giller, et al., 2021). Moreover, the choice of crops, notably the use of cover or catch crops, can be very effective in reducing the load of nitrogen (N) and phosphates (P) into surface waters (Abdalla, et al., 2019). Regarding fertilization, both the type and the amount of fertilizer used, as well as the timing of application affect the impact of fertilizers on surface and ground water quality (Vries et al., 2021). To mitigate these potential impacts, regulations are already in place. For example, the application of manure is restricted or prohibited during winter, to reduce the risk of direct nutrient losses through run-off when soils are saturated or frozen (Midler, et al., 2022)

Irrigation may also enhance the leaching of nutrients and pesticides in the soil and ground and surface water (and also under specific circumstances to air). This happens especially in case of excessive inefficient irrigation which can lead to soil saturation (Wei et al., 2024). When soils become saturated, the excess water drains away, carrying nutrients and pesticides into water bodies. Irrigation on sloping terrain is even riskier as excessive irrigation water can also lead to increased topsoil erosion washing away nutrients to surface waters.

Lowering the groundwater table to facilitate workability of the soil will decrease the solubility of phosphate (P) but increases the possibility for nitrate (N) to leach. Increasing groundwater tables on the other hand may increase leaching of P but also decreases the displacement of nitrate due to the emission of it as either N_2 or N_2O (Wei, et al., 2024).

Adverse water quality effects may also occur from spraying with pesticides and herbicides, especially when they contain metals. For example, metals like arsenic and copper can be found in surface waters, largely due to drift. Drift-control measures are partially enforced within the EU. Despite mitigation measures, the accumulation of metals in soils and surface waters from these treatments can still be significant (Grung, et al., 2015).

Summarizing, the two sub categories according to which the environmental performance of the crop on water quality is evaluated are:

2a) Risk for leaching to ground and surface water due to fertilisers

2b) Risk for losses from spraying with pesticides & herbicides

3) Water quantity

Within Europe, there is a great variability in the availability of water resources and, resulting in a marked spatial variability of agricultural water management practices and consumption. Climate is the main factor that determines agricultural water consumption; there are regions where irrigation is the only source of water for crop cultivation (for example, over summer in the Mediterranean regions), while in other regions, irrigation is used as a supplement to rain-fed agriculture. Irrigation technology is also a major factor influencing the level of agricultural water

consumption. More specifically, in the EU three types of irrigation systems are generally used: 1) surface (gravity) irrigation where water is lead along the ground often flooding a whole parcel, 2) sprinkler irrigation where water is propelled over crops under high pressure, and 3) drop/drip irrigation where every plant is being watered drop by drop with micro sprinklers. The last 2 methods are the main irrigation methods used in the EU now these days, although this differs per EU country (JRC, 2019). The most water efficient technology is the drip irrigation while the surface irrigation system is the least efficient. On the other hand, there are also plenty locations in Europe where there is sufficient precipitation and agricultural activities can be fully rain-fed. However, climate change, with its associated rising temperatures and shifts in cropping patterns, is leading to an expansion of regions where irrigation is being introduced.

The main negative effect of large-scale irrigation and drainage practices is related to loss of natural habitats, particularly wetlands (Ramsar.org, 2023). Beside this effect, the pumping and over exploitation of natural water sources can lead to a complete destruction of the water balance at catchment level leading to dehydration and salinity problems in all natural and semi-natural habitats, including areas bordering with agricultural lands (Bisselink, et al., 2020).

According to the agri-environmental indicator on irrigation (Eurostat, 2019), irrigation practices present both advantages and disadvantages. One significant disadvantage is that excessive irrigation can lead to accumulation of salts in the soil which negatively impact plants' growth and workability of the soil. In severe cases, it can even lead to complete soil degradation followed by land abandonment. Salt accumulation occurs through the following mechanisms: 1) the evaporation of irrigation water, which leaves salts behind, 2) rising groundwater tables which can be enhanced by over-application of irrigation and, 3) capillary water movements bringing soil water to the surface where it evaporates and leaves salts behind (Eurostat, 2019).

The evaluation of the environmental impact will be done according to the total minimal water requirement and the water use efficiency (WUE) of the crop (Kakabouki, et al., 2021). The first factor is taken into account in the mapping of the climate suitability for the crop. This implies that if in one location there is not enough precipitation to let the crop grow in a rain-fed situation, the location will not be selected as suitable for the crop. The WUE of every crop will be determined through literature and the crops that have a higher WUE will be prioritized over the ones with lower values.

4) Biodiversity

Different farming activities/operations exert different influences, both positive and negative on biodiversity depending on the total acreage and the way they are implemented in farm lands. These pressures can be categorised into:

1) Direct local influence: such as habitat fragmentation, habitat diversification, canopy structure and soil cover;

2) Indirect influence via the environment: such as eutrophication, acidification, water balance effects and also climate change.

The underlying mechanisms linking land use, land management changes and biodiversity impact are based on the principle that the species population viability depends on the amount and quality of habitat, spatial configuration of the habitat within the landscape and landscape permeability. These four elements influence the capacity of populations to disperse across the landscape, to access essential resources (e.g. feed, roost, find shelter), to encounter with other individuals, to

successfully reproduce themselves and to maintain a large and healthy population. If these landscape measure factors are disrupted through changes in land cover and/or land management, this may, depending on the magnitude of the changes and the type and presence of biota, lead to adverse effects.

In evaluating the potential impacts of agricultural practices on biodiversity, the focus here is on how certain management practices affect biodiversity, primarily through their influence on habitat quality. Negative impacts arise from practices such as: irrigation leading to depletion of water sources, drift and leaching of pesticides, use of herbicides and fertilizers and their effect on local biota; but also landscape structural changes which influence the ability of species to disperse in the landscape and disrupt foraging routes and isolate remnant populations (Klebl, et al., 2024). In principle, land management practices that are compatible with biodiversity conservation are to be applied. These include the use of domestic species and local varieties, avoiding monocultures and invasive species, preferring perennial crops and intercropping, use of methods causing low erosion and machinery use, low fertilizer and pesticide use and avoiding active irrigation[3].

The introduction of crops that provide food sources for wild species, for example insects, can be very beneficial for biodiversity. Plants with long flowering seasons, producing pollen as well as nectar with high sugar content, help to collect healthy food for honey bees and other pollinators for the winter (Bufe & Korevaar, 2018).

In conclusion, the two sub categories according to which the crops impact on biodiversity is evaluated are:

4a) Habitat quality - Practices leading indirectly to loss of habitat quality such as eutrophication, acidification, disturbance of water balance needs to be avoided. This implies that application of pesticides, herbicides and/or fertilisers should be minimized and cropping practices that increase erosion and leaching should be avoided.

4b) Species viability contribution which depends on amount and quality of habitat, spatial configuration of the habitat within the landscape and landscape permeability. To evaluate this principle, with respect to the selected intermediate crops the following aspects are relevant:

1) Whether the crop flowers for a longer period of time and also at moments in the year in which few other crops are flowering (such as in early spring, winter and middle of summer in a Mediterranean climate).

2) Whether it contributes to crop diversity at the landscape level. This happens when an additional less common crop is added to the local crop mix. Arable landscapes in the EU have become less diverse in crop mix since fewer types of crops have become produced more and more in monocultural systems (e.g. wheat, barley, grain maize, potatoes, sugarbeet, rice) (VELDE, et al., 2025) (Gawdiya, et al., 2025). Monocultures contribute to reduced biodiversity and ecosystem imbalances, while more crop diversity in agricultural landscapes promotes resilience in agroecosystems with lower pest pressure (Gawdiya, et al., 2025).

[3] This does not constitute a comprehensive biodiversity assessment. Rather, it provides a qualitative basis grounded in key biodiversity-impacting principles to identify which crops and practices are likely to perform better and where negative effects can be minimised or avoided.

3) Whether it increases the landscape structural diversity (Hufnagel, et al., 2020). This happens when a crop introduced enhances the structural diversity of the landscape, for example by increasing the variation in plant height within and between fields, thereby contributing to more heterogeneous spatial crop arrangements and this creates new habitats for specific species of e.g. mammals, insects.

4c) Invasive species - Use of invasive species should be avoided. This aspect is mentioned here, but will not be evaluated more specifically since invasive species were excluded from the selection of crops for this study.

5) Technological readiness level (TRL)

The TRL level of the crop can range between 1 to 9. The TRL level is scored according to the factors presented in Figure 1. To assess the TRL of the crops under this study, key cultivation steps were evaluated such as the adaptability of each crop to different climatic zones, the availability of propagation material, and the access to suitable machinery for mechanical cultivation.

Figure 1 Example: Factor scores for Camelina Sativa determining the TRL scoring.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

 = TRL >7, industrial production available at demonstration (TRL 8) or commercial scale (TRL 9)

 = 5≤TRL≤7, production available at pilot (TRL 5-6) and small-scale demonstration scale (TRL 7)

 = 3≤TRL<5, experimental scale from research to production development

 = TRL<3, only basic research data available

When the entire cultivation process, from sowing to harvesting, is well established and technically feasible, the crop is considered to have reached TRL 7. At TRL 7-8, cultivation can be demonstrated in pilot or demonstration fields. When the crop is grown under real farming conditions at commercial scale, it is considered to have reached TRL 9. When at least one of the critical cultivation stages, such as seed availability or the lack of appropriate harvesting machinery, is not yet fully developed or organized, the TRL is considered below 7, typically ranging from TRL 5 to 7. In such cases, the crops are generally cultivated in pilot or experimental fields, rather than under full-scale farming conditions.

When multiple critical cultivation stages require further development, such as limited seed availability, insufficient agronomic knowledge, or lack of appropriate machinery, the TRL is considered below 5, typically ranging from TRL 3 to 5. In these cases, the crops are usually confined to experimental fields, where initial testing and optimization take place.

In the factsheets, the TRL scoring is specified for production level in climate zones, availability of propagation material and mechanization separately. Also a total TRL score is given per crop taking into account the total scoring on all criteria. This total score can range between 1-9 as explained in the former.

2.3. RESULTS OF THE PRIORITIZATION OF INTERMEDIATE CROPS

As part of the final prioritization, the aim is to select at least one oil crop and one lignocellulosic crop suitable in every climate zone. For simplicity, the EU is classified into three main climate zones, North, Central and South (see Appendix 2). For the considerations regarding points 2 (water quality), 4 (biodiversity) and 5 (TRL) above, this classification into these 3 climate zones is followed. For the selection of crops regarding point 1 (Climate suitability), the three main climate zones are further split as follows (see Appendix 2 - map with environmental zones making up the three and five climate zones):

1) North
2) Central:
    a. Central - Atlantic
    b. Central - Continental
3) Mediterranean:
    a. Mediterranean - North and Mountains
    b. Mediterranean - South

2.3.1. Climate Suitability

The initial list of crops includes 7 oil crops and 4 lignocellulosic crops (See Table 1 in Chapter 2). The climate suitability of each crop was mapped according to 6 climate requirements as described in Section 2.2 (Section 1.2- Climate requirements). These requirements were mapped and evaluated against both current and climate conditions in 2050 under the SSP5-8.5 scenario, which represents the most extreme global warming pathway[4]. A further presentation of the impact of other climate change scenarios used in the study are reported in Chapter 3. The climate suitability per crop is extensively described in the 11 crop factsheets that are included in Appendix 5 of this report.

[4] SSP5-8.5 reflects the highest radiative forcing pathway and the most rapid climate change impacts, with projected global temperature increases of 3.3-5.7 °C above pre-industrial levels by 2100.

Table 3 Overview of climate suitability per crop according to current and future climate scenario (for details see crop factsheets in Appendix 5).

Crop - summer/winter	North		Central - Atlantic		Central - Continental		South - Mediterranean North & mountains		South - Mediterranean South	
	Current climate	2050 climate	Current climate	2050 climate	Current climate	2050 climate	Current climate	2050 climate	Current climate	2050 climate
Camelina- summer										
Camelina - winter										
Carinata/Ethiopian mustard-summer										
Carinata/Ethiopian mustard-winter										
Crambe - summer										
Crambe - winter										
Safflower - summer										
Safflower - winter										
Sunflower - summer										

Crop - summer/winter	North		Central - Atlantic		Central - Continental		South - Mediterranean North & mountains		South - Mediterranean South	
	Current climate	2050 climate	Current climate	2050 climate	Current climate	2050 climate	Current climate	2050 climate	Current climate	2050 climate
White Mustard - summer										
Castor bean - summer										
Biomass Sorghum - summer										
Industrial Hemp - summer										
Sunn Hemp - summer										
Kenaf - summer										

In Table 3, the summary of the climate suitability per environmental zone for oil and lignocellulosic crops is presented. Among them, four oil crops can be grown as both winter and summer/spring intermediate crops, namely, Camelina, Carinata, Crambe and Safflower. The four lignocellulosic crops can only be grown as summer crops. From the overview in Table 3, it becomes clear that the Northern climate zone has the fewest suitable crops while the Central zone has the most.

The Southern climate zone, overlapping with the Mediterranean zone, is very suitable for all crops in terms of growing season length and Growing Degree Days (GDD). The limiting factor however is precipitation. Since the climate suitability is mapped following a rain-fed situation, precipitation falls short for most crops in the Mediterranean-South region that are on the field in the summer period. The most suitable crops for the Mediterranean region are therefore oil crops that can replace the winter fallow period in conventional crop rotations. This applies to Camelina, Carinata, Crambe and Safflower.

Among the four lignocellulosic crops evaluated, the best option for the South is Sorghum, a crop with relatively lower minimal water requirements than Industrial Hemp, Sunn hemp and Kenaf. Still the yields will remain very modest even for sorghum if no irrigation is applied. Therefore, some irrigation for lignocellulosic crops, that grow in the South and only in summer, would still be recommended particularly during the establishment phase of the crop.

The Central region, consisting of the Atlantic and Continental zones (see Appendix 2), has a broad suite of suitable crops and many of the oil crops can primarily grow as summer crops and some of them as winter crops but only in the Atlantic zone. The suitability for summer crops is good, as water availability is generally higher in this zone as compared to the South. Some oil crops have however a lower suitability as winter crop due to the occurrence of killing frost levels, especially in the continental part. However, under the case of intense climate change, these very cold days are expected to decrease and the length of the growth season and GDD may increase. As a result, the range of crops in the Central zone is expected to increase. For example, the agricultural area in the Central zone where oil crops such as Camelina, Carinata (Ethiopian mustard) and Safflower can be grown as winter crops will increase. A similar effect is observed for lignocellulosic crops, such as, Sorghum and Industrial hemp, but now in the summer period. Although the suitability of these crops is not highly efficient, climate change can lead to increases in the area having the right length of growth season and GDD.

In the Northern zone, the area suitable for intermediate crops is certainly more limited because of the large number of killing frost days. However, climate change is expected to increase the suitable area. This for example applies to Camelina, Crambe and White mustard, but also in a less extent to Safflower and Sunflower. All the oil crops should be best grown as summer crops. For the four lignocellulosic crops, their suitability is very limited, but in the future, there could be an expansion of suitable areas under the influence of climate change, for Sorghum to be grown as a summer intermediate, particularly in the Baltic states and in the South of Sweden along the coast.

In conclusion, from a climate suitability perspective, the top oil and lignocellulosic crops per climate zone would be as follows:

North:

1) Oil crops: 1. Camelina - summer, 2. Crambe - summer, 3. White mustard - summer, 4. Sunflower-summer
2) Lignocellulosic crops: None

Central - Atlantic:

1) Oil crops: 1. Camelina - summer, 2. Crambe - summer, 3. Sunflower-summer, 4. White mustard - summer, 5. Safflower - summer, 6. Carinata - summer, 7. Camelina - winter, 8. Crambe - winter
2) Lignocellulosic crops: 1. Sorghum - summer

Central - Continental:

1) Oil crops: 1. Camelina - summer, 2. Crambe - summer, 3. Sunflower-summer, 4. White mustard - summer, 5. Safflower - summer, 6. Camelina - winter
2) Lignocellulosic crops: 1. Sorghum - summer

South - Mediterranean North and Mountains:

1) Oil crops: 1. Camelina - winter, 2. Crambe- winter, 3. Safflower - winter, 4. Carinata - summer, 5. Carinata - winter, 6. Sunflower - summer
2) Lignocellulosic crops: 1. Sorghum - summer

South - Mediterranean South:

1) Oil crops: 1. Camelina - winter, 2. Crambe- winter, 3. Safflower - winter, 4) Carinata - winter
2) Lignocellulosic crops: None

2.3.2. Suitability to become an intermediate crop fitting to rotational fallow periods

The crop needs to be added to the conventional crop rotations in the EU without requiring additional land. This implies it should be able to perform all its growth phases either in the rotation summer fallow period or in the winter fallow period.

Land use change impacts arise when the production of an intermediate crop leads to displacement or reduction of primary food crops. Intermediate crops that cannot complete their growth cycle within the fallow period may delay the cultivation of primary crops, thereby affecting the supply potential of essential food production.

The crops that can easily fit in the summer fallow period of a conventional rotation, which generally runs in the Northern hemisphere from June until end of September, and have been proven to function well in such rotations are Camelina, Crambe and Sunflower (Hossain, et al., 2019), (Volsi, et al., 2021), (Scott, et al., 2021), (several EU project results e.g. BIKE, MIDAS, CARINA). In the central and eastern part of EU, lignocellulosic crops like Biomass Sorghum and Sunn hemp have been proven to fit into a summer fallow (Zegada-Lizarazu, et al., 2021). Using White mustard should also work well, but less experience has been derived for it.

Moreover, Camelina and Crambe have demonstrated the ability to complete their growth phases when fitted in the winter fallow period of conventional rotations in a wide number of EU regions (Gesch & Archer, 2013), (Potter, et al., 2023). For the four lignocellulosic crops, their introduction in the summer fallow period has been proven to work in different field trials in the EU performed in different EU projects (e.g. BECOOL, BIKE, MAGIC, CARINA) as described in more detail in the respective factsheets of these crops (Appendix 5).

Crops that have proved not to efficiently fit in both the summer or winter fallow period for conventional food crop rotations are Safflower and Carinata/Ethiopian Mustard. This is a conclusion coming from several field trials done in the EU (IENICA, Crops2Industry, Eurobioref, MAGIC, MIDAS, IASIS) which showed that these crops

need to be established in early spring (or earlier like mid-February in the South or later in Central EU), and be harvested in September or later. This means that these crops cannot become a secondary crop with food crops that are mostly grown as winter crops in the EU such as wheat, barley or oil seed rape that cover a growth cycle from October/November until May/June when they are harvested. This implies that Safflower and Carinata can be regarded as more mid-season crops rather than intermediate crops.

So overall, it can be concluded that 9 of the 11 selected crops are in principle suitable to be added to existing rotations as an intermediate crop, because their length of growth season and GDD are relatively short and they have been proven to fit in either the winter or summer fallow periods that are followed in the North, Central and/or South Europe.

2.3.3. Yield levels

To determine which crop performs better in terms of yield can be challenging, as yields are strongly dependent on locational factors, annual weather variability and types of varieties used. For the comparison and prioritization exercise at this stage, we compared the minimum, maximum and average yield levels identified in a wide range of published field trial results to provide a more complete perspective. For reporting the yield levels, public references have been used and included in the crop specific factsheets (Appendix 5). For Sunflower and Industrial hemp yield data were used from Eurostat statistics instead, because these are commercial crops that already grow at large scale in most EU countries.

For the seven oil crops, a comparative figure of the yields range expressed in tonnes of oil seed per hectare (Figure 2) and in tonnes of oil yield per hectare (Figure 3) are presented. Notably, the divergence between the average and maximum/minimum values for the different crops is generally not large, typically not exceeding 0.5 t/ha. For the average values, Sunflower comes out as the best performing, followed by Carinata and Crambe. In addition, Carinata demonstrates significant variability in yield, a result of the many field trials conducted in different locations and conditions for it. Considering the maximum yield values, Sunflower comes out first together with Castor followed by White mustard and Carinata. Camelina, Crambe and Safflower though show the most stable results, with smaller extremes in yields reported.

The conclusion for oil crops is that Sunflower, Carinata and Crambe are the best performing in terms of yield levels. Sunflower seed yields can be expected to be around 2.5 tonnes seeds per hectare, although for this one fewer field trial results are publicly available. For Carinata and Crambe, crop yields up to 2 tonnes seeds per hectare seem to be realistic. For Camelina, Safflower and White mustard, the seed yields are more likely to remain around 1.5 tonnes seed yield per hectare. Castor yields show strong extremes and it is more difficult to draw an average seed yield conclusion.

For the four lignocellulosic crops, the yield difference between Sorghum and the rest is large (see Figure 4). For the average ranges, Biomass sorghum comes out as highest, followed by Sunn hemp. For the maximum values, Kenaf comes out first followed by Biomass sorghum, while Industrial hemp is clearly shown to be the lowest performing by a significant margin. It should be mentioned however that the number of reference points for Kenaf is very limited. The conclusion for lignocellulosic crops is clear; the highest yields can be reached with Sorghum ranging on average between 14 and 21 t_{dm}. This is followed by Kenaf with between 13 and 18 t_{dm}.

Figure 2 Overview of oil seed yields (tonnes/ha) (for sunflower data points are based on EU statistics for 27 EU member states and UK, rest based on literature references included in the crop specific factsheets in Appendix 5). Figure is based on average, minimum and maximum yield levels reported in literature. Not all references report the three levels.

Figure 3 Overview of oil yields (tonnes/ha) (seed yield × oil content) (for sunflower data points are based on EU statistics for 27 EU member states and UK, rest based on literature references included in the crop specific factsheets in Appendix 5).

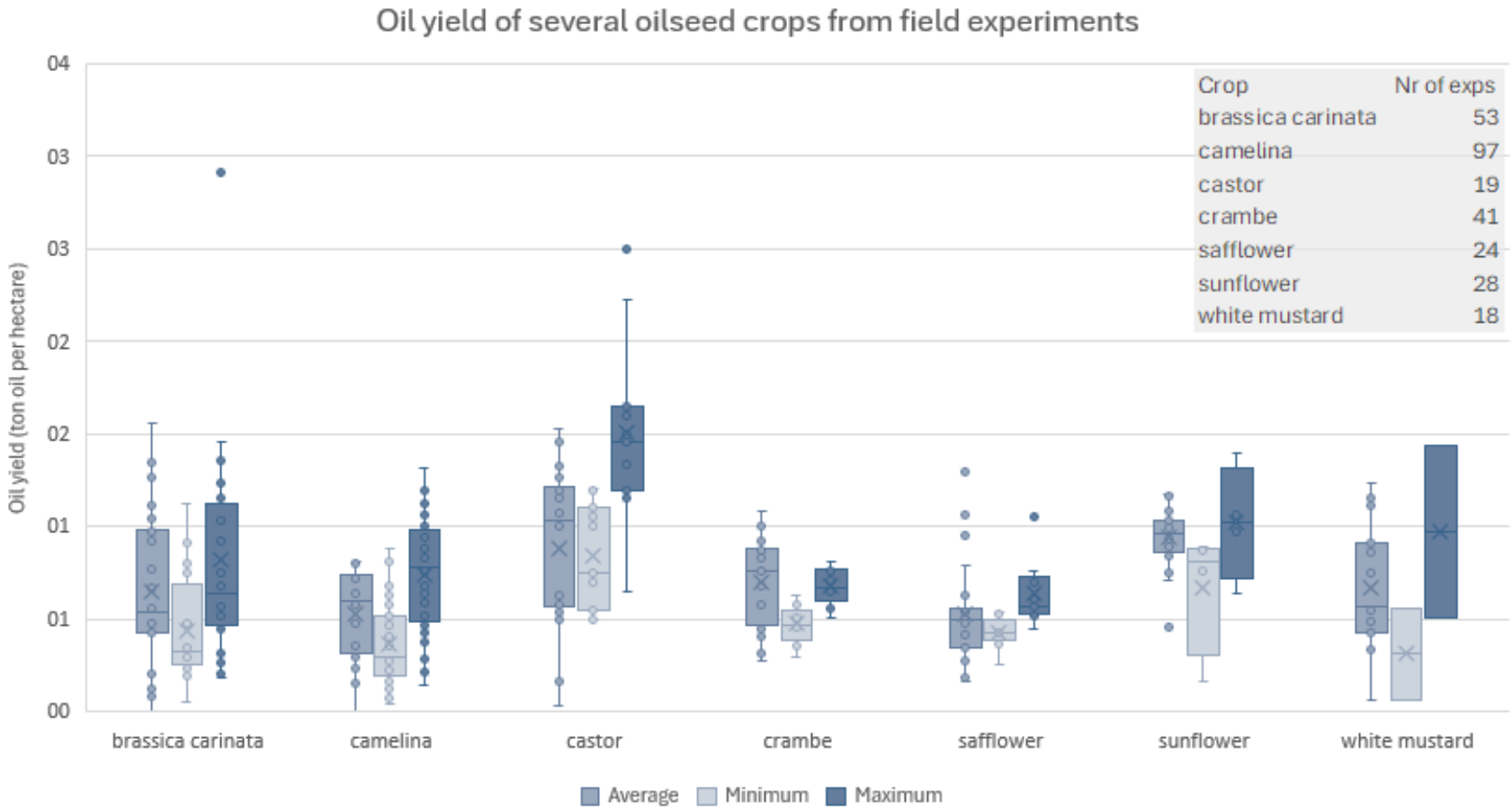
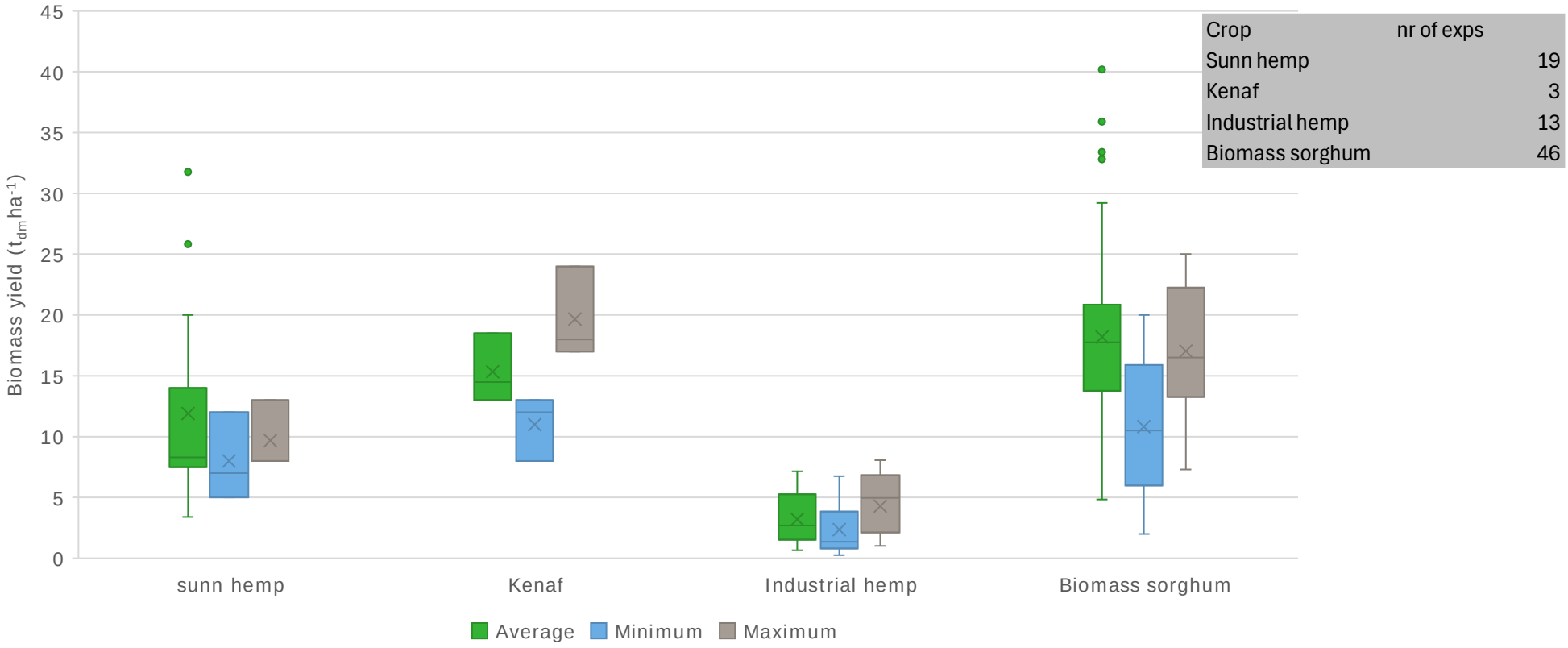


Figure 4 Overview of biomass yields (t_{dm}/ha) (for Industrial hemp data points are based on EU statistics for 13 EU countries where hemp is grown commercially, rest based on literature references included in the crop specific factsheets in Appendix 5). NOTE: Figure is based on average, minimum and maximum yield levels reported in literature. Most references report only one figure and this is reported as an average. This explains why averages and maximum yield levels in the figure are not that different.



2.3.4. Environmental performance

Here, a summary of the environmental performance evaluations per crop is presented, using the criteria for scoring explained in former section 2.2. The environmental performance of each crop, when used as intermediate/cover crop, is scored individually and reported in the respective factsheet (see Appendix 5) based on a qualitative risk and opportunity assessment. The scoring is conducted relative to a scenario where the land would otherwise remain fallow within the rotation, whether during the winter or summer period. Thus, the assessment considers the incremental environmental impacts or benefits of introducing an intermediate crop compared to maintaining a rotational fallow period. As discussed in section 2.2, the environmental performance was evaluated for:

1) Soil health

2) Water quality

3) Water quantity

4) Biodiversity

Specifically, the scoring is given on a comparative basis with the objective of benchmarking the different oil and lignocellulosic crops. This approach means that no definitive conclusions can be drawn regarding the absolute environmental impacts of these crops, but rather, it allows for conclusions about which crops perform better relative to the others and relative to leaving the soil bare during the rotational fallow period.

1) Soil Health:

For soil health performance, 3 different sub-indicators were scored, namely soil structure, organic carbon content, and soil biodiversity as explained already in section 2.2 (see .

Table 4). The effects of the introducing an intermediate crop to the conventional crop rotation can lead to some additional disturbance of the soil, and adversely affect the soil structure. This cannot be avoided because every crop needs mechanization to establish and harvest it and possibly the use of nutrients and plant treatment products. For most crops this can be mitigated however, by applying a no till establishment.

In relation to the effect on soil organic carbon, the contribution of the crops is generally positive, since the crops serve as a cover that prevents erosion and the roots bring extra carbon to the soil, particularly those that have large and deep roots (Lewandowski, 2015), (Pancaldi & Trindade, 2020), (Cossel, et al., 2020). Exceptions are Sunflower and Castor that are less dense and still leave the soil largely bare.

In terms of soil biodiversity, the effect is neutral for the crops that do not need any plant protection products, while it is negative where some additional pesticides or herbicides are required. This is because pesticides and herbicides also kill beneficial soil organism such as invertebrates and also microbes (Klebl, et al., 2024). The crop performing most negative is Sunflower which generally requires higher inputs because of relatively high disease and pest pressure.

In conclusion, the oil crops that are most beneficial to soil health, with the exception of some soil structural disturbance risk, are Camelina and Crambe. For the lignocellulosic crops, this applies to Sorghum and Sunn hemp.

Table 4 Crop performance in relation to soil health aspects.

Crops	Soil structure	Soil organic carbon	Soil biodiversity
Camelina- summer			
Camelina - winter			
Carinata/Ethiopian mustard-summer			
Carinata/Ethiopian mustard-winter			
Crambe - summer			
Crambe - winter			
Safflower			
Sunflower - summer			
White Mustard - summer			
Castor bean - summer			
Biomass Sorghum - summer			
Industrial Hemp - summer			
Sunn hemp - summer			
Kenaf - summer			

The scoring options are as follows:

Colour	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

2) Water quality:

For water quality, two different sub-indicators were scored per crop, as extensively described in every crop factsheet in Appendix 5. In Table 5Table 5, the summary of the scoring on these 2 aspects is presented.

The introduction of an intermediate crop to the conventional rotation generally has a positive effect as prevents leaching of nutrients to groundwater. Generally, this is more effective for lignocellulosic crops than for oil crops, because of their deeper rooting systems (Pencaldi and Trindade, 2020). Especially Sunn hemp is very effective when it comes to nutrient leaching prevention, because it also fixates nitrogen which entails no need for any additional nitrogen application (Zegada-Lizarazu, et al., 2021). However, there are some exceptions. Sunflower has no positive effect on nitrogen leaching prevention because of the limited soil coverage. For Castor the nitrogen leaching may even increase because of its low soil coverage and need for high nitrogen inputs.

The risk of water pollution from spraying is neutral for most oil crops, with the exception of Sunflower and Castor that need more plant protection then the other oil crops. For lignocellulosic crops, this applies to Industrial hemp and Kenaf, that need higher inputs of pesticides than Sorghum and Sunn hemp.

The overall conclusion for the water quality impact of oil crops is that it can be negative only for Sunflower and Castor. For lignocellulosic crops, there is some increased risk for adverse effect on water quality due to spraying, particularly in

Industrial Hemp and Kenaf applications, but prevention of leaching on ground water quality works out positive.

Table 5 Crop performance in relation to water quality.

Crops	Risk for leaching to ground and surface water	Risk for loss from spraying pesticides, herbicides
Camelina- summer		
Camelina - winter		
Carinata/Ethiopian mustard-summer		
Carinata/Ethiopian mustard-winter		
Crambe - summer		
Crambe - winter		
Safflower		
Sunflower - summer		
White Mustard - summer		
Castor bean - summer		
Biomass Sorghum - summer		
Industrial Hemp - summer		
Sunn hemp - summer		
Kenaf - summer		

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

3) Water quantity:

The impacts of the crops on water quantity are presented in Table 6. Generally, the oil crops selected have low to very low water requirements (100 mm precipitation in the growth season is enough) and therefore their contribution to the total water demand of the agricultural system is limited. This works even better for crops such as Camelina, Crambe and Safflower that can be grown in winter when there is enough water available, even in the South of Europe. For Castor, the water demand is higher than for the other oil crops as it requires at the minimum >250 mm of rain in the growing season. Summarizing, all oil crops can in principle be grown without irrigation, even in the South but then only when they are grown as winter intermediates.

Regarding lignocellulosic crops, Sorghum is the crop that can cope best with low water availability because it has a very high water use efficiency (Dalton, et al., 2024). The other crops need more water; hence, it is challenging to grow them in the South without irrigation. For Sorghum, irrigation would of course also be beneficial for increasing the yield, but it is generally not a necessity in most of the South, to ensure crop survival. Sunn hemp water requirement is still lower than that of Kenaf and Industrial hemp.

Concluding, the crops with the lowest impact are Camelina and Crambe from the oil seed category and Sorghum from the lignocellulosic group.

Table 6 Crop performance in relation to water quantity.

Crops	Water quantity
Camelina- summer	
Camelina - winter	
Carinata/Ethiopian mustard-summer	
Carinata/Ethiopian mustard-winter	
Crambe - summer	
Crambe - winter	
Safflower	
Sunflower - summer	
White Mustard - summer	
Castor bean - summer	
Biomass Sorghum - summer	
Industrial Hemp - summer	
Sunn hemp - summer	
Kenaf - summer	

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

4) Biodiversity

For biodiversity performance, three different sub-indicators were scored (see Table 7), namely habitat quality, species viability contribution and invasive species.

Habitat quality is closely linked the potential use of pesticides and herbicides that might be needed for certain crops to ensure their growth (See Section 2.2). The effects of introducing an intermediate crop to the crop rotation will for most oil crops not lead to a negative effect on the habitat quality, except for Safflower, Sunflower, White mustard and Castor that require higher inputs of pesticides and nutrients than the other crops, as already mentioned in the former section (water quality) and is extensively described for these crops in the factsheets in Appendix 5. For the lignocellulosic crops, pesticide inputs are generally not necessary, except for Kenaf.

Regarding species viability, most of the crops selected have a positive effect because all of them provide extra food to pollinators and insects and contribute to landscape diversity. Importantly, most of these crops, when grown as intermediate crops, flower in periods when flowers in the fields are scarce offering support to biodiversity. The scores in relation to viability in Table 7 are only neutral for castor because it does not provide very attractive flowers to insects and no attractive shelter options to wild animals. Finally, none of the selected crops is invasive.

Overall, the best performing crops in terms of biodiversity are Camelina, Carinata and Crambe among the oil crops and Sorghum and Sunn hemp among the lignocellulosic. This is primarily related to their lower pesticide and herbicide input requirements which helps to maintain habitat quality, in contrast with the other crop alternatives, but also the provision of food to insects and shelter to wild animals.

Table 7 Crop performance in relation to biodiversity.

Crops	Habitat quality	Species viability contribution	Invasive species
Camelina- summer			
Camelina - winter			
Carinata/Ethiopian mustard-summer			
Carinata/Ethiopian mustard-winter			
Crambe - summer			
Crambe - winter			
Safflower			
Sunflower - summer			
White Mustard - summer			
Castor bean - summer			
Biomass Sorghum - summer			
Industrial Hemp - summer			
Sunn hemp - summer			
Kenaf - summer			

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

2.3.5. Technology Readiness Level (TRL)

TRL is scored according to the four aspects summarized in Table 8, namely production level, propagation material, locations where suitability has been tested and available mechanisation available (see Section 2.2 for further details). The TRL level of the crop can range between 1 to 9. To reach an average TRL equal or above 7, the suitability should be  in at least 2 of the three environmental zones (ENZs) and for propagation material and mechanization available (at least at pilot or demonstration scale). A TRL 9 is reached only for crops that are fully commercial.

Oil crops with the highest TRL (= 9) are White mustard and Sunflower. White mustard is already widely used as cover crop in France, Germany and the Netherlands to reduce nitrogen leaching and improve soil structure as part of advanced conditionality measure. Sunflower is also a common oil crop, widely produced all over Europe. Oil crops with the lowest TRL are Safflower and Castor bean. Specifically, for Safflower the propagation material is still limited (there is hardly any seed available for varieties with high-oleic content) and has not been widely tested in different regions across Europe (see for details crop factsheets in

Appendix 5). For Castor, the mechanization is still not well developed. For the other oil crops, the TRL is at 6 or 7 based on the availability of propagation material. The lower TRL score on propagation material for Carinata, and Crambe is related to the limited number of companies that sell seeds for these crops and the limited number of suitable varieties available on the market.

For the lignocellulosic crops, Biomass sorghum and Industrial hemp have the highest TRL, while for the other two, the experience in the EU is still limited and propagation material is limited.

Table 8 TRL scores for the different intermediate crops.

Crops	Production level	Suitability tested in ENZ			Propagation material	Mechanization available	Total TRL score
		North	Central	South			
Camelina	🙂	🙂	🙂	🙂	🙂	🙂	7
Carinata/Ethiopian mustard	🙂	🙁	😐	🙂🙂	😐	🙂	6
Crambe	🙂	🙁	🙂	🙂	🙂	🙂🙂	7
Safflower	🙂	🙁	😐	🙂🙂	😐	🙂🙂	5
Sunflower	🙂	🙂🙂	🙂🙂	🙂🙂	🙂🙂	🙂🙂	9
White Mustard	🙂	🙂	🙂🙂	🙂🙂	🙂🙂	🙂🙂	9
Castor bean	🙂	🙁	😐	🙂	🙂	😐	5
Biomass Sorghum	🙂	😐	🙂🙂	🙂🙂	🙂🙂	🙂🙂	9
Industrial Hemp	🙂	😐	🙂🙂	🙂🙂	🙂🙂	🙂🙂	9
Sunn Hemp	🙂	🙁	😐	🙂🙂	😐	🙂🙂	6
Kenaf	🙂	🙁	😐	🙂🙂	😐	🙂	5

🙂🙂 = TRL >7, industrial production available at demonstration (TRL 8) or commercial scale (TRL = 9)

🙂 = 5<=TRL=>7, production available at pilot (TRL 5-6) and small-scale demonstration scale (TRL 7)

😐 = 3<TRL<5, experimental scale from research to production development

🙁 = TRL<3, only basic research data available

2.3.6. Integrated selection of oil and lignocellulosic crops

An integrated overview of the scoring on all selection aspects per crop is presented in Table 9. Based on this, an overall selection of crops per climate zone is made.

North Europe:

- Oil crops: 1. Camelina - summer, 2. Crambe - summer, 3. White mustard-summer
- Lignocellulosic crop: none

For the North zone, it is concluded that oil crops can only grow in the summer fallow period of conventional rotations in Northern Europe. Camelina, Crambe and White mustard are all suitable in terms of climate conditions and their yields can be moderate to high. Although Sunflower could be considered an additional option due to its good compatibility with climate conditions, its negative performance on environmental metrics, particularly concerning water use and soil impacts, makes it a less sustainable choice and is not prioritised in the final crop selection.

- Camelina and Crambe demonstrate good suitability as intermediate crops, although their TRL levels require further development. White mustard is a good choice because it is already commercial.
- The environmental performance of these crops is generally positive due to low input needs in pesticides and herbicides, good soil coverage and the potential to contribute to biodiversity.
- Due to the cold climate conditions in the North, no lignocellulosic crop is suitable.

Central Europe:

Central - Continental:

- Oil crops: 1. Camelina - summer, 2. Crambe - summer, 3. White mustard-summer, 4. Camelina - winter
- Lignocellulosic crop: Sorghum - summer

The prioritization of crops in the central - Continental regions of Europe follows the same logic as for the North. In the Central Europe though, the agricultural area suitable for intermediate crops is larger. Among oil crops, the same options as in Northern Europe were selected, with the additional inclusion of camelina grown during the winter period. In addition to oil crops, Sorghum is selected as the preferred lignocellulosic crop. Unlike in Northern Europe, Sorghum is well-suited to the climate conditions of Central Europe and has been identified as the best performing lignocellulosic crop based on climate suitability, yield, environmental performance and TRL metrics. Again Sunflower is excluded because of its overall more negative environmental performance.

Central - Atlantic:

- Oil crops: 1. Camelina - summer, 2. Crambe - summer, 3. White mustard - summer, 4. Camelina - winter, 5. Crambe - winter
- Lignocellulosic crop: Sorghum - summer

The prioritization of crops in the central - Atlantic is almost similar to that of the continental, but because of the milder winter this region has a broader suitability in part of its territory for Camelina and Crambe grown as a winter crop. The area suitable for biomass Sorghum is more limited than in the Continental part of the central zone, but under influence of climate change it is likely to increase strongly over the next 25 years.

South Europe:

Mediterranean North & Mountains:

- Oil crops: 1. Camelina – winter, 2. Crambe - winter, 3. White mustard - summer
- Lignocellulosic crop: Sorghum – summer

Mediterranean South:

- Oil crops: 1. Camelina – winter, 2. Crambe - winter
- Lignocellulosic crop: none

The high temperatures and extended drought periods experienced across the Mediterranean countries of Europe present significant limitations for the production of intermediate crops, particularly during the summer period and most strongly for the Mediterranean South part. For this reason there is a difference in the selection of suitable crops between the Mediterranean North and mountains and the Mediterranean South.

In the Mediterranean North, there is a bit more water available during spring, making it easier to still produce some oil crops such as White mustard and biomass Sorghum in summer without irrigation, provided that the harvest of the primary crop is done in time.

Table 9 Integrated scoring of crops for final prioritisation.

Common name	Climatic suitability (current and future - if suitability increases towards future, the future suitability is scored)					Compatibility as intermediate crop (fits in existing rotations)	Yield	Environmental performance				TRL
	North (Atlantic-North, Nemoral)	Central - Atlantic	Central - Continental	South Mediterranean North & mountains	South - Mediterranean South		(t seeds/ha or t_{dm}/ha)	Soil health	Water quality	Water quantity	Biodiversity	Total TRL score
Camelina (summer)												
Camelina (winter)												
Carinata/Ethiopian mustard (summer)												
Carinata/Ethiopian mustard (winter)												
Crambe (summer)												
Crambe (winter)												
Safflower (summer)												
Safflower (winter)												
Sunflower (summer)												
White Mustard (summer)												
Castor bean (summer)												
Biomass Sorghum (summer)												
Industrial Hemp (summer)												
Sunn hemp (summer)												
Kenaf (summer)												

3. METHODOLOGY AND SCENARIOS OVERVIEW

3.1. OVERVIEW OF FACTORS DRIVING FUTURE SCENARIOS

When it comes to the calculation of the future availability potentials of the selected intermediate crops per climatic region (see Chapter 2), different scenarios need to be developed to explore uncertainties in moving towards a more circular and biobased economy with an additional demand for biomass resources for advanced biofuels. Scenarios are an effective tool that the research community uses to address relationships between components of a system, such as socio-ecological impacts of technological, societal or political innovations, or relationships between sectors. Scenarios serve as representations of possible futures and enable exploration of how developments might unfold under varying conditions.

The first step to take in building scenarios is to identify the factors that drive the future of intermediate crops production in the EU. These factors need to be specified per scenario and quantified (territorially) to determine the eventual intermediate crop production availability. In

Table 10, these factors are presented. In the first column, the general factors are specified. In the second column, it is explained how they influence the future potential of intermediate crops. In the third column, it is specified what data and approach is used and where this is further explained in this report.

Table 10 Scenario factors determining future potential for intermediate crops.

Factor	Influence on future potential for intermediate crops	Data/method
1)Different future climate change scenarios	Shifts can be expected towards 2040 and 2050 in terms of Growing Degree Days and evapotranspiration which will have influence of the spatially specific yield crop performance and management requirements.	Crop yield simulation for the entire EU-27 taking into account of daily weather factors for current and future climate scenarios. Input data are from CHELSA V2 for selected number of CMIP6 scenarios (see Appendix I).
2)Yield development expectations	Yields of selected crops can be expected to increase under the influence of technological innovations	Historic crop yield development data, experts' views and assumptions on expected technological stimulation
3) Rotations and space for inclusion of intermediate crops	Crop rotations need to be understood for EU-27 to determine in combination with what conventional crops and when (spring/summer or winter) there is space for inclusion of an intermediate/cover crop. Analysis is done per NUTS-3 region.	HRL Cropland 2017-2022
4)Different land use development expectations towards 2050	Future developments in land use determine where and on how much land in rotational systems can be available for intermediate cropping systems.	A recent study (AGRI/2022/OP/0005) accomplished by WENR (DG AGRI, 2025) provides detailed land use expectation for 2050 in Business as Usual and Sustainable Agriculture scenarios following EGD/F2F policy goals.
5)Intermediate crop mix scenarios	1) Only oil crops across EU 2) Only lignocellulosic crops across EU	The suitable oil crops and lignocellulosic crops per climate zone were already presented in chapter 2 (section 2.3.6). Selection of best crop per region depends on the biomass yield (see section 3.4).

1) Climate impact:

Crop growth is determined by eco-physiological factors. The main factors are crop water availability, temperature, length of growing season, which are all influenced by local climate which manifests trough daily weather and soil characteristics and cultivar. It needs to be noted that in addition to the biophysical conditions, the human factor, particularly the cropping system and agronomic practices are also very influential and these are extensively described in the crop specific factsheets presented in Appendix 5.

Climate and soil factors are spatially diverse across Europe. The intermediate crops that are presented in Chapter 2 and selected as most suitable, are not yet widely produced in agricultural lands in the EU. Data about their yield performance can only be derived from field experiments in specific locations in Europe. In order to obtain an overview of actual yields that can be derived in all regions of the EU, a crop growth simulation modelling is done in this study. The detailed approach and the resulting crop yield levels for all EU regions are presented in Chapter 4. The crop yield simulations are run for the current climate conditions and for two different climate change scenarios namely SSP1-2.6 and the SSP5-8.5. SSP1-2.6 is consistent with the Paris Agreement targets and projects a relatively limited global mean temperature increase of ~1.8 °C (range 1.3-2.4 °C) above pre-industrial levels by 2100, whereas SSP5-8.5 represents a high-emissions pathway, with projected warming of ~4.5 °C (range 3.3-5.7 °C). Further details about these two climate change scenarios are further explained in Chapter 4.

2) Yield increase:

Beside the local weather and soil data, yield levels are also determined by technological developments. (Schils, et al., 2018) (referring to Sylvester-Bradley, 2010) discussed the scope for further yield improvements and indicates that there are four strategies that enhance yields: 1) breeding, 2) engineering (mechanization), 3) chemistry (application of inputs) and farming logistics.

Because of this, it can be expected that yields will also increase in time, even when climate and soil characteristics remain stable. In this study, yield increase factors are used to reflect the technological yield increases towards the future. For conventional crops, a reasonable approach to estimate future yield increase expectations would be to extrapolate yield increase from the past towards the future. However, for the intermediate crops analysed, no reference data exist on past yield increases, because these crops are relatively novel and statistical data on production and yield levels are not available. An alternative approach is therefore followed, which is to consider and assess historic yield increases for conventional oil and fibre crops in EU regions. This is further explained in Chapter 4 (section 4.5).

3) Rotations and space for inclusion of intermediate crops:

Intermediate crops need to be integrated into existing agricultural systems without causing additional land demand both now and in the future. This implies that these crops have to grow in the fallow period of an existing rotation. So instead of growing just one crop a year on the same parcel of land, there are now two crops grown of which one is the conventional food crop and the other is the intermediate crop.

Identifying the land availability for intermediate crops implies identifying the land area where rotational fallow is applied and identifying the moment (summer or winter) and the length of this fallow period. After all, the length of the growing period the intermediate crop needs to perform its full growth cycle should fit with the fallow period available. In Chapter 5, a detailed explanation is given for how

fallow land is identified, as well as the moment and the length of the fallow period. This information is identified using the High-Resolution Cropland layer 2017-2022.

4) Land use changes towards the future:

Beside the identification of fallow land in conventional rotations, one also needs to take land use changes into account as land use in agriculture is dynamic. The current land use can therefore not be used to assess the future land availability for intermediate crops. This study therefore needs information on what land use changes are to be expected in the EU-27 towards 2050. In Chapter 5, two alternative future scenarios for land use development within agricultural lands are presented which will serve as inputs in the scenarios in this study.

5) Intermediate crop mix scenarios:

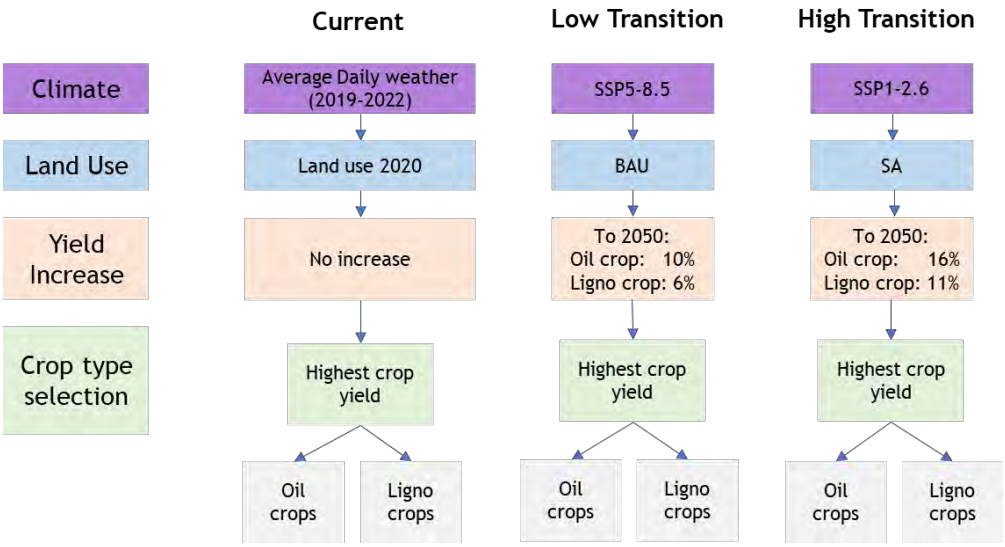
Two crop mix options for the scenarios were chosen to calculate the biomass availability potential:

- Only oilseed crops: Optimal crop selection is made based on oilseed yield. The best crop per region was prioritised according to highest oil yield per hectare.
- Only lignocellulosic crops: This implies use of Biomass sorghum only as this crop was the only one selected to be suitable for use as an intermediate crop that produces lignocellulosic biomass.

3.2. SELECTION OF SCENARIOS AND METHODOLOGICAL IMPLEMENTATION

The scenarios in this study differ according to the 5 factors or combinations thereof, as presented in Figure 5 and discussed in the previous section. In total, six different crop mix scenarios are implemented: Two represent the current situation, based on average land use 2019-2023) and differ according to the crop type only. Four different scenarios represent future conditions and differ according to the crop type, future land use, climate and yield increase expectations. Two of them represent the 'Low transition' (LT) case, where the transition to a circular biobased economy is not stimulated through policy, nor there is wide carrying capacity by society to support this. The opposite applies to the two 'High transition' (HT) crop type scenarios in which both policy and society are supporting transition and addressing climate mitigation very actively.

Figure 5 The six crop mix scenarios implemented in this study covering current and different future cases for estimating intermediate crops potentials across EU-27.



Climate change in the *High transition* (HT) scenarios will be modest because measures are taken both through policy and by society to mitigate GHG emissions and capture carbon. This stronger government and societal ambition to mitigate climate change is consistent with the targets of the European Green Deal (EGD). Moreover, the future land use changes take place in a policy context in which Farm to Fork (F2F) targets for a more sustainable agricultural production are expected to be met also in combination with societal changes supporting these such as transition from protein towards more vegetal based diets (for more details see Appendix 5). In this context, it can also be expected that more investments are made in research and innovation which will lead to higher yield increases.

In the *Low transition* (LT) scenarios, climate change will go fast in line with the SSP5-8.5 which reflects the highest radiative forcing pathway. Policy and society are not strongly interested in mitigating climate change, but are more focused on economic and social developments that are coupled with continuing to rely on fossil resources and the adoption of resource and energy intensive lifestyles around the world. Land use follows a business-as-usual pathway which implies that current trends urban sprawl, climate change, land degradation, land abandonment, intensification, extensification, diets, are expected to continue. Also, Farm to Fork and wider Green Deal policy goals are not addressed with new policy instruments. Society's interest to adopt changes in lifestyles and pay for maintenance and improvements in ecosystems services connected to production of food does not increase. The investments made in research and innovation are lower in this context and therefore also future crop yield developments are expected to be lower than in the *High transition* scenarios.

In all scenarios, the selection of the best crop in every region is determined by the potential yield level per ha. Specifically, within the oil crop scenario, the crop with the highest oil per hectare yield is selected in every region.

4. CROP YIELD SIMULATIONS OF INTERMEDIATE CROPS FOR CURRENT AND FUTURE USE IN EU-27

Following the approach and scenario modelling structure described in Chapter 3, to determine the regions in Europe where intermediate crops could successfully be cultivated, a crop suitability analysis was first conducted. Based on the suitability classification results for each crop, yield simulations under different climate scenarios were then carried out using a water productivity-based crop model (AquaCrop, Doorenbos & Kassam, 1979). With this model, the yields potentials of the selected intermediate crops were generated.

The intermediate crops selected in Chapter 2 and modelled for attainable yield are:

- Camelina (summer and winter annual) (Camelina sativa (L.) Crantz)
- Sunflower (Helianthus annuus L.)
- White Mustard (Brassica alba or B. hirta, a.k.a. Sinapis alba)
- Crambe (summer and winter annual) (Crambe abyssinica Hochst x R.E. Fries)
- Carinata/Ethiopian mustard (summer and winter annual) (Brassica carinata A. Braun)
- Biomass sorghum (Sorghum bicolor (L.) Moench)

At this stage, results for the different crops are presented considering climate, weather and biophysical properties, while the influence of land use changes and restrictions arising from the integration of intermediate crops into existing conventional crop rotation schemes, as described in the next chapter, is introduced as an additional layer to derive the final availability results.

4.1. CLIMATE CHANGE IMPACT MODELLING

4.1.1. Climate Scenarios

The suitability analysis and the yield simulations were conducted using a climatic historic scenario (2019-2023) as a baseline (current situation) and two different climate change scenarios towards 2050: SSP1-2.6 (Sustainability) and SSP5-8.5 (Fossil-Fuelled Development). As explained in Section 3.1, these two scenarios represent the extremes of possible climate futures and were also used in the land use change and arable land availability calculations towards 2050.

SSP1-2.6 is consistent with the Paris Agreement targets and projects a relatively limited global mean temperature increase of ~1.8 °C (range 1.3-2.4 °C) above pre-industrial levels by 2100, whereas SSP5-8.5 represents a high-emissions pathway, with projected warming of ~4.5 °C (range 3.3-5.7 °C). The narratives underlying these scenarios, together with their associated emissions pathways and climate change impacts, are described in Riahi, van Vuuren et al. (2017) and are summarised in Appendix 5. These two scenarios were selected for this study because, first, they are among the few for which sufficiently detailed data are available to support modelling, and second, they span the range of possible climate change outcomes and their impacts on arable land and crop production. While it is not possible at present to determine which pathway is most likely to occur, it is already evident that current global trends are not aligned with the modest climate change trajectory projected under SSP1-2.6 (WMO, 2024).

To understand better how the different climate change scenarios are likely to affect crop suitability and growth, an overview is given of how temperature and precipitation changes. In terms of average temperature change (see Figure 6), it is clear that SSP5-8.5 will experience a larger temperature rise all over the EU-27. However, even under the SSP1-2.6 scenario, a temperature rise is also expected. By 2050, for the SSP1-2.6, the average temperature rise will be 1.72 ˚C and for the SSP5-8.5 it will be 2.55 ˚C across the EU-27. The highest temperature increases are expected towards the Northeast in Baltic states and Scandinavia.

In both scenarios, the precipitation levels will also change by 2050. On average, the yearly precipitation will decline more significantly in the SSP5-8.5 than in the SSP1-2.6 scenario (see Figure 7). In SSP1-2.6, precipitation declines are expected mostly in Southwestern EU, while increases in precipitation will take place in the rest of EU, especially in certain areas of central EU. In SSP5-8.5, the declines in precipitation are much larger and more widely spread all over Southern and Central EU, while towards the North, particularly in Baltics and Scandinavia precipitation will increase importantly (see Figure 7).

Figure 6 Absolute change in annual average day temperature from 2020 to 2050 for the SSP1-2.6 and SSP5-8.5 scenarios.

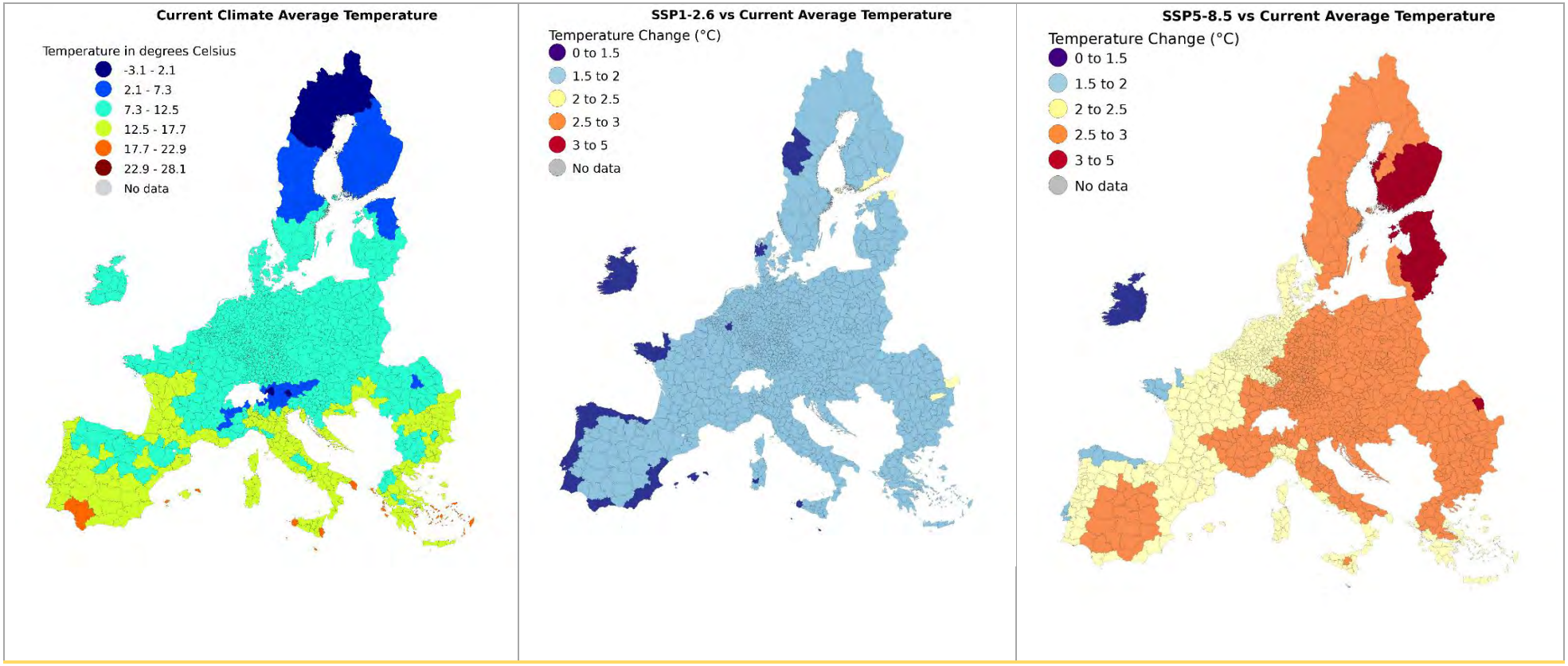
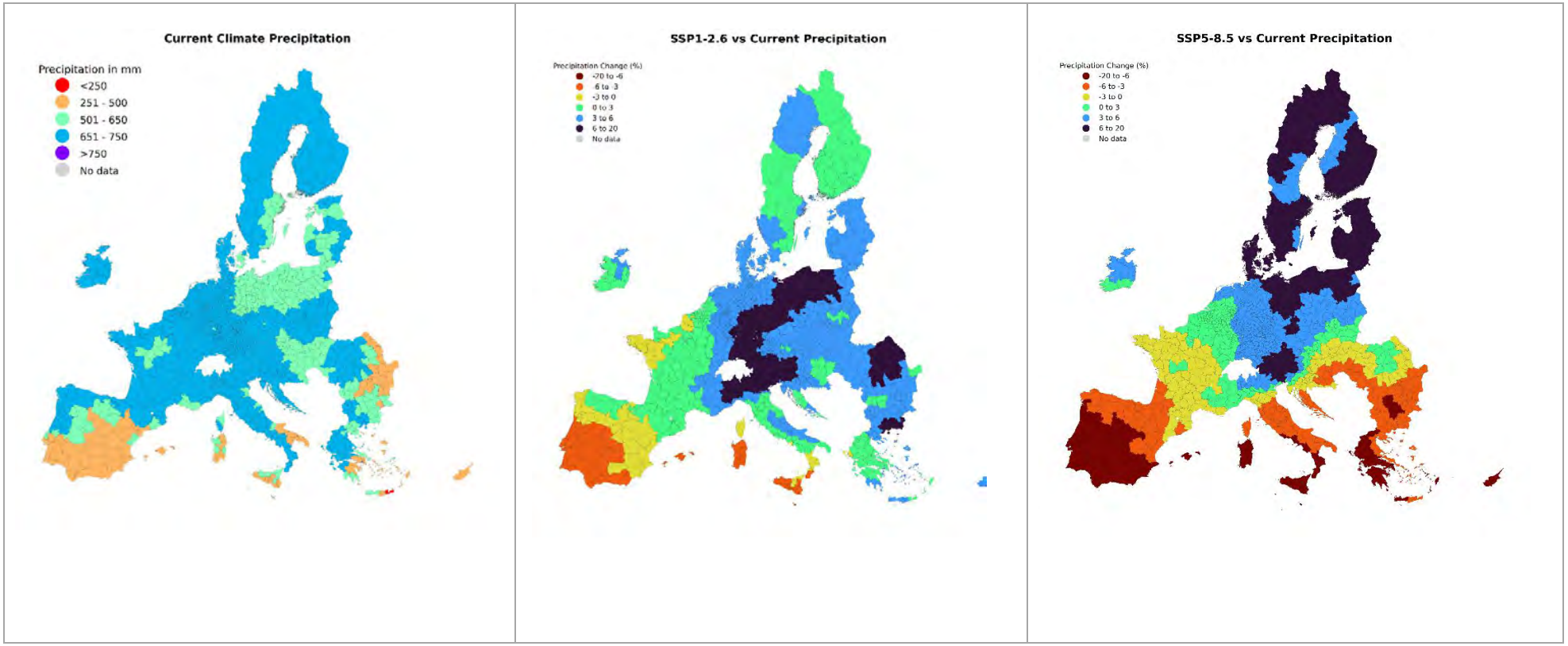


Figure 7 Changes in average precipitation from 2020 to 2050 for the SSP1-2.6 and SSP5-8.5 scenarios.



4.1.2. Meteorological Input Data

Both the suitability assessment and the crop yield simulation models use input daily climatic data of the following variables: minimum, average, and maximum temperatures (°C), rainfall (mm), and reference evapotranspiration (ET_0, mm). For the current scenario (weather data 2019-2023), the meteorological data used was sourced from AGERA5 (Copernicus Climate Change Service, 2019), provided by Copernicus Climate Change Service. The dataset comprises interpolated data from grid cells of 0.1° x 0.1 °. The gridded information used for this study represent the average conditions over a 5-year period (2019-2023) for each day of the year, detailing each variable for every NUTS-3 region.

For the simulation of the crop yields considering current climate and climate in the two climate change scenarios, the following approach was taken:

1. Data Acquisition: Data for each required climate variable was downloaded in the form of geographic maps from the CHELSA V2 dataset (Karger et al., 2017a, 2018) for the year 2050, using the GFDL-ESM4 model under the SSP1-2.6 and SSP5-8.5 scenarios. CHELSA data provided monthly averages for the period between 2040-2070. For further details on CHELSA, see Appendix 3.

2. Evapotranspiration (ET0) Calculation: To calculate ET_0 for the future scenario, a script was utilized, which processed the climate variables obtained from CHELSA (see Appendix 3).

3. Annual average calculation: The annual average for each climate variable was calculated. Using GIS software, the annual average for Tmin (minimum temperature), Tmax (maximum temperature), and average temperature was determined for each NUTS-3 region. For precipitation and evapotranspiration, zonal statistics were performed, with the annual sum used for each variable.

4. Creation of climate factors: Daily weather data were not directly available for the future climate scenarios, only monthly figures; hence, a climate factor approach was applied on the base of adjusting the baseline (current) daily data. For Tmax, Tmin, and Tavg, the factor was calculated by dividing the annual average temperature of the future scenario by that of the baseline scenario, and this ratio was then multiplied with the baseline daily values to generate future daily values. For ET_0 and precipitation, the factor was defined as the difference between the future and baseline annual values, which was then added to the baseline daily data. For more details see Appendix 3.

5. Application of climate factors: These factors were then applied to the daily weather data from the AGERA5 dataset for each NUTS-3 region.

4.2. CROP SUITABILITY MODEL APPROACH

4.2.1. Determining Factors

To identify which crops can be effectively cultivated across different NUTS-3 regions in Europe, five key agro-climatic factors were considered which are presented in Table 11. The specific thresholds per suitability factor applied to the intermediate crops are presented in Table 12.

Table 11 Suitability factors considered and specific assumptions applied (see also Table 12 for specific factors per crop used).

Agro-climatic factors	Assumptions made for suitability of crops
Heat Stress: The crop's tolerance to sustain high temperatures, defined as the ability to withstand temperatures above 32 °C for periods of 3, 6, or more than 9 consecutive days.	Heat Stress was only applied to Camelina, Crambe, Carinata (both summer and winter types), and Safflower (summer and winter) because these are known to be sensitive to this. This stress factor was calculated based on the number of days exceeding 32 °C during the critical reproductive stages. For summer crops, the evaluation period was July to September, which corresponds to the mid-to-late growing stages where heat can negatively impact grain filling and yield formation. For winter crops, heat stress was assessed during March to May, a period that also aligns with reproductive development. This seasonal distinction reflects crop sensitivity during key physiological stages, particularly for oilseed crops where heat during grain formation can substantially reduce yield
Killing Frost Tolerance: The crop's capacity to survive frost events, assuming frost conditions persist for at least 7 days	This factor was applied only to winter annual crops, reflecting their vulnerability to prolonged frost periods. Typically, crops cannot survive more than five consecutive days below a certain temperature. However, since the model did not simulate consecutive days but rather the total number of days below the threshold throughout the year, the criterion was changed to seven days in total.
Growing Degree Days (GDD): A temperature-based index indicating whether a crop can complete its physiological development in a region. It is based on the accumulation of daily mean temperatures above a crop-specific base temperature. (see Table 12)	The start of the season was defined as the first occurrence of five consecutive days where the average daily temperature exceeds the crop-specific base temperature. For summer crops, this search was constrained to begin after May 1st, to avoid premature initiation in spring. For winter crops, the search began after October 1st. In a few cases, if no starting day was found within the defined window, the region was excluded for that crop, and the start day was marked as null. End of the Growing Season: The end of the growing season was determined as the day when the crop's required cumulative GDD was reached, starting from the identified planting date. If the GDD requirement could not be met within the year, the region was excluded for that crop, and the end day was also set as null.
Minimum Length of the Growing Season (LGS): The minimum number of days with suitable thermal conditions (above base temperature) required to reach maturity. Expressed in days (see Table 12)	The length of the growing period was calculated as the difference between the end day and the start day. If the crop did not reach the required GDD, no growing season length was computed either. Additionally, if the calculated season length was shorter than the crop minimum required LGS, the value was set to the minimum LGS defined in the crop parameters to ensure physiological feasibility.
Minimum Precipitation During the Growing Season: The threshold amount of rainfall needed during the crop's growing period to support development and avoid severe water stress.	The total precipitation was accumulated only for the effective growing period (i.e. from start to end day) in each region. If no valid growing season was found (i.e. missing start or end date), precipitation was not computed, and the region was considered unsuitable.

Table 12 Crop parameters and suitability factors for each of the studied crops

		1=Annual/ 2=perennial	Purpose: 1= (oil) seeds 2=biomass	Minimum length of growth season (LGS) (days)	Minimum of growth degree days (thermal time GDD)	Base temperature (°C)	Killing frost (°C) No go= 0 Crop can still handle it = 1 Crop can easily handle this frost = 2			Killing Frost	Heat Stress	Precipitation: threshold of minimum rainfall in growing season: No go = 1, Rainfall meets threshold of crop: 0.25, Meets well with crop precipitation need: 0						
							-5 to 0 °C	-10 to - 5 °C	< - 10 °C	(°C)	(°C)	>1000 mm	1000-800 mm	800 - 500 mm	500 - 300 mm	300 - 200 mm	< 200 mm	<100 mm
Camelina sativa (L.) Crantz	Camelina (summer-annual)	1	1	90	1200	4	2	1	0	-	32	0.25	0	0	0	0	0.25	1
Helianthus annuus L.	Sunflower (summer annual)	1	1	100	1350	5	2	0	0	-	Heat resistant	0	0	0	0	0	0.25	1
(Brassica alba or B. hirta, a.k.a. Sinapis alba)	White Mustard (summer annual)	1	1	77	1200	4	1	0	0	-	Heat resistant	0	0	0	0	0.25	0.25	1
Crambe abyssinica Hochst x R.E. Fries	Crambe (summer annual)	1	1	120	1400	4	0	0	0	-	32	0.25	0.25	0	0	0	0.25	1
Brassica carinata A. Braun.	Ethiopian mustard (summer annual)	1	1	140	2000	4	0	0	0	-	32	0.25	0.25	0	0	0	0.25	1
Ricinus communis L.	Castorbean (summer annual)	1	1	130	1200	9	0	0	0	-	Heat resistant	0	0	0	0	0.25	1	1
Carthamus tinctorius L.	Safflower (summer annual)	1	1	120	1750	5	1	1	0	-	32	0.25	0.25	0	0	0.25	1	1
Camelina sativa (L.) Crantz	Camelina (winter-annual)	1	1	160	1300	4	2	2	2	-15	32	0.25	0	0	0	0	0.25	1

		1=Annual/ 2=perennial	Purpose: 1= (oil) seeds 2=biomass	Minimum length of growth season (LGS) (days)	Minimum of growth degree days (thermal time GDD)	Base temperature (°C)	Killing frost (°C) No go= 0 Crop can still handle it = 1 Crop can easily handle this frost = 2			Killing Frost	Heat Stress	Precipitation: threshold of minimum rainfall in growing season: No go = 1, Rainfall meets threshold of crop: 0.25, Meets well with crop precipitation need: 0						
							-5 to 0 °C	-10 to - 5 °C	< - 10 °C	(°C)	(°C)	>1000 mm	1000- 800 mm	800 - 500 mm	500 - 300 mm	300 - 200 mm	< 200 mm	<100 mm
Crambe abyssinica Hochst x R.E. Fries	Crambe (winter annual)	1	1	150	1500	4	1	0	0	-5	32	0.25	0	0	0	0	0.25	1
Brassica carinata A. Braun.	Ethiopian mustard (winter annual)	1	1	120	1800	4	0	0	0	-5	32	0.25	0.25	0	0	0	0.25	1
Carthamus tinctorius L.	Safflower (winter annual)	1	1	135	1900	5	1	1	0	-10	32	0.25	0.25	0	0	0.25	0.25	1
Sorghum bicolor (L.) Moench	Biomass sorghum (summer)	1	2	120	1400	8	1	0	0	-	Heat resistant	0.25	0	0	0	0.25	0.25	1
Canabis sativa L.	Industrial Hemp (summer)	1	2	90	1800	5	2	1	0	-	Heat resistant	0	0	0	0	0.25	1	1
Crotalaria juncea L.	Sunn hemp (summer)	1	2	60	1300	8	0	0	0	-	Heat resistant	0	0	0	0	0.25	1	1
Hibiscus cannabinus L.)	Kenaf (summer)	1	2	90	1200	9	0	0	0	-	Heat resistant	0	0	0	0.25	1	1	1

4.2.2. Yield reduction factor approach in mapping the suitability

To integrate the effects of multiple limiting climatic factors on crop suitability across NUTS-3 regions, a yield reduction factor methodology was applied. This approach assigns a percentage yield reduction to each limiting factor, resulting in a cumulative yield reduction score per crop per region. The rules applied are based on interviews with experts doing field experiments with these crops in different EU projects (MIDAS, BIKE, MAGIC, CARINA, IENICA, Crops2Industry, Eurobioref, IASIS, BECOOL, see Appendix 1 for explanation of these projects).

The following rules for each limiting factor were applied:

1. Killing Frost (binary condition): if the crop is exposed to sustained frost conditions that exceed its tolerance threshold, a 100% yield reduction is applied.

Regions where killing frost occurs under these conditions are classified as unsuitable.

2. Heat Stress: Based on the number of consecutive days with temperatures exceeding 32 °C:

- ≥3 consecutive days → 25% yield reduction
- ≥6 consecutive days → 50% yield reduction
- 9 consecutive days → 75% yield reduction

3. Precipitation Deficit: Total precipitation during the growing season (from crop-specific start to end day). Yield reductions were applied as follows:

- ≥ optimal precipitation → 0% yield reduction
- ≥ minimum but < optimal → 25% yield reduction
- < minimum precipitation → 100% yield reduction

If a crop is unable to complete its growing season due to unmet GDD or LGS requirements, the precipitation value for that region is omitted.

4. Growing Degree Days (binary condition): if the accumulated GDD in a region does not reach the crop's minimum requirement, the crop is considered physiologically unable to complete its development, resulting in 100% yield reduction.

5. Length of Growing Season (binary condition): if the calculated growing season is shorter than the crop-specific minimum LGS, a 100% yield reduction is applied.

If a region cannot reach the required GDD or minimum LGS, it is marked as unsuitable, and no precipitation or heat stress analysis is conducted. A GAMS script was used to automate the integration of yield reductions from all factors for each crop across all NUTS-3 regions. The script calculated a total yield reduction score by summing the penalties from applicable limiting factors.

An exhaustive analysis of all possible limiting condition combinations (43 in total) was implemented. The final suitability classification for each crop-region pair was determined using the following criteria:

- If the cumulative yield reduction score exceeded 75%, the crop was considered unsuitable for that region.

- If the crop could not complete its physiological development due to unmet GDD or LGS requirements, the region was also considered unsuitable, regardless of other factors.

This integrated yield reduction approach ensures that only crops with reasonable productivity potential under current and projected climate conditions are identified as suitable. The methodology was applied to baseline climate conditions and the two future climate change scenarios, providing a robust and spatially explicit assessment of crop-climate suitability across the continent. For the specific mapped suitability per crop also consult the factsheets in Appendix 5 of this report.

4.2.3. Crop suitability results

In the following figures the crop suitability changes in time in the current and future climates are presented for the six selected intermediate crops.

Figure 8 Climate suitability mapped for Camelina as summer in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

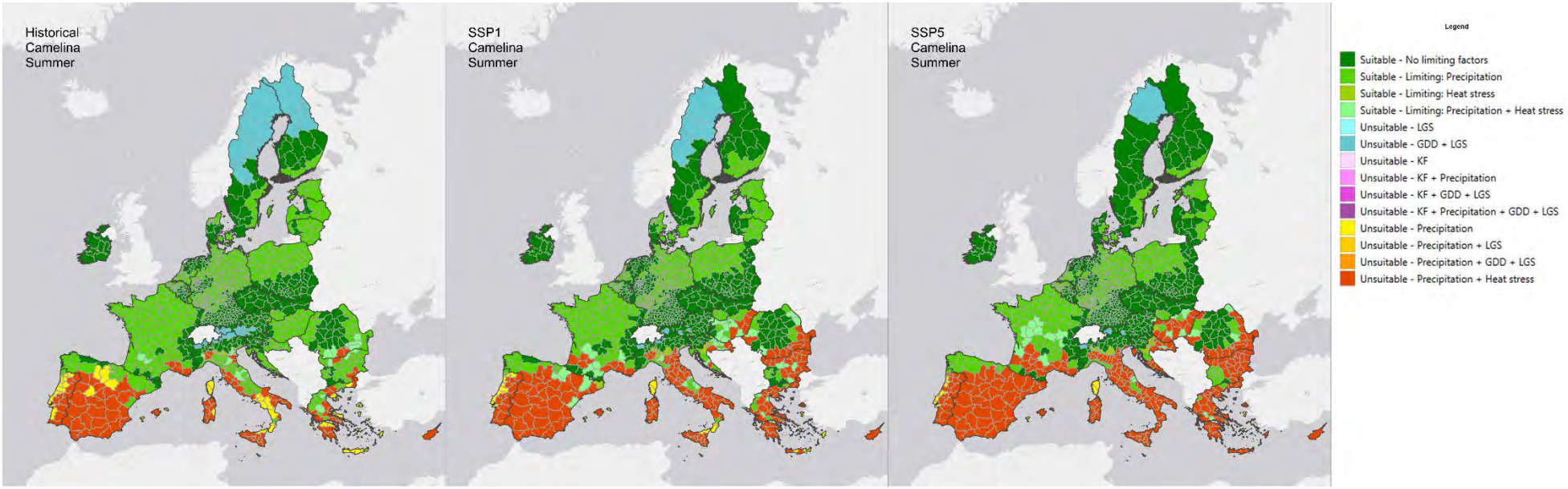


Figure 9 Climate suitability mapped for Camelina winter intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

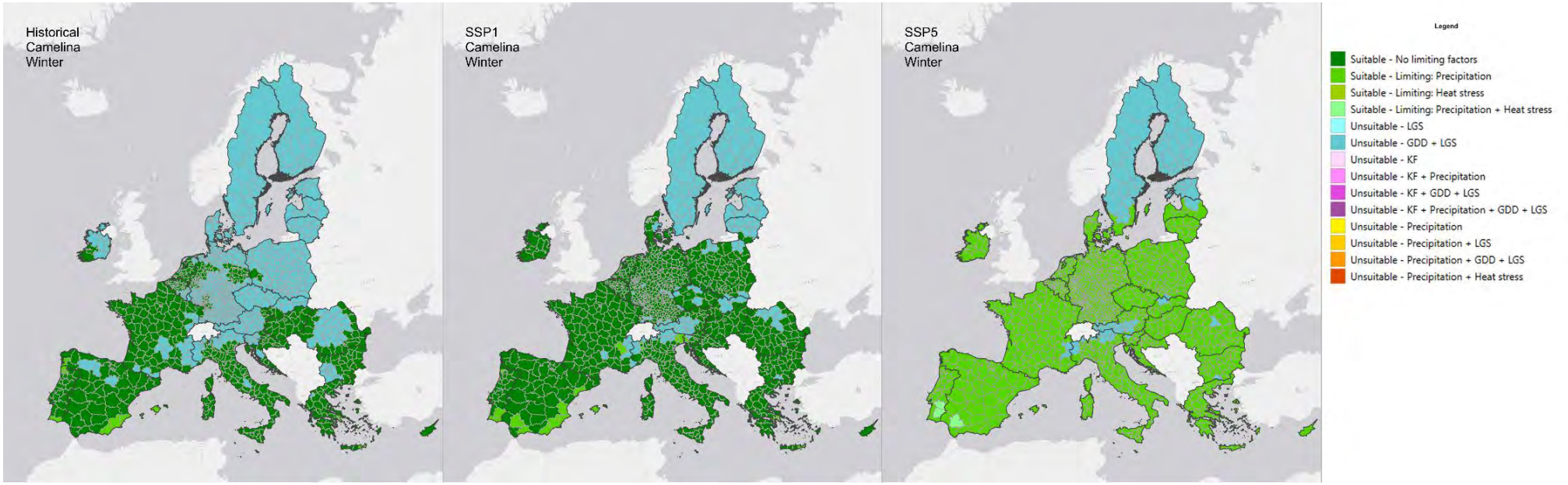


Figure 10 Climate suitability mapped for Sunflower used as summer intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

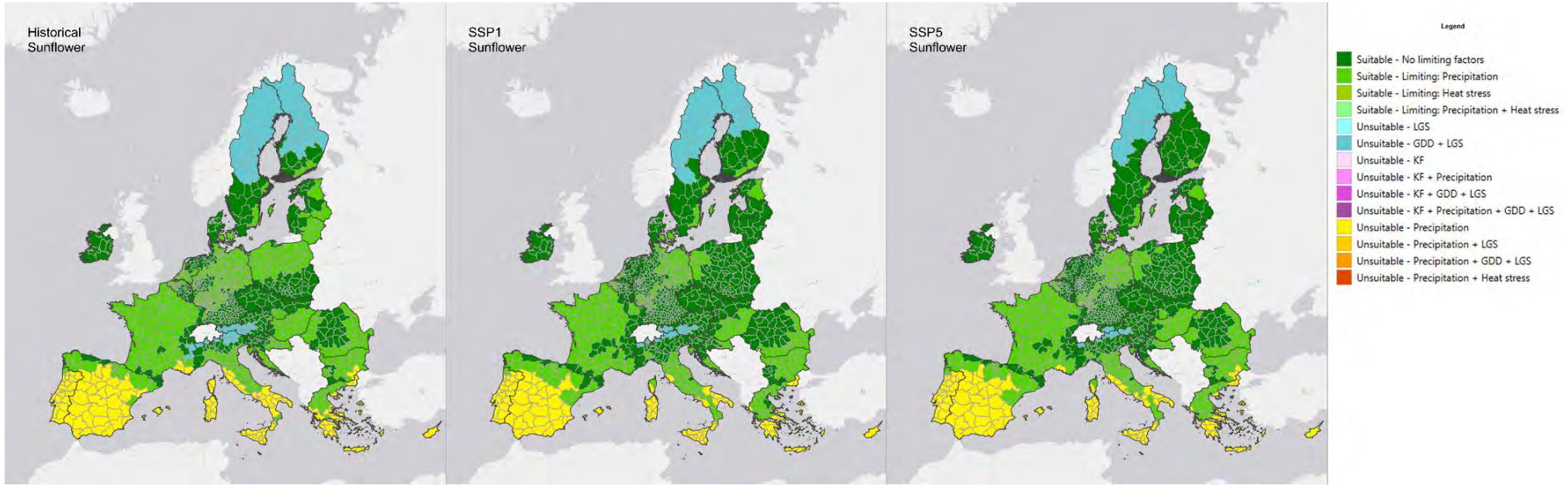


Figure 11 Climate suitability mapped for White mustard used as summer intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

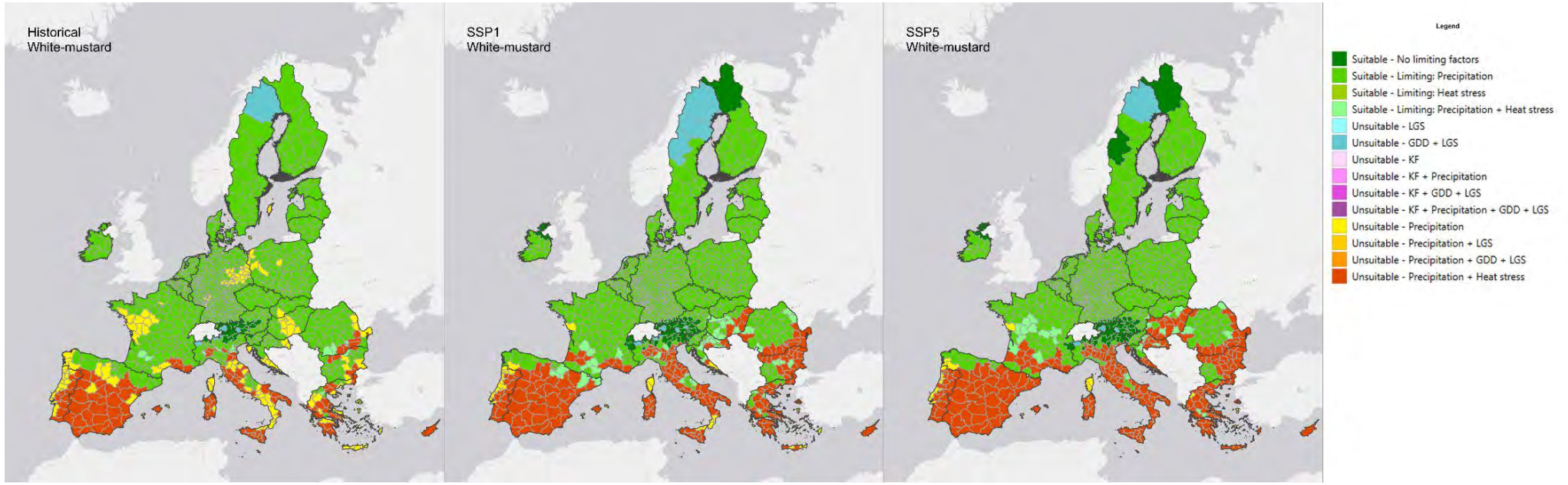


Figure 12 Climate suitability mapped for Crambe used as summer intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

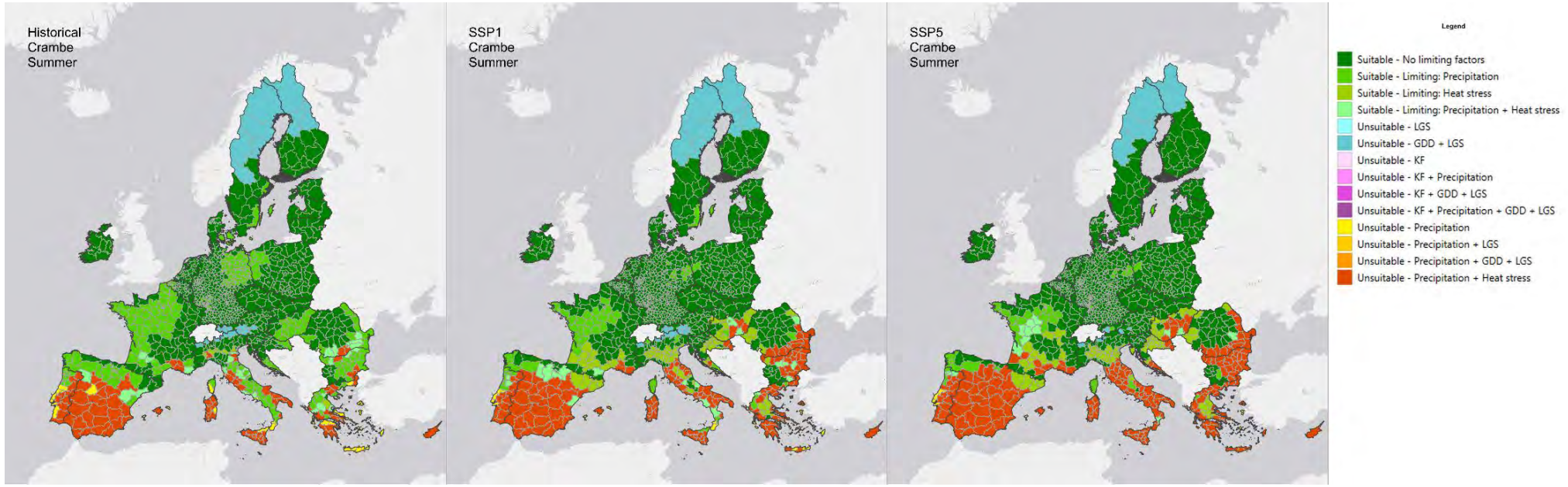


Figure 13 Climate suitability mapped for Crambe used as winter intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

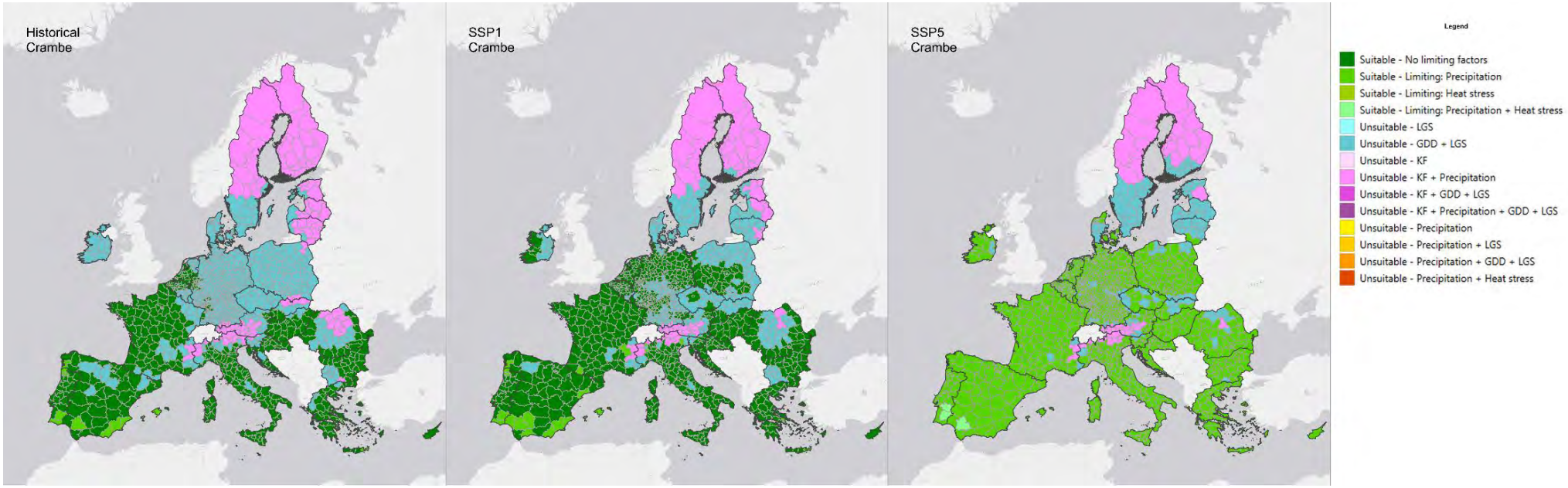


Figure 14 Climate suitability mapped for Ethiopian mustard (Carinata) used as summer intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

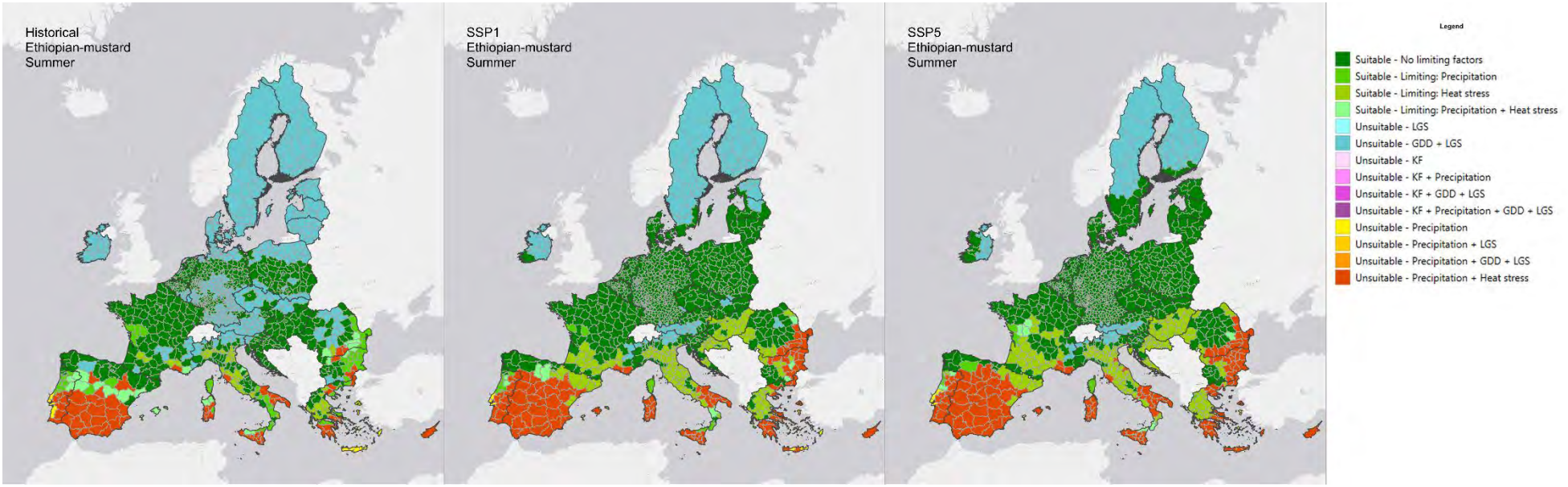


Figure 15 Climate suitability mapped for Ethiopian mustard (Carinata) used as winter intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.

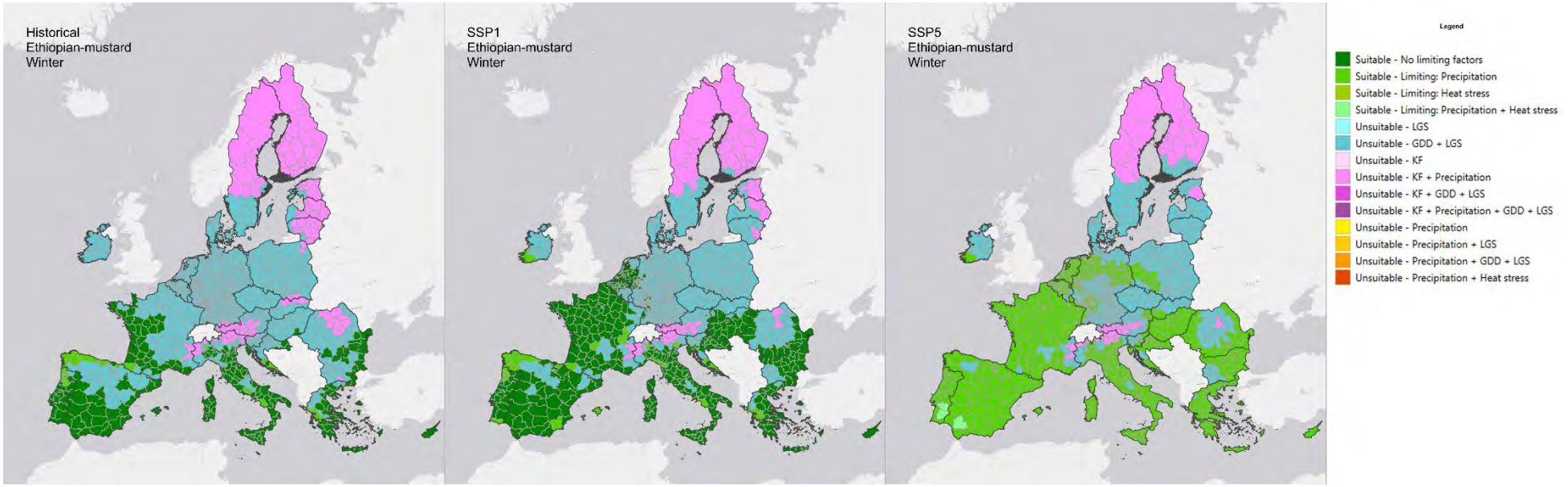
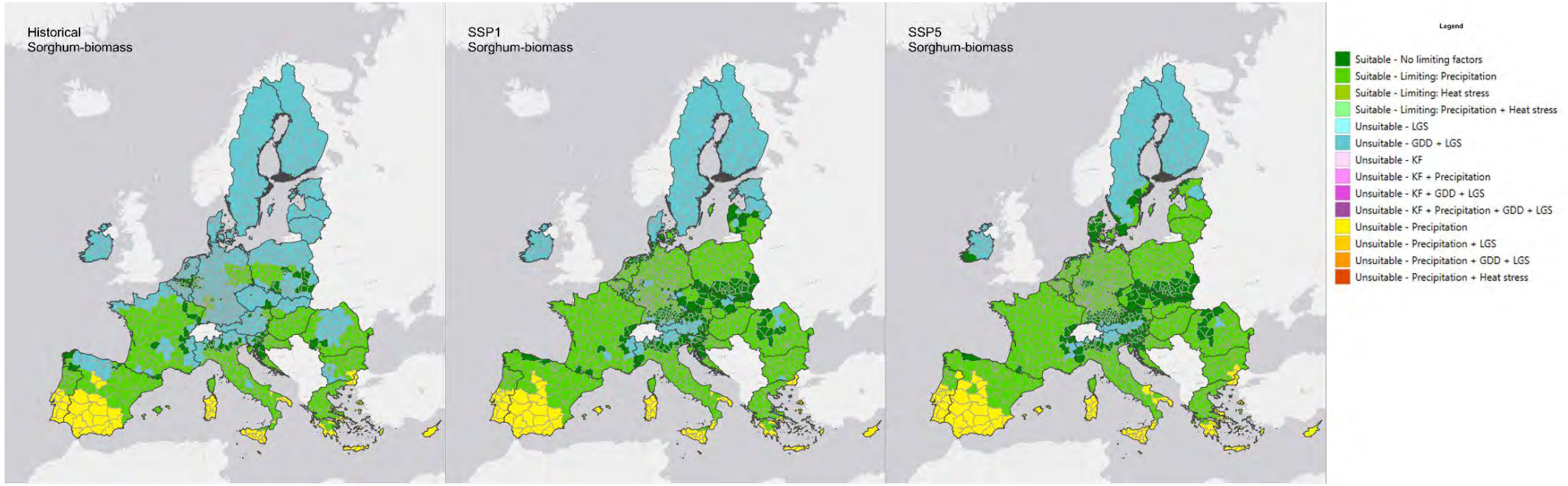


Figure 16 Climate suitability mapped for Biomass sorghum used as summer intermediate in current climate and in 2050 for SSP1-2.6 and SSP5-8.5.



4.3. CROP YIELD MODEL

For modelling the yield potential we used as a baseline the AquaCrop model (Dees & et al., 2017). AquaCrop is a crop water productivity model developed by the Land and Water Division of the FAO (Doorenbos and Kassam, 1979 cited by Dees & et al., 2017). In this study, the model was implemented in GAMS.

AquaCrop estimates biomass yield by integrating daily weather data with crop-specific phenological parameters that influence growth specified in Appendix 4. These parameters were sourced from previous projects such as S2BIOM, MAGIC, and MIDAS. For crops that had not been previously modelled, a literature review was conducted to define the required parameters, which were then refined with input from project experts when necessary.

The yield model was run using the start day, end day, and growing season length outputs from the suitability model. This ensured consistency in the growing period considered by both models and allowed the yield results to be spatially constrained by suitability, effectively eliminating areas unsuitable for production.

4.3.1. Yield potential estimation

The AquaCrop model links crop water use to crop yield by assuming that net biomass production per hectare is directly proportional to water productivity and crop water use (Dees & al., 2017). This relationship is expressed as:

Equation 1. $$B = WP \cdot \sum ETc$$

Where:

- B = biomass produced cumulatively (Mg ha^{-1}), data for every NUTS-3
- ETc = crop's evapotraspiration (either mm or m^3 per unit surface), summed over the time period in which the biomass is produced - the temperature is above the minimum growing temperature of the crop (°C)
- WP is the water productivity parameter (either kg of biomass per m^2 and per mm, or kg of biomass per m^3 of water transpired)

For each crop, the potential productivity was estimated according to two steps (Dees & et al., 2017):

1) The maximum biomass, or yield potential (Bpot), assuming no limits on water and nutrients.

For getting the Yield Potential (Y) of each crop, the Harvest Index it is used. These relationships are expressed as (Dees & et al., 2017):

Equation 2. $$Bpot = \Sigma ET0 \cdot Kc \cdot WUE$$

Equation 3. $$Y = HI \bullet B$$

Where:

- Bpot is the biomass potential produced cumulatively (Mg ha^{-1}), data for every NUTS-3

- ET0 is the daily evapotranspiration for reference crop, with the summation over the time period in which the biomass is produced in growing season (mm), data for every NUTS-3
- Kc: Crop coefficient by calculating for each growth stage (assumed constant value at the different development phases of the crop)
- WUE is the water productivity parameter or water use efficiency (either kg of biomass per m2 and per mm, or kg of biomass per m^3 of water transpired), (assumed constant value in all the crops stages)
- HI is the Harvest index. Ratio of yield to biomass (%) (assumed constant value)

Y Yield potential (Mg ha^{-1}), data for every NUTS-3

For estimating crop production across all regions, it was essential to gather data on the phenological requirements of the crops (see Appendix 4).

4.4. TECHNOLOGICAL CROP YIELD DEVELOPMENT EXPECTATIONS TOWARDS 2050

This section explains how the factor 'yield development expectations' towards 2050 is incorporated into the scenarios of this study. As already discussed in section 3.1, yield can be expected to also increase over time, even when climate and soil characteristics remain stable (which will not happen because of climate change). Improvements in yields occur through four pathways: 1) breeding, 2) engineering (mechanization), 3) chemistry (application of inputs) and farming logistics which are all related to technological improvements (Schils, et al., 2018).

The question addressed here is to determine which crop yield improvements should be assumed in this study for the two main scenario groups: *'Low Transition'* scenarios and *'High Transition'* scenarios (see Figure 5). The best approach is to estimate future yield increase expectations based on past examples. However, for the intermediate crops in this study, no reference data exist on past yield increases. Therefore, as an alternative, historical yield trends of conventional crops are used as a reference.

For the oilseed crops, oilseed rape is selected as the benchmark, as it is widely cultivated across EU regions and provides comprehensive data on yield evolution over time (Table 13). For the High transition scenario, a continuation of the yield change trend from the past is expected towards 2050. For the Low Transition scenario, it is expected that the yield increase will amount to 50% of the yield increase from the past.

Table 13 Yield developments in the past for conventional oil crops in EU-27, used as reference for yield increase assumptions towards 2050 (source: Eurostat).

For oil crops (EU27 - weighted average)	Yield change over 25 years	Average annual yield increase
Rape and turnip rape seeds (total)	14.63%	0.59%
Winter rape and turnip rape seeds	9.89%	0.40%
Spring rape and turnip rape seeds	16.15%	0.65%
Sunflower seed	12.58%	0.50%
Based on this, the following yield increase 2025-2050 is assumed:		
Low Transition scenario	9.89%	0.40%
High Transition scenario	16.15%	0.65%

Source data: Eurostat regional crop production data: [apro_cpshr] Crop production in EU standard humidity by NUTS 2 region

For Biomass sorghum, data on historical yield developments have not yet been systematically collected for the EU. Therefore, to establish expectations for future yield improvements, a reference crop needs to be identified. The most logical choice would be maize, given its agronomic similarities with sorghum and its widespread cultivation across Europe. However, the statistical data available from Eurostat present certain limitations. The first is that the data for maize refers to grain maize and not forage maize. Only forage maize would be a fair comparison because like Biomass sorghum it is harvested for the total biomass. Secondly, observed yield developments for maize are significantly influenced by increasing irrigation in certain regions, which skews the overall trend. As a result, maize data cannot be used as a fully reliable reference for estimating sorghum yield developments. So instead, fibre flax is used, a fibre crop that is harvested in total for its biomass and is grown over a wide number of EU countries (see Table 14). For the High transition scenario, the yield trend from the past continues to 2050, while for the Low Transition scenario the yield increase will amount to 50% of the yield trend from the past.

Table 14 Yield developments in the past in fibre flax in EU-27 to be used as reference for yield increase assumptions for biomass sorghum towards 2050.

For lignocellulosic crops (EU27-weighted average)	Yield change over 25 years	Average annual yield increase
Fibre flax (EU-27 - weighted average)	11.22%	0.45%
Based on this, the following yield increase is assumed for biomass sorghum:		
No Transition scenario	5.6%	0.2%
High Transition scenario	11.22%	0.45%

Source data: Source data: Eurostat regional crop production data: [apro_cpshr] Crop production in EU standard humidity by NUTS-2 region

4.5. CROP YIELD SIMULATION RESULTS

The results of the yield simulations for the selected oil crops and Sorghum are presented in this section. In the following figures, first, the crop yields are presented for the current climate conditions and only for the regions that are suitable to grow these crops as intermediate crops in either the summer or winter

season. For the oil crops (see Figure 17, Figure 18, Figure 19), Camelina and Crambe yields reach their highest level in winter, especially in the south of Europe, while when they are grown as a summer intermediate, the yields remain quite modest. This is also the case for White Mustard, which can only be grown as a summer intermediate. Sorghum is suitable as a summer intermediate in most of central and central Atlantic zones in the EU. Yields of between 15 and 20 t_{dm}/ha are realistic and even higher towards the South, provided there is enough precipitation (see Figure 20).

However, it should be noted that the presented results do not yet account for the limitations arising from fitting intermediate crops into the existing growing windows within conventional crop rotation cycles, nor for potential land use change impacts. These aspects are discussed in the following chapter in order to be incorporated into the analysis to derive the final intermediate crop availability estimate.

Figure 17 Yields (ton seeds/ha) for Camelina grown as intermediate crop under current climate conditions in summer (left map) and in winter (right map), only mapped for the suitable areas as rainfed crop (no irrigation).

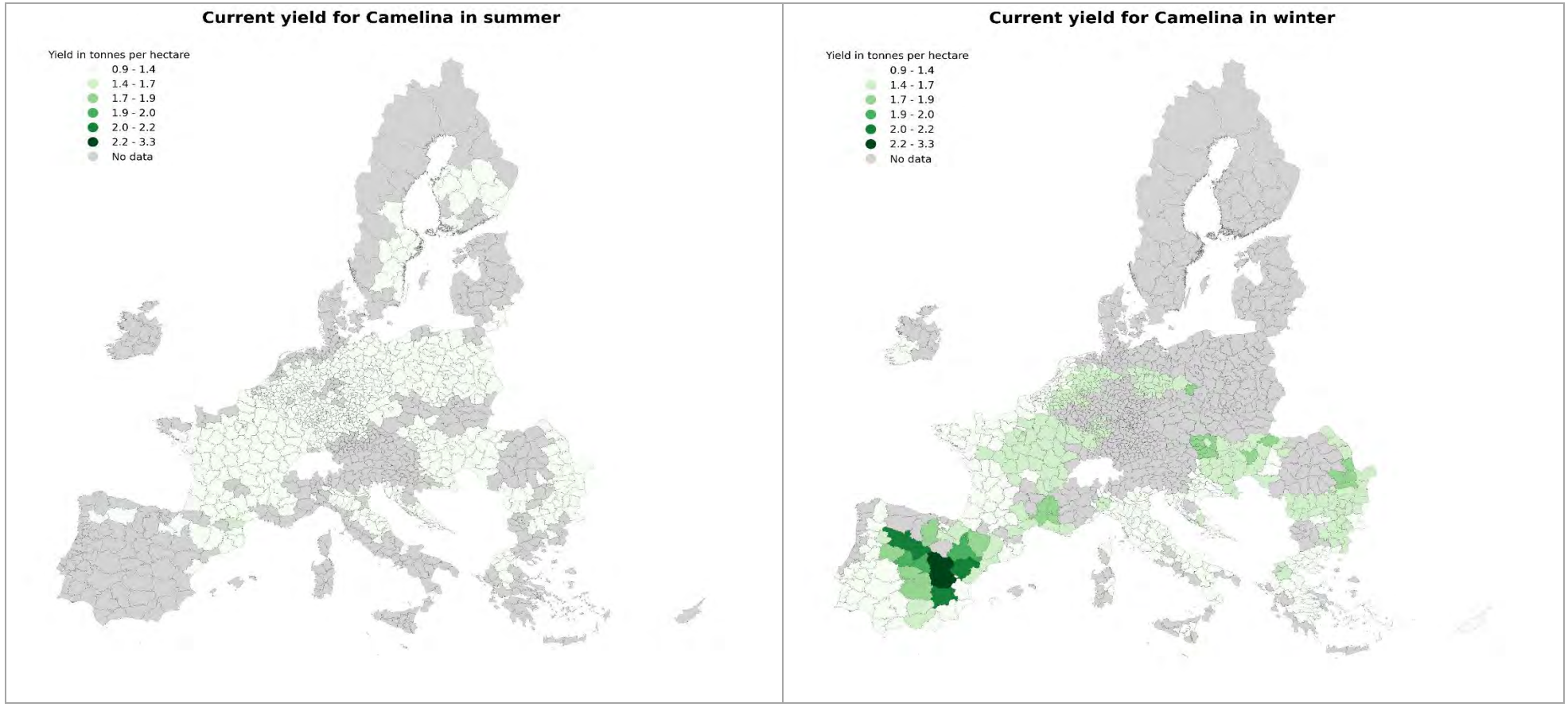


Figure 18 Yield (ton seeds/ha) for Crambe grown as intermediate crop under current climate conditions in summer (left map) and in winter (right map), only mapped for the suitable areas as rainfed crop (no irrigation).

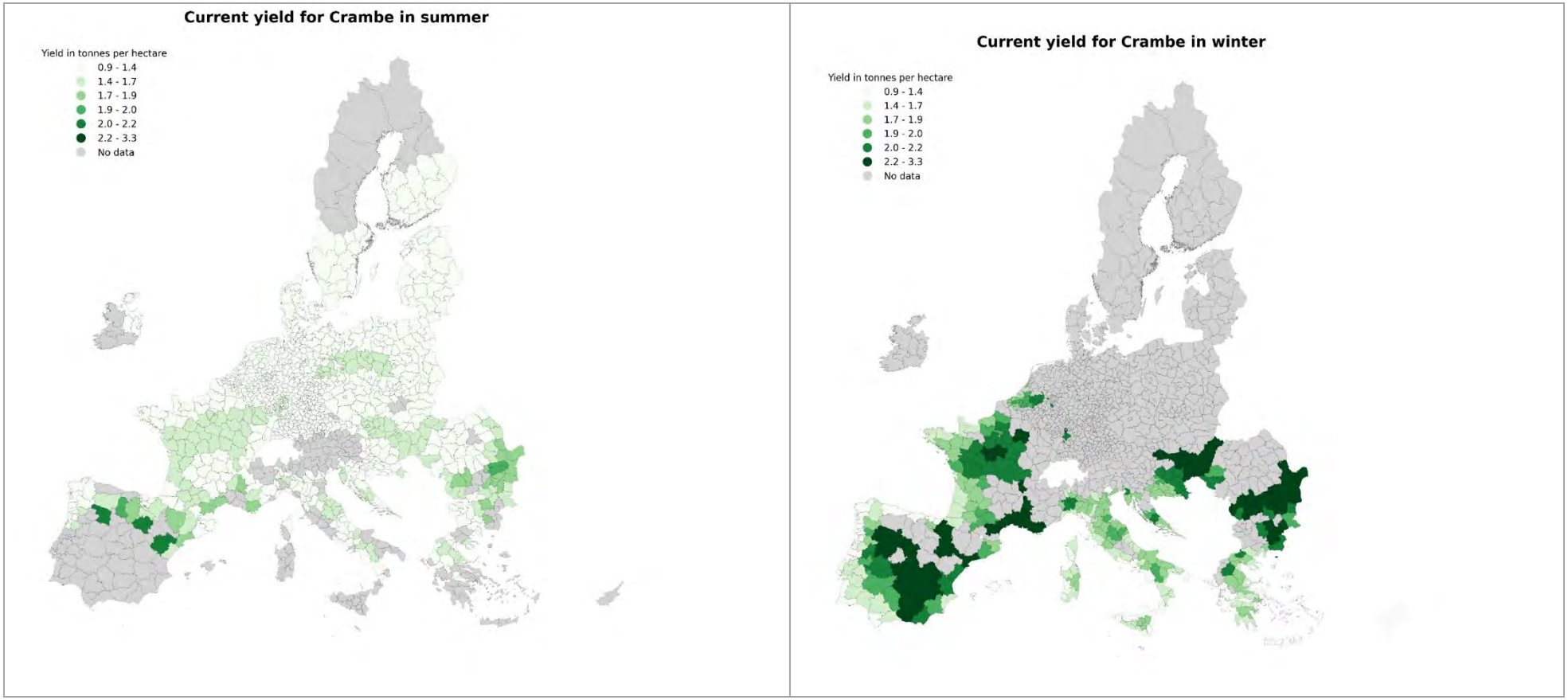


Figure 19 Yield (ton seeds/ha) for White mustard grown as intermediate crop under current climate conditions in summer as rainfed crop (so no irrigation), only mapped for the suitable areas.

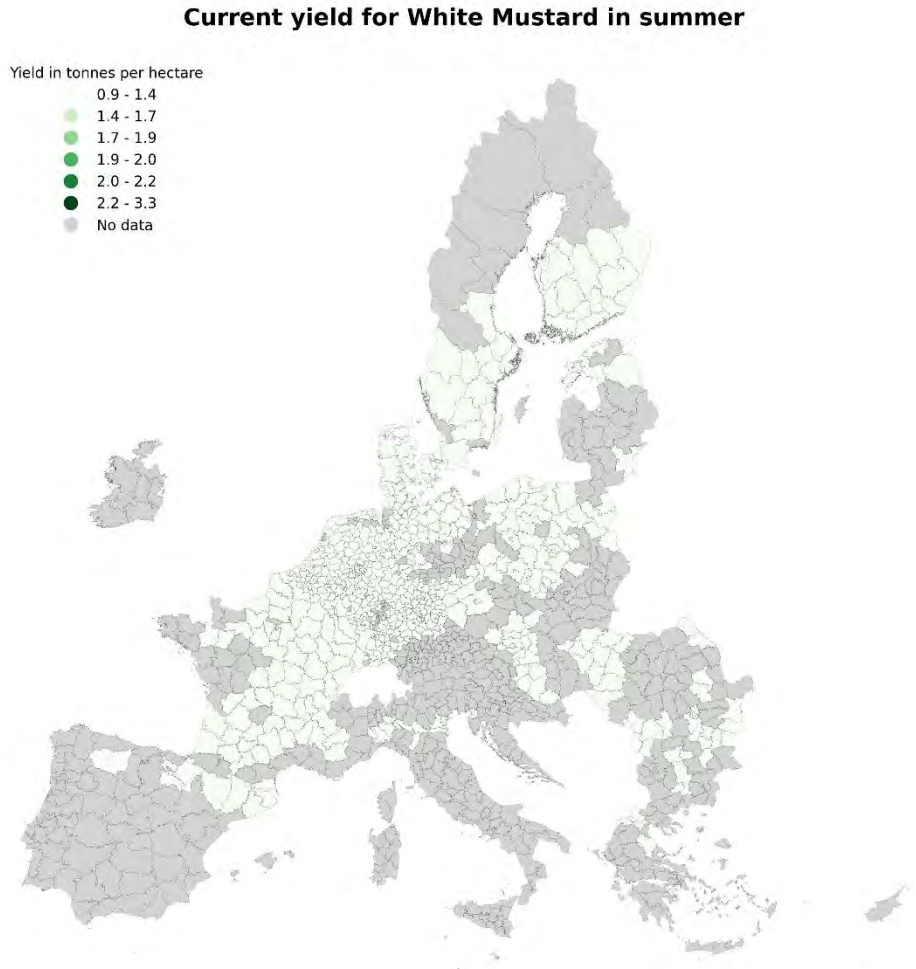
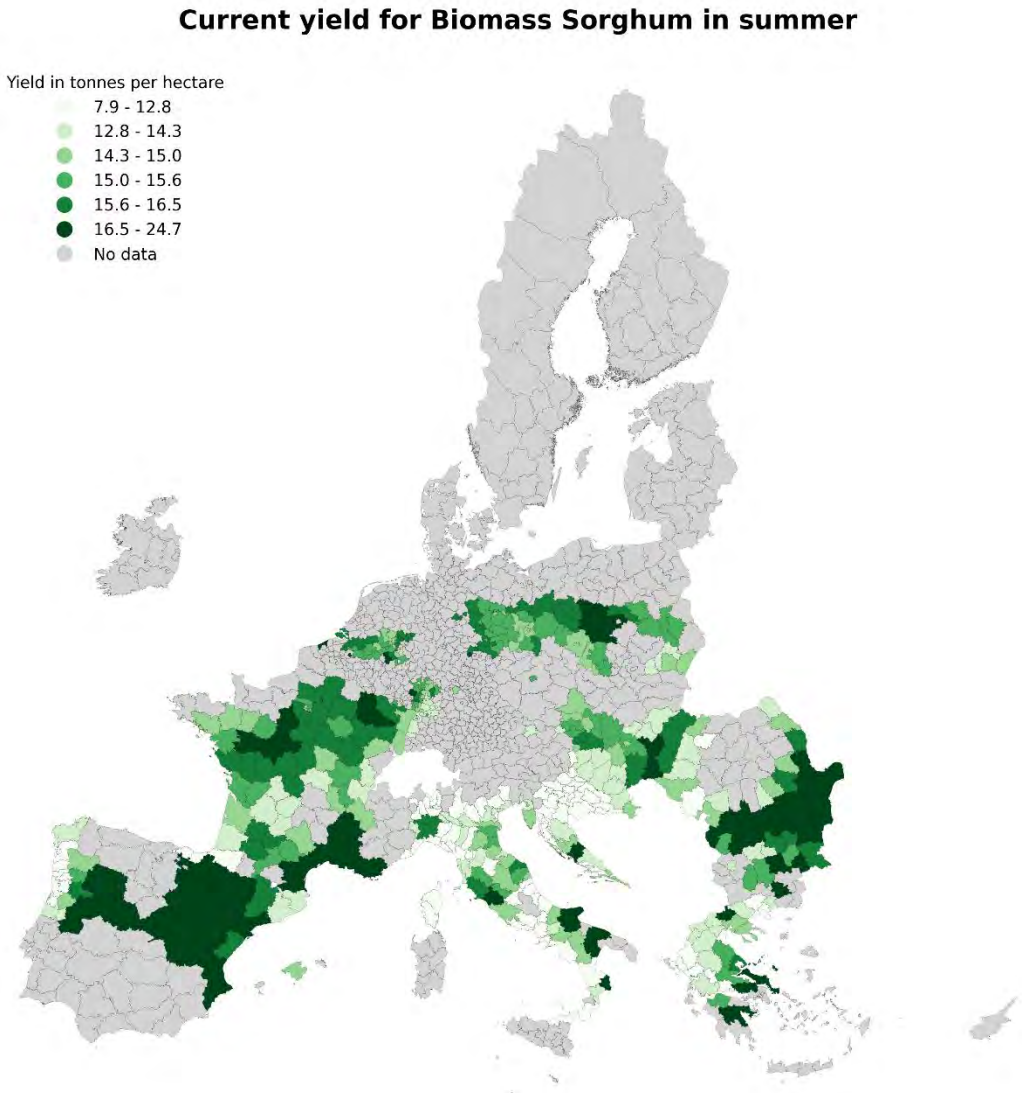


Figure 20 Yield (t_{dm}/ha) for Biomass sorghum grown as intermediate crop under current climate conditions in summer as rainfed crop (so no irrigation), only mapped for the suitable areas.



5. CURRENT AND FUTURE LAND AVAILABILITY FOR INTERMEDIATE CROPS IN EU

In this Chapter, an overview of land use and crop rotations in the EU are presented in order to better understand where intermediate crops can be fitted into existing agricultural systems without causing additional land demand now and in the future. In the next section, first, an explanation is given of the common crop rotations applied in the arable lands across EU-27, highlighting the typical winter and summer crops cultivated in different regions. This analysis enables an estimate of the EU area (both at country and regional level) potentially available for introducing intermediate crops. Finally, the chapter outlines the approach used to assess future land use impacts on land availability for intermediate crops.

5.1. CURRENT SITUATION OF CROP ROTATION

To provide an overview of the agricultural practices, it is important to note that most arable lands in EU-27 fall under the following environmental zones: Mediterranean, Atlantic, Lusitanian, Continental, Pannonian and Nemoral (see map in Appendix 2). In the Mediterranean zone, winters are mild, but summers are very hot and dry. This means that arable land crops can be best grown in winter and harvested in spring unless irrigation is used. As a result, lands are mostly left fallow during the hot, dry summer period. In case of irrigation, also summer crops can be combined with winter crops, allowing two harvests per year, though this is not a very common practice. An exception is found in the arable lands of the Mediterranean mountain and north zones (see Appendix 2), where colder winters also lead to winter fallow practices.

In the Atlantic, and certainly Lusitanian zone, both summer and winter periods are relatively mild, with moderate temperatures and precipitation more evenly spread throughout the year. In these zones, both summer and winter rotations are common, though more than one harvest per year for conventional crops is unusual.

In the Continental, Pannonian and Nemoral zones, summer rotations are more common because of the severe cold winters, and in the Nemoral zone due to the short growing season. Summer fallow periods still occur though, especially toward the southern part of the Continental and the Pannonian zones because of the dry and hot summer periods.

EU-wide data published by EUROSTAT[1] for the year 2016 and very recently also for 2023 provide some first insights into the crop cover and rotation status in EU, highlighting the distribution of winter and summer crops, the use of cover crops in winter, and the implications for soil cover across both seasons (see Figure 21).

According to Eurostat (2016 and 2023), shown in Figure 21, the following can be concluded for EU-27 (excl. UK):

1. In 2023, 55% of the arable land (52 million hectares) was used for winter crops. In 2016 this share was only 47% which implies that there has been an increase in the use of winter crops in arable lands. In most cases, winter crops are combined with a summer fallow period, although this cannot be concluded with certainty as the source data only specify the case of a winter cover crop presence.

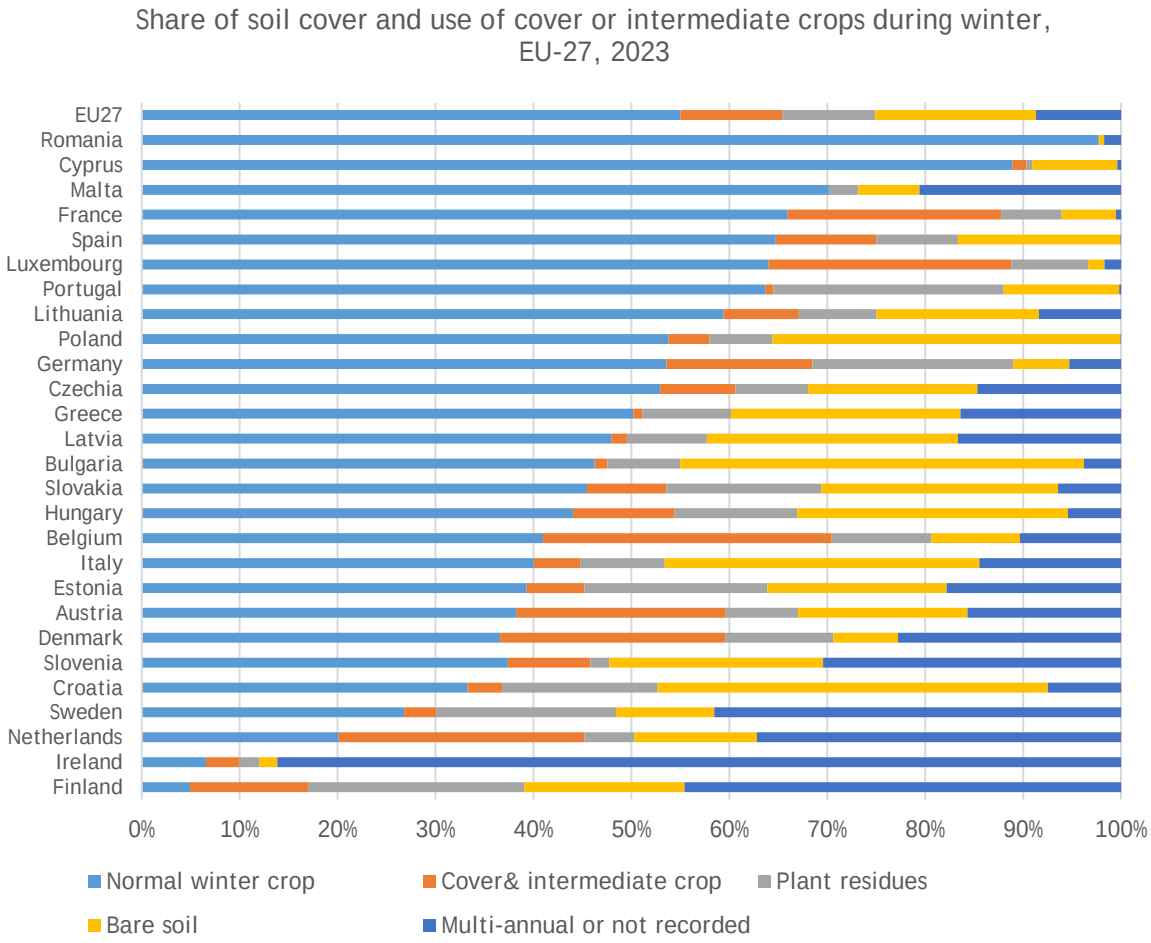
[1] Soil cover by arable land area, farm type, crop rotation and NUTS 2 region and Agri-environmental indicator - soil cover - Statistics Explained

2. There are marked differences in the use of winter crops between EU countries with clearly higher shares in southern countries (Cyprus, Spain, Portugal, France, Malta and Greece) and also central European countries like Romania, Poland, Germany, Luxembourg, Lithuania and Czechia. The smallest winter crop share is found in Scandinavia where cold winters make the growth of arable crops challenging. There are also low shares of winter crops in central and Atlantic countries like Ireland, the Netherlands, Denmark (Figure 21) which has to do with the large area of temporary rotational grasslands. These grasslands are ploughed up after 1, 2 or 3 years and are therefore included in the arable land class. The grassland has a good coverage of the soil, also during winter time.

3. The current use of cover or intermediate crops in winter amounts to 10% (10.0 million hectares) on average for EU-27 in 2023 and this area increased towards 2023 because in 2016 it amounted to 8% of arable land (7.1 million hectares). The driver in this has most probably been the Good Agricultural and Environmental Conditions (GAEC standards) requiring soil cover as a pre-requisite to obtain CAP payments.

4. There are many countries with high shares of arable land in winter reported as uncovered or having a stubble cover. In 2016, this was the case for 30% of the arable land (28 million hectares) in EU-27. Towards 2023, this area declined to 26% (25 million hectares). Bare or stubble land cover is particularly common in central European and Balkan countries such as Bulgaria, Poland, Croatia, Hungary, Slovakia and Slovenia, but also in Lithuania, and in the south in Italy and Greece.

Figure 21 Soil cover in winter in EU-27 in 2023 expressed as a percentage of total arable land.



From the data presented in Figure 21, it appears that the area available for growing intermediate crops in summer and winter can be quite significant because intermediate crops can take the place of the soil that is left bare, but also the place of the currently used unproductive cover and intermediate crops (in winter).

Alternative datasets that provide further insights into the fallow area between two main crop rotations in the EU come from LUCAS and the more recent Copernicus HRL Croplands product. The LUCAS data are only discussed in Appendix 6, because they are not providing the detailed information needed for this study. The HRL Croplands dataset is the best to identify fallow land lying bare in conventional rotations in EU-27 because of its high temporal and spatial resolution which provides insights into the length of the fallow period between harvesting and establishment of the main crops both in winter and summer. In the next section, the data extracted and analysed from this HRL Cropland dataset is further discussed. Together with Eurostat data, they will serve as the basis for identifying land availability for intermediate crops in this study.

5.2. CROP ROTATION AND FALLOW LAND AVAILABILITY

The High-Resolution Layer Croplands[2] is a recent product by Copernicus that provides at pan European level a classification of croplands into 19 crop type classes at a spatial resolution of 10 meters for the years 2017-2021. In addition to crop type, the dataset also includes annual cropping patterns at 10 m resolution. Part of the crop pattern information covers the presence of bare soil before the establishment and after the harvest of the main crop. Bare soil is indicative for the rotational fallow period that may be available for growing intermediate crops. A major advantage of the HRL Cropland product compared to LUCAS is that it provides not only the occurrence of bare soil but also the duration of bare soil periods (in days) before sowing and after harvest. Another advantage of the HRL cropland data, as compared to the LUCAS data, is that it covers the entire European territory (wall-to-wall) at high spatial resolution.

5.2.1. Crop rotations in EU-27 and length of fallow land available based on HRL Cropland

After processing and analysis of the HRL Cropland data, a very precise overview was derived concerning the rotational fallow land in the EU (Table 15). In total, almost 38 million hectares of land were identified as lying fallow in summer, which amounts to 38% of the total arable land. In winter, there is even more bare land that can be considered as rotational fallow and it amounts to almost 40.5 million hectares which is 41% of the arable land. Countries with the highest proportion of fallow lands in summer are Denmark, Lithuania, Poland, Czechia, Latvia, Bulgaria and Cyprus (Table 15). Highest shares of winter fallow are found in Hungary, Netherlands, Belgium, Romania, Croatia, Slovakia, Slovenia, Bulgaria, and Germany.

Table 15 Overview per EU-27 country of rotational fallow land in winter and in summer (source: HRL Cropland 2017-2022).

	Arable land	Area with summer fallow	Area with winter fallow	% Arable land with summer fallow	% Arable land with winter fallow
Austria	1,321,780	487,882	591,242	37%	45%
Belgium	865,480	265,444	507,285	31%	59%
Bulgaria	3,473,810	1,548,648	1,661,542	45%	48%
Cyprus	93,210	93,000	43,699	100%	47%
Czechia	2,529,850	1,346,355	916,158	53%	36%
Germany	11,681,400	6,374,274	5,702,421	55%	49%
Denmark	2,366,110	1,352,817	551,892	57%	23%
Estonia	710,590	255,353	232,104	36%	33%
Greece	1,716,440	341,974	830,537	20%	48%
Spain	11,493,780	555,382	872,827	5%	8%
Finland	2,248,000	465,466	760,366	21%	34%
France	16,954,710	5,821,579	8,014,892	34%	47%
Croatia	866,320	275,740	452,223	32%	52%
Hungary	4,150,960	1,484,939	2,311,937	36%	56%
Ireland	440,730	213,515	91,777	48%	21%
Italy	7,055,820	1,967,857	2,357,437	28%	33%

[2] High Resolution Layer Croplands – Copernicus Land Monitoring Service

	Arable land	Area with summer fallow	Area with winter fallow	% Arable land with summer fallow	% Arable land with winter fallow
Lithuania	2,300,970	1,490,817	490,056	65%	21%
Luxemburg	61,660	20,374	20,528	33%	33%
Latvia	1,359,900	761,287	183,580	56%	13%
Malta	7,480	1,620	1,019	22%	14%
Netherlands	1,008,900	143,769	628,134	14%	62%
Poland	11,140,340	5,893,148	4,412,101	53%	40%
Portugal	847,330	98,282	268,099	12%	32%
Romania	8,406,560	2,886,524	3,731,352	34%	44%
Sweden	2,526,050	868,128	367,920	34%	15%
Slovenia	177,790	2,090	84,403	1%	47%
Slovakia	1,307,120	456,627	635,252	35%	49%
EU-27	99,352,400	37,864,391	40,461,713	38%	41%

It should be mentioned that the fallow land period in winter and summer is not mutually exclusive. It is well possible that fallow periods are present both in winter and summer. What counts is the length of the fallow period.

In absolute terms, the largest summer and winter fallow areas are found in the Central regions of Europe, located in both the Continental and the Atlantic environmental zones. In the Mediterranean areas, the available area of bare land is smaller both in absolute and relative terms, largely because of the larger presence of permanent crops (e.g. vineyards, olives, fruit) leaving less for arable rotational land use. By far the smallest amount of fallow land is found in the North and the Alpine regions.

Whether the fallow land is really suitable for the production of intermediate crops in practice also depends on the length of the fallow period. This is information that can also be derived from the HRL Cropland layers. The result is mapped for the different classes of days in fallow in Figure 22. More than 70% of the bare land in summer is lying fallow for less than 60 days which is too short to grow an intermediate crop to full maturity. For example, the minimum number of days required for Camelina is 90 days. Another 10% of the bare land in summer is fallow between 60 and 90 days, 7% between 90 and 109 days, 8% between 110 and 139 days and the remaining 3% for 140 days or longer. Countries with high arable land shares with long fallow periods above 90 days are mostly located in the North, specifically in Sweden, Finland, Baltic States, but also in Czechia, Austria, Croatia, Poland, Slovakia and the Netherlands.

For the bare land in winter, the length of the fallow period is generally longer than summer fallow in most countries. 34% of the winter fallow land has a short length of maximum 59 days. This very short winter fallow period is mostly concentrated in countries in the south of Europe such as in Cyprus, Spain, Malta, Portugal, Italy but also in the west such as in Ireland. 47% of the bare land in winter lies fallow between 110 and 169 days and this is mostly seen in regions in Austria, Bulgaria, Czechia, Baltic states Sweden, Finland, Croatia, Hungary, Slovakia and Slovenia. Including an intermediate crop in this winter fallow period is not so easy because the Growing Season Length (GSL) of an intermediate crop is longer in winter than in summer. Consequently, even though the winter fallow period is generally longer it does not imply that intermediate crops have more room to be included in the rotation.

Figure 22 Days in summer fallow per NUTS-3 region (source: HRL Cropland 2017-2022).

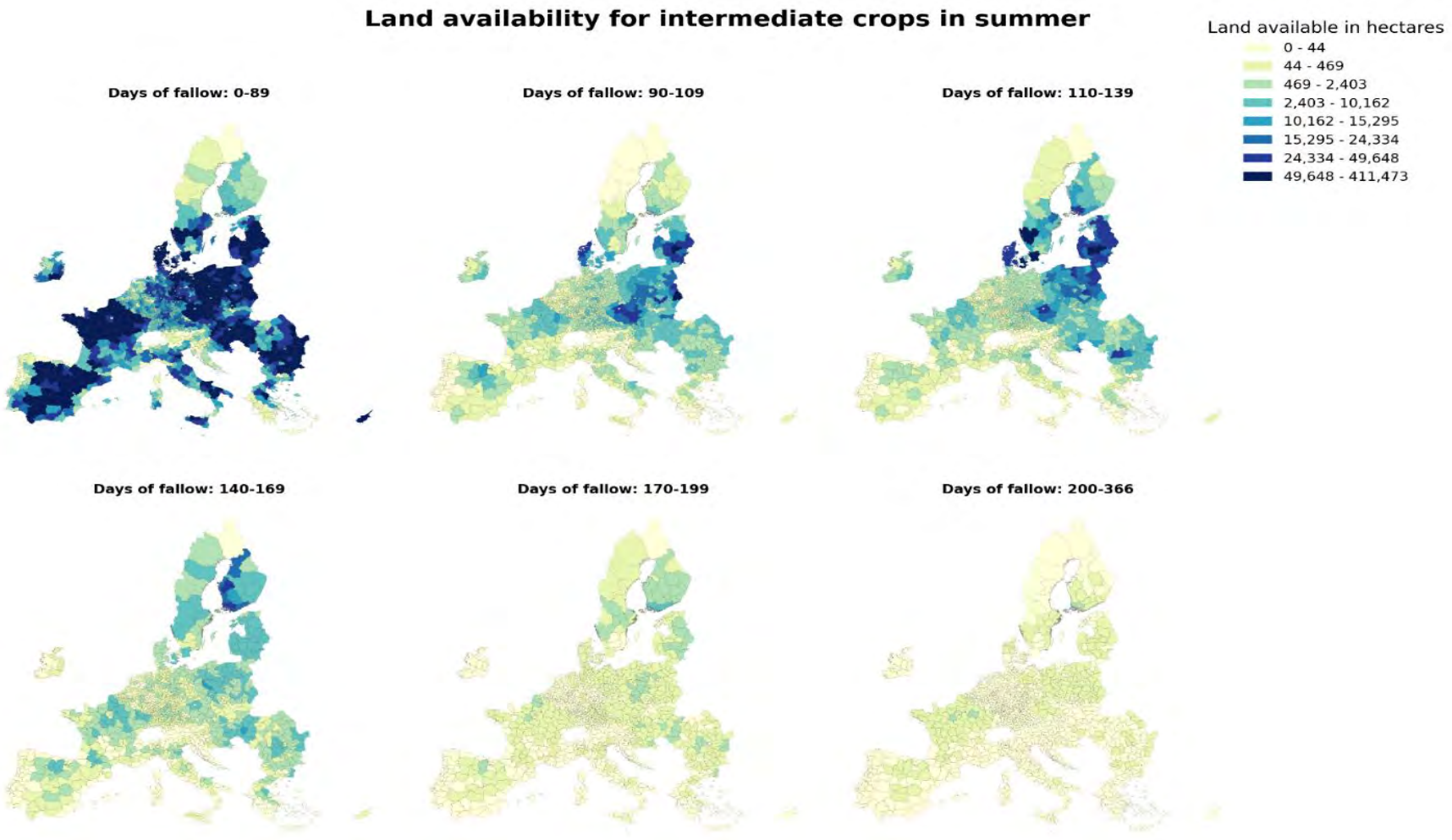


Figure 23 Days in winter fallow per NUTS-3 region (source: HRL Cropland 2017-2022).

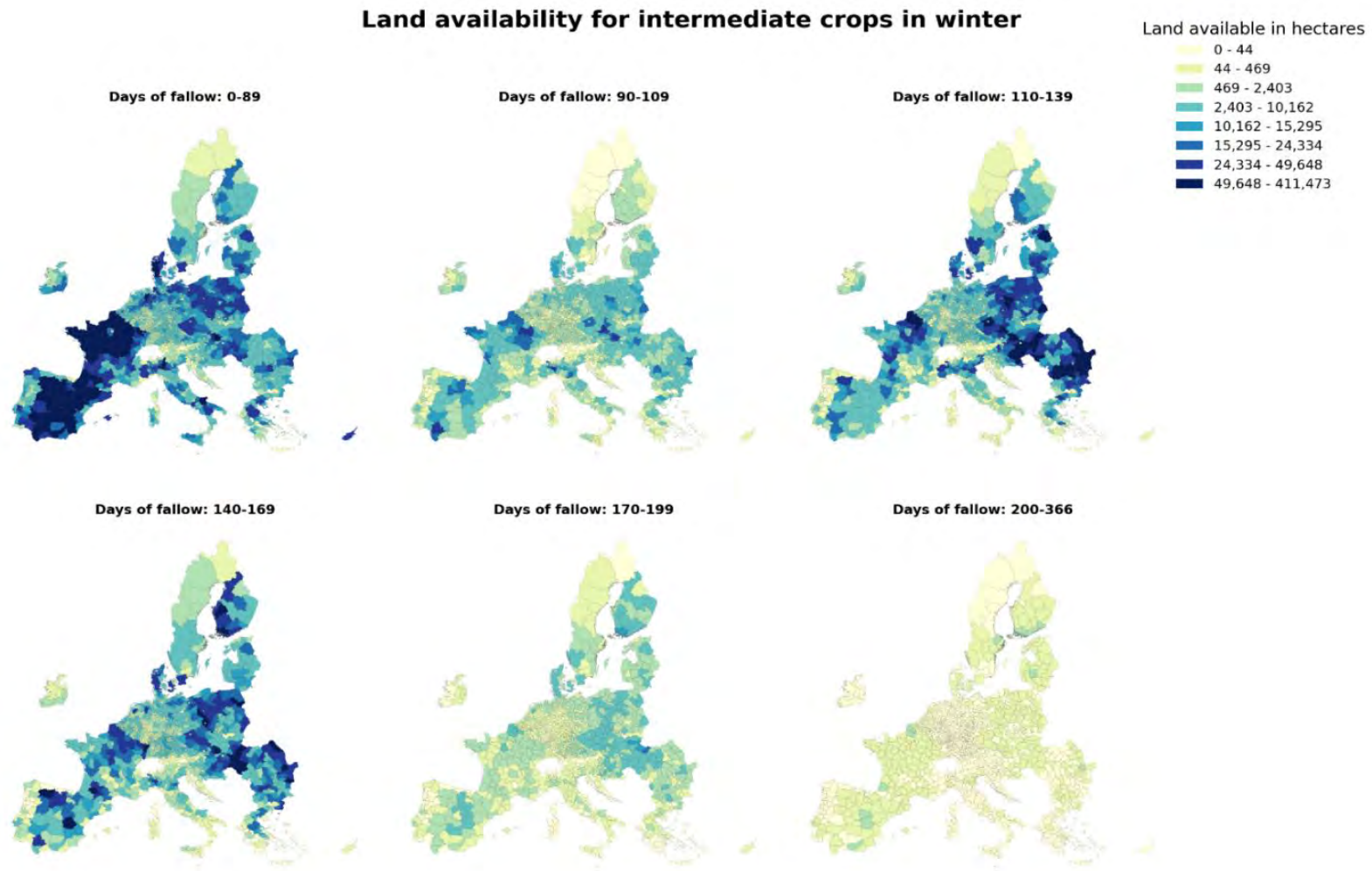
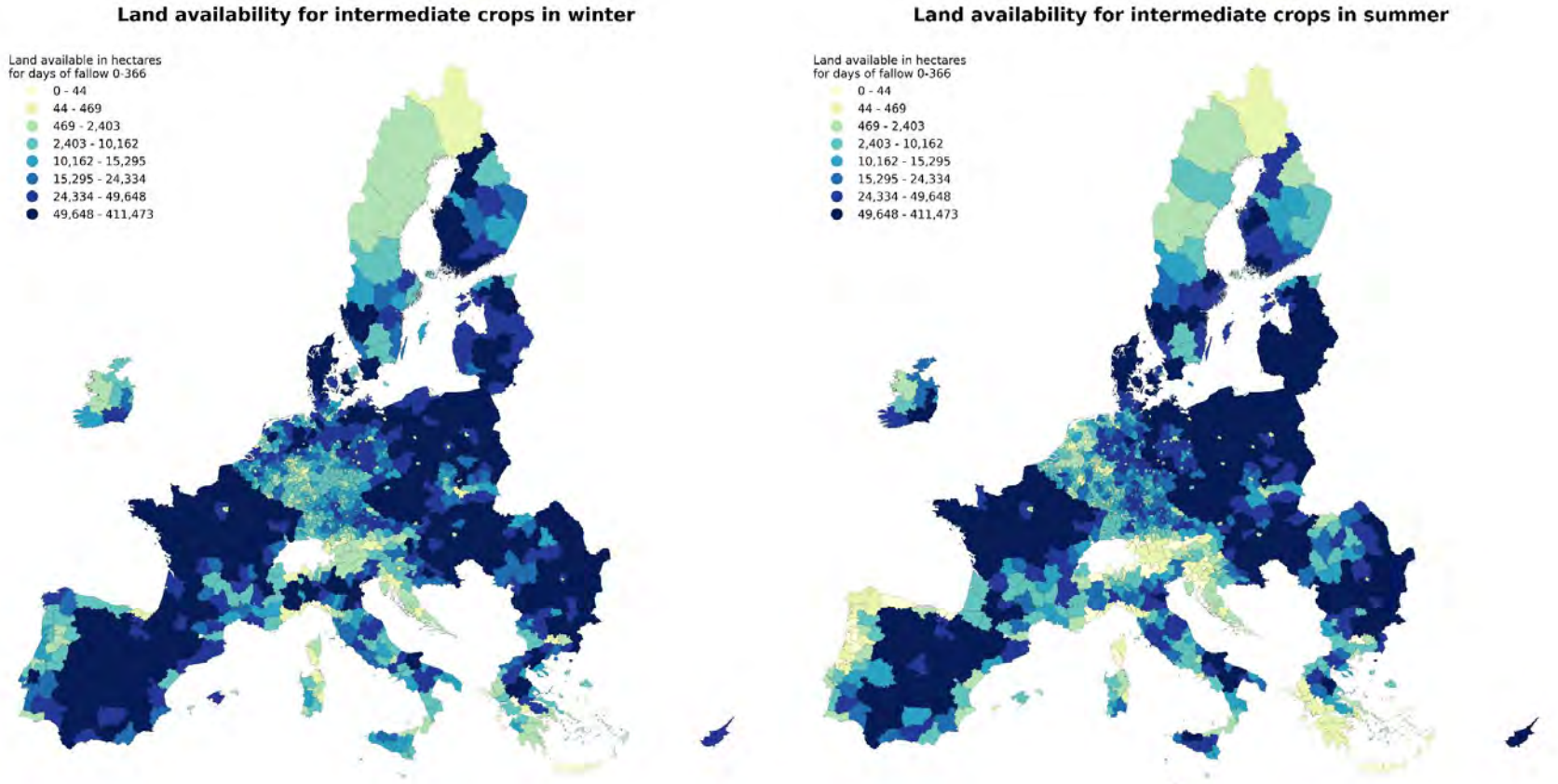


Figure 24 Arable land area per region in summer fallow (left map) and in winter fallow (right map) per NUTS-3 region (source: HRL Cropland 2017-2022).



5.3. FUTURE LAND USE IN EU

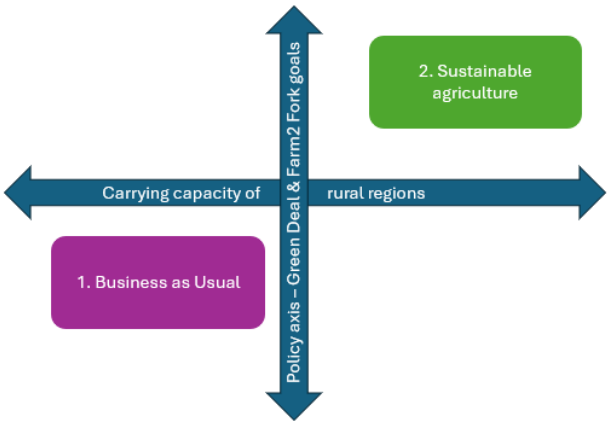
5.3.1. Introducing the land use change scenarios

Future land use changes will affect the availability of land for intermediate crops. In a study for DG Agriculture, future land use changes were modelled under two scenarios for 2050 (DG AGRI, 2025). The results of that study are used here to understand what land use changes in agricultural land towards 2050 can be expected. In that land use change study, agricultural land was analyzed in relation to changes in use and land management, competition, and, synergies of agriculture with other land use sectors and also between food, feed, energy, and non-food biomass production. The study modelled these land use changes with the iCLUE model at 100 m grid, but final results were aggregated to NUTS-3 regions. The two developed scenarios in this land use study to project land use change trends towards 2050 are the following (see also Figure 25):

- Business and usual (BAU): current trends/ drivers of urban sprawl, climate change, land degradation, land abandonment, intensification, extensification, diets, are expected to continue. Also Farm to Fork (F2F) and wider Green Deal (EGD) policy goals are not addressed with new policy instruments. Society's interest to adopt changes in lifestyles and pay for maintenance and improvements in ecosystems services connected to production of food does not increase. In principle, this scenario is a continuation of the policy situation pre-2020.
- Sustainable Agriculture (SA): drivers are expected to be brought in line with the Green Deal and the Farm to Fork targets and ambitions and all associated targets are expected to be met also in combination with societal changes supporting these such as a protein transition towards more vegetal based diets.

More details about the assumptions taken in this land use study are discussed in Appendix 6.

Figure 25 Positioning of two land use change scenarios. Horizontal axis shows carrying capacity of rural territories to respond to EU and national policy targets (Left=low capacity/Right = high capacity). Vertical axis refers to the interest of the political system to develop and implement the policies directed to the achievement of the goals of the EGD & F2F (top= high interest/bottom= low interest).



5.3.2. Land use change expectations towards 2050

In the BAU scenario, agricultural land in total declines by as much as 8 million hectares while in the SA scenario it could be limited to 1.4 million hectares. In the BAU scenario, the main reason for this loss is the decreasing competitiveness of agricultural production especially in regions where productivity is low and where economic margins dictated by world market prices are not reached. This is strengthened by land take by built-up area and climate change effect. In the SA scenario there is more active policy involvement which implies more support to regions to improve the carrying capacity of regions to implement the EGD and F2F measures. Therefore, the policy goals are reached and more land is sustained in agricultural production supported by better access to labour and stimulation of (local) market demand.

The decrease in agricultural land in the BAU scenario is largely caused by an overall decline in annual crops as these will decrease by 7 Mha between 2020 and 2050 (

Figure 26), with an additional smaller decline related to a shift towards perennial crops which expand by 1.2 Mha over the same period (see Table 16).

In the SA scenario, there is a cropland increase between 2020 and 2050 at EU level, although outcomes vary between countries and regions. This is accompanied in most regions by a large increase in the perennial crop area which often goes together with a decline in certain annual crops (see

Figure 26 and Table 16). The loss in annuals amounts to 7.9 Mha, shifting the share of annuals in agricultural land from 48% in 2020 to 44% in 2050. The decline in annuals and the other categories is almost completely compensated by a steep increase in perennials of 15 million ha at EU level (Figure 24 and Table 16). The perennial area share, which includes both fruits and nut trees, but also perennial biomass crops (e.g., Miscanthus, biomass sorghum etc.), will therefore shift from 8% in 2020 to 16% in 2050 over the entire EU. Shifts towards less annuals and more perennials are seen in both the BAU and the SA but are regionally specific (see Table 16).

Table 16 Summary of land use changes in cropland 2020-2050 for the BAU and SA scenarios (DG AGRI, 2025).

	2020 (ha)	2050 BAU scenario (ha)	2050 SA scenario (ha)	% Change 2020-2050 in BAU scenario	% Change 2020-2050 in SA scenario
Root Crops	3,066,100	2,876,200	2,839,400	-6%	-7%
Maize	24,048,600	21,994,600	21,942,100	-9%	-9%
Cereals	53,950,900	50,253,000	48,148,900	-7%	-11%
Other crops	13,299,600	12,191,200	13,553,400	-8%	2%
Total arable	94,365,200	87,315,000	86,483,800	-7%	-8%
Total perennials	16,368,000	17,549,300	31,454,300	7%	92%
Total cropland	110,733,200	104,864,300	117,938,100	-5%	7%

For the estimates of future land availability for intermediate crops, the changes in total arable land and in crop mix towards 2050 have been used to extrapolate the fallow land availability from 2023 (as presented in former section) towards 2050 and the results are given in Table 17. Despite the expected reduction in total arable land, this does not translate into a decline in rotational fallow land during winter,

where intermediate crops can be grown in specific regions. This is because the loss of arable land is accompanied by shifts in the crop mix, which offset the decline. In the SA scenario, the increase in available fallow land, particularly in winter, is more pronounced (Table 17).

Changes in fallow days across different fallow-length classes remain relatively small over time (Table 17). The data indicate that the length of the summer fallow period stays largely stable, whereas the winter fallow period shifts towards longer fallow classes, but only in the SA scenario (Table 17).

Table 17 Overview per EU-27 country of relative changes in rotational fallow land in winter and in summer between 2020 to 2050 in both land use change scenarios (source: HRL Cropland 2017-2022 and (DG AGRI, 2025)).

Fallow length	2020 winter (ha)	2050 BAU scenario winter (ha)	2050 SA scenario winter (ha)	2020 summer (ha)	2050 BAU scenario summer (ha)	2050 SA scenario summer (ha)
0-59 days	13,935,651	16,684,474	17,942,508	27,129,990	25,285,986	25,182,700
60-89 days	3,560,978	3,616,412	3,888,943	3,814,245	3,395,498	3,405,330
90-109 days	2,900,412	2,755,471	2,964,466	2,541,902	2,154,403	2,230,184
110-139 days	10,834,296	10,133,424	10,016,057	3,191,377	2,768,147	2,886,105
140 -169 days	8,234,196	7,551,970	7,797,061	1,030,930	924,657	925,973
170-199 days	940,160	824,139	1,611,022	123,775	104,278	104,522
200-366 days	56,020	48,461	82,222	32,173	31,126	29,954
Total Fallow land	40,461,713	41,614,351	44,302,279	37,864,391	34,664,094	34,764,768

Figure 26 Shifts in annuals between 2020 and 2050 in BAU (left) and SA scenario (right) (DG AGRI, 2025).

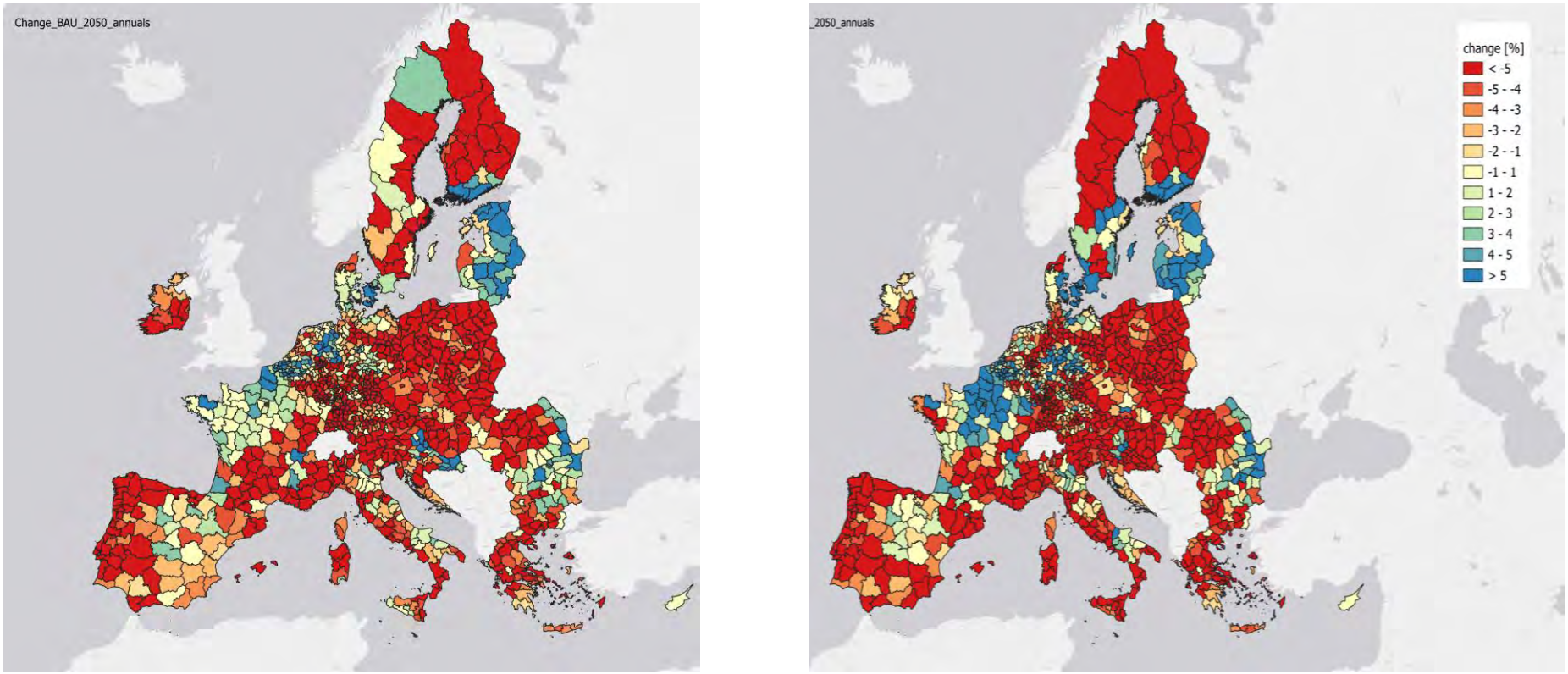
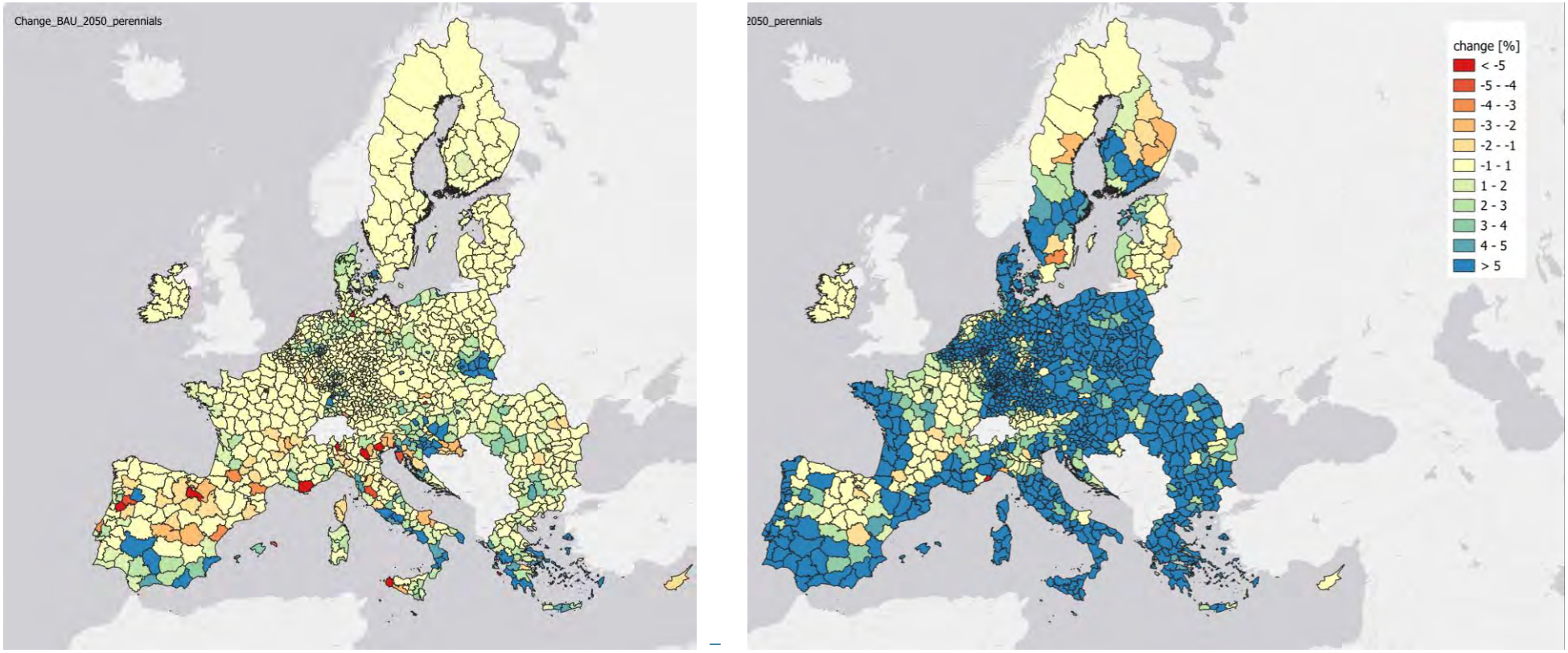


Figure 27 Shifts in perennials between 2020 and 2050 in BAU (left) and SA scenario (right) (DG AGRI, 2025).



6. RESULTS - LAND AND BIOMASS POTENTIALS FROM INTERMEDIATE CROPS

6.1. INTRODUCTION

In this chapter, the potentials for land and biomass availability in the six different scenarios are presented. The scenario approach and definition of the scenarios was already explained in Chapter 3. The potentials presented here are therefore presented for six scenarios (see Figure 5):

1) Current scenario (average of land use 2019-2023) - oil crops and biomass sorghum grown as summer intermediates
2) Current scenario (average of land use 2019-2023) - oil crops grown as winter intermediates
3) Low transition (LT) scenario 2030-2040-2050 - oil crops and biomass sorghum grown as summer intermediates
4) Low transition (LT) scenario 2030-2040-2050 - oil crops grown as winter intermediates
5) High transition (HT) scenario 2030-2040-2050 - oil crops and biomass sorghum grown as summer intermediates
6) High transition (HT) scenario 2030-2040-2050 - oil crops grown as winter intermediates

First the potentials from intermediate crops grown in summer are discussed followed by potentials from winter intermediates.

6.2. POTENTIALS FOR INTERMEDIATE CROPS GROWN IN SUMMER

6.2.1. Land availability in summer

Land availability for intermediate crops is determined by:

1) presence of a summer fallow period in the rotational cropping systems of conventional (mostly) food crops,
2) length of the summer fallow period,
3) availability of an intermediate crop in every region that can perform its full growth cycle in the summer fallow periods available
4) future climate that determines the local weather parameters enabling the growth of intermediate crops in water limited cropping systems in different locations, including the length of the cropping period needed
5) future land use (crop mix) expectations that may influence the availability of rotational fallow periods to incorporate the intermediate crop.

In the former Chapter, it was already explained how these factors apply to different EU-27 (NUTS-3) regions for both current and future conditions and how they were analysed in a spatially explicit way for the whole EU-27. Here, the results of the integrated assessment of land availability for intermediate crops in summer for 2050

are presented. The corresponding results for the other evaluated years, 2030 and 2040, are reported in Appendix 7.

In total 10 million hectares of land would be currently available for intermediate crops in summer across EU-27 (Table 18). This indicates that this land is not only available as fallow land, but the fallow land length and the climate is sufficient to make it suitable to grow at least one of the six selected suitable intermediate crops. Towards 2050, the land availability will decrease by almost 13% and 14% respectively in the HT and the LT scenario. This decrease is mostly related to changes in arable land and related fallow land availability and climate factors. Climate change will lead to a shift in the land that is suitable for production of one or more of the intermediate crops. This pattern of change at regional level will be more diverse however (see Figure 28).

Table 18 Land available (in hectares) suitable to grow at least one intermediate crop during summer across EU-27.

Country	Current scenario (average 2019-2023)	2050 HT scenario	2050 LT scenario
EU-27	10,004,144	8,666,196	8,585,973

The size of the land available in the current and future scenarios is summarized per country in

Figure 28 and at regional level in

Figure 29. The countries with the largest current land availability for intermediate summer crops are Poland, Germany, France, Czechia, Romania. Looking ahead to 2050, substantial decreases in available land are projected for Poland and Romania. Conversely, France, Denmark, Sweden is expected to have an increase in land availability. The overall EU-wide trend is negative, with more countries projected to lose than gain land suitable for intermediate crops.

Some differences also emerge between the HT and LT scenarios for 2050. This is most prominent for France, Germany, Denmark and Sweden where the fallow land expectations in the HT scenario lead to a larger land availability than in the LT corresponding to a stronger climate change situation (SSP5-8.5 radiative forcing).

When looking at the land availability at regional level, the overall trend shows an increase in land availability towards Northern Europe (see

Figure 29). In the top 10 of regions with the largest oil seed potential under the current conditions are 4 regions in Lithuania, 3 in Latvia, 1 in Poland, 1 in Czechia and 1 in Denmark. By 2050, under the HT scenario, the top ten regions shift and are predominantly located in Denmark, Sweden, Lithuania, Latvia and Finland. Under the LT scenario, the top ten regions shift even more strongly towards the Baltic States. A detailed overview of the results per region is given in Appendix 8.

The diversity in land availability for the different countries over time is the outcome of the interplay of climate change factors (Chapter 4), but also expected changes in land use in the different policy contexts of Business as Usual (BAU) and Sustainable Agriculture (SA) land use change scenarios (see also chapter 5 and Appendix 5).

Figure 28 Land availability for summer intermediate crops for the current and the HT and LT scenarios in 2050.

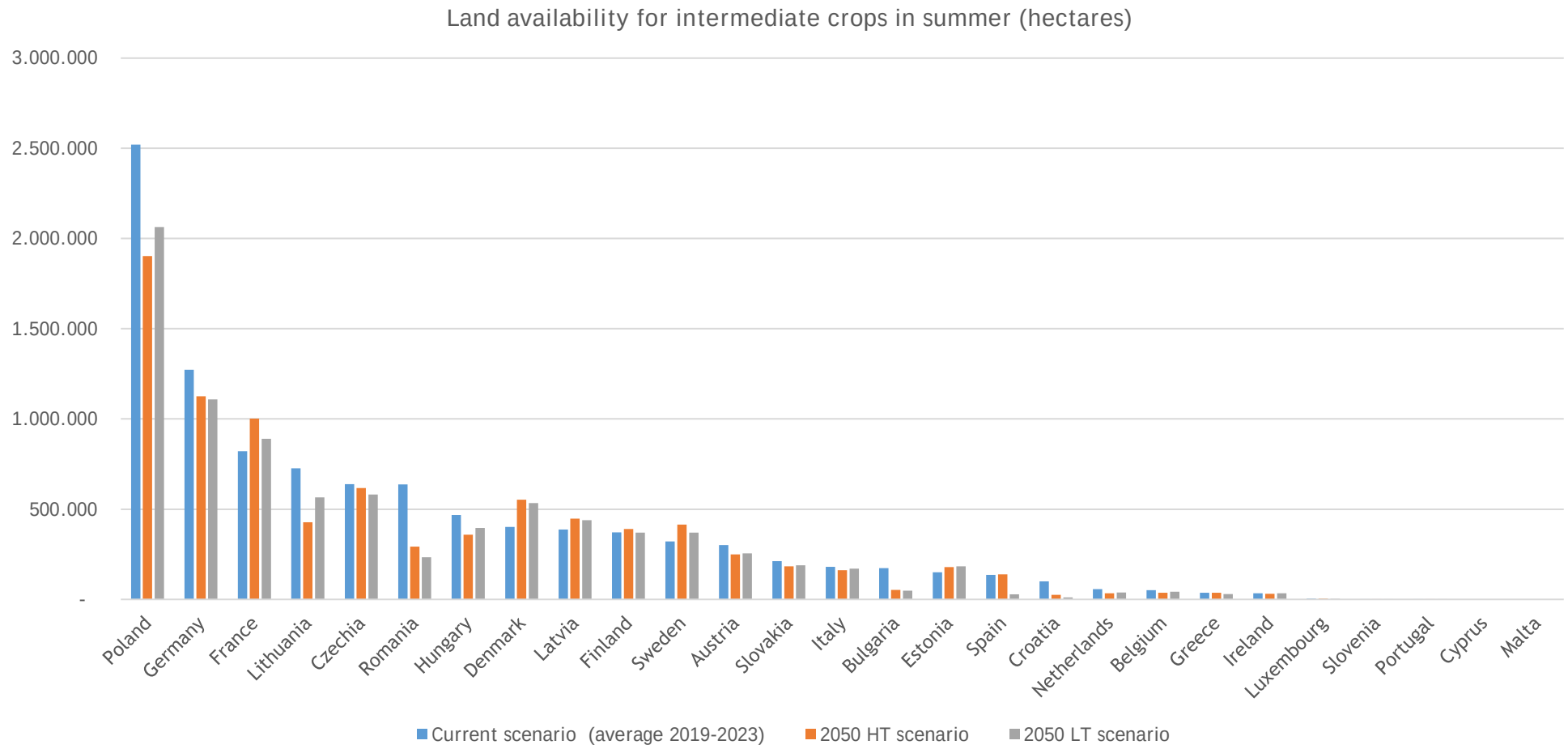
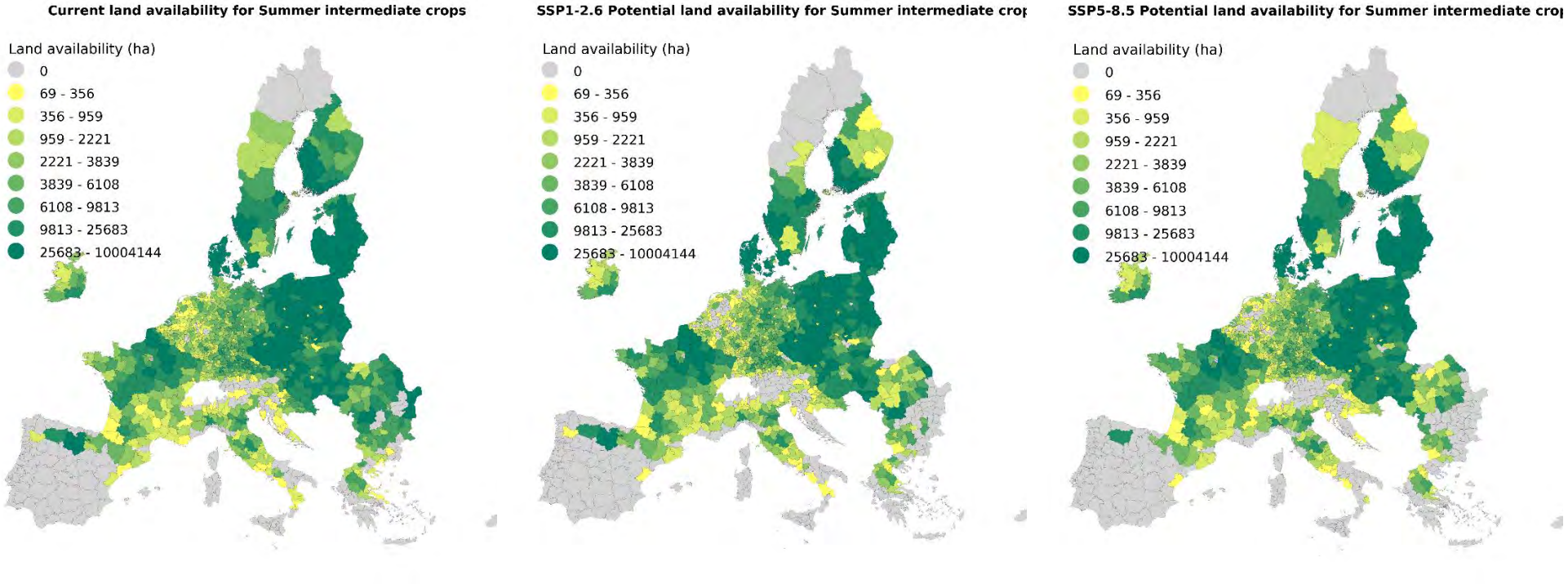


Figure 29 Land availability suitable for at least one summer intermediate crop in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050 at regional level.



6.2.2. Biomass availability in summer

In terms of potentials for summer intermediate crops, there are considerable differences between the current and the future potentials, particularly for the lignocellulosic crop Biomass sorghum. Under current conditions, the total oil crop seeds potential amounts to 10 million tonnes. Towards 2050, it could amount to 13.3 and 12.7 million tonnes in the HT and LT scenario respectively (see Table 19). This increase is most strongly caused by climate change which leads to a shift in crop mix towards higher yielding oil crops. The climate suitable for Crambe and White mustard will expand strongly towards 2050 in both HT and LT scenarios which implies that the potential crop mix will shift almost entirely towards White mustard in 2050, while in the current climate Camelina dominates (see Figure 33). For Biomass sorghum, the land area suitable to produce this crop will increase very strongly under the influence of climate change (see Figure 35). Furthermore, the expected future yield increase under influence of technical innovations will also help to make the potential grow more towards the future, both for oil crops as for Biomass sorghum.

For intermediate oil crops, the maximum share of the fallow land suitable is currently 26% and 25% by 2050. For biomass sorghum this share amounts to only 3% but with climate change it may increase to 5% to 8% respectively in HT and LT scenarios. This maximum is the outcome of the combined factors of the length of the fallow period, which needs to fit to the GSL of the crop, and the climate suitability in terms of temperature but also precipitation/evapotranspiration. The latter factor is important because the starting point is that intermediate crops need to be able to grow without applying irrigation. Water availability in summer (June-September) is therefore very limiting in the southern regions of the EU-27 and will become even more limiting towards the future.

Table 19 Biomass potentials for only oil crops and for only biomass sorghum scenarios grown as summer intermediates.

	Current (2019-2023) scenario	2050 HT scenario	2050 LT scenario
Oil crops mix scenario			
Oil crops land (hectares)	10,004,144	8,666,196	8,585,973
Share of available fallow land used	26%	25%	25%
Oil crops (tonnes seeds)	9,749,604	13,229,277	12,697,486
Oil potential (Mtoe)[1]	3.45	4.68	4.49
Biofuel potential[3]	3.1	4.2	4.0
Ligno crops mix scenario			
Biomass sorghum land (hectares)	1,012,466	1,856,995	2,831,948
Share of available fallow land used	3%	5%	8%
Biomass sorghum (tonnes dry mass)	12,762,911	27,553,648	39,893,834
Biomass sorghum (Mtoe)[2]	5.33	11.53	16.67
Biofuel potential[3]	2.1	4.6	6.7

1) Assuming an oil content of 40 wt% and LHV of 37 MJ/kg
2) Assuming an LHV of 17.5 MJ/kg
3) Conversion yield (energy units) to biofuel: For oil = 90%, For lignocellulosic biomass = 40%

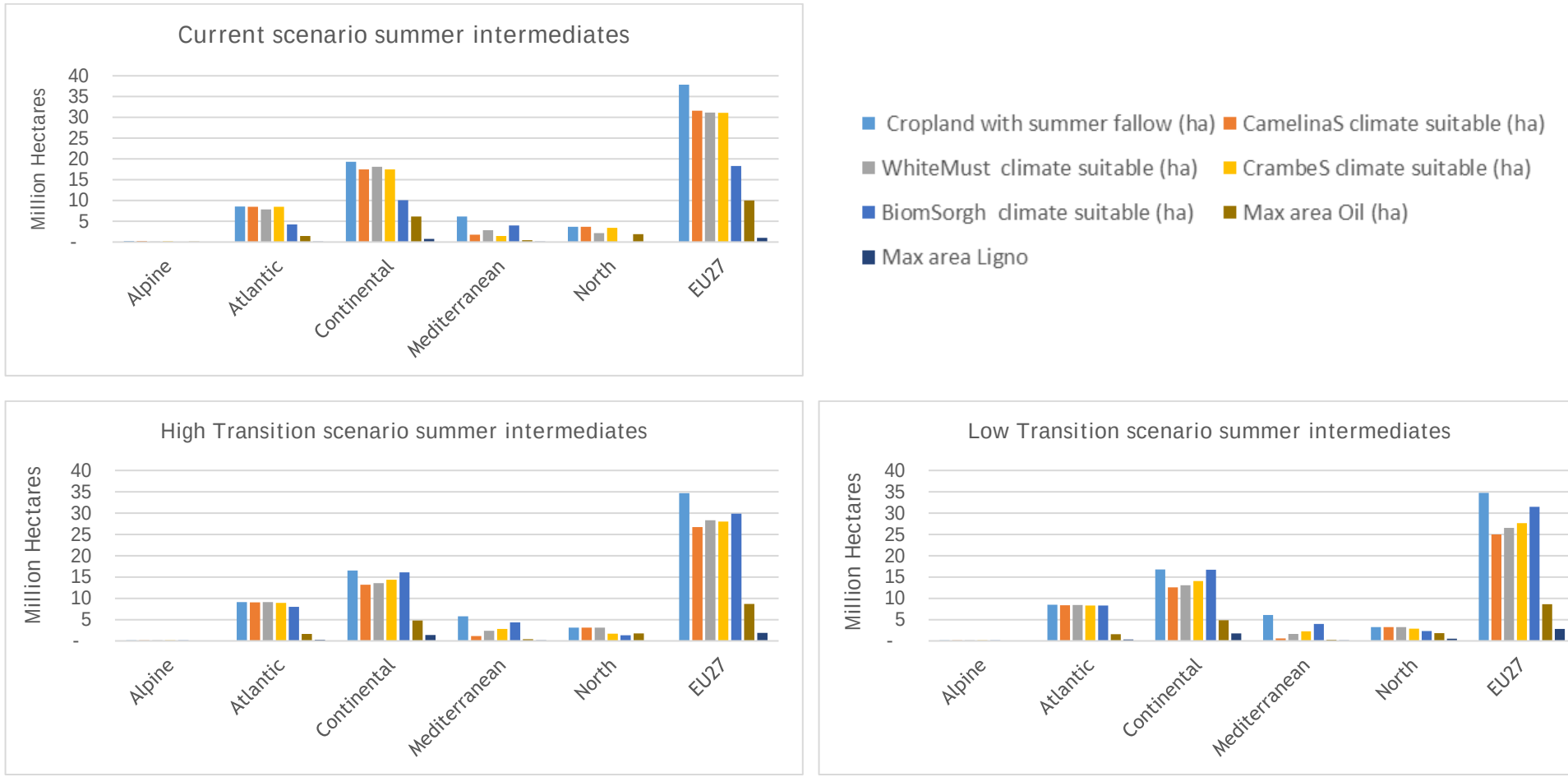
Figure 30 presents both the total summer fallow cropland area and the share of area that is climatically suitable for each intermediate summer crop. They also show the remaining suitable area once the second requirement-alignment between the fallow period and the crop-specific length of the growing season (LGS), is applied (max area).

Under current conditions, the three oil crops show an average climate suitability of around 82% of EU-27 land with summer fallow. Camelina and crambe are climatically suitable across most climate zones, with the exception of the Mediterranean. White mustard performs better in the Atlantic and Continental zones during summer, but shows lower suitability in the Alpine, Mediterranean, and Northern zones. Overall, most EU climate regions, apart from the Mediterranean, demonstrate good adaptability for the cultivation of intermediate crops and associated biomass production. In Southern Europe, however, high temperatures and water stress significantly constrain their deployment, with climatic conditions representing the primary limiting factor. In these areas, lignocellulosic crops appear to be a more suitable option when maximising land use is the objective, as they generally exhibit greater tolerance to heat and water limitations.

By 2050, this climatic suitability shifts. Suitability declines particularly in the Mediterranean and Continental zones for camelina and white mustard, while improving in the Northern zone due to the rise in temperature. For crambe, future climate conditions appear more favourable in the Mediterranean but less so in the North. In contrast, the lignocellulosic crop biomass sorghum shows a substantial increase in climatically suitable area towards 2050, especially under the LT scenario representing the most extreme climate change pathway.

When comparing the relative influence of climatic suitability and fallow period length on the deployment of intermediate crops, the latter emerges as the more significant constraint (see also Figure 30). This indicates that aligning the fallow duration with the crop-specific length of the growing season (LGS) constitutes the primary limiting factor for most crops. An exception is observed in Mediterranean regions, where heat stress can also be among the most dominant constraints in specific regions. Biomass sorghum also deviates from the general pattern, as climatic suitability is more limiting than fallow length in the Northern and Alpine climate zones. However, this relationship shifts towards 2050 under changing climatic conditions (see Figure 30).

Figure 30 Area (ha) climatically suitable and area (ha) where climate and rotation match with LGS needs of oil and lignocellulosic (=sorghum) intermediate summer crops (for detailed data see Appendix 7).



When comparing the availability potentials across crop types, the amount of land suitable for lignocellulosic crops, such as biomass sorghum, is substantially smaller than for oil crops. Biomass sorghum is a tropical C4 crop, meaning it can only grow under sufficiently high temperatures. When these conditions are met, the crop grows rapidly due to its high photosynthetic efficiency and effective water use. However, if temperatures are too low during the growing season, the plant cannot survive or complete all its growth stages. Under the future scenario with the strongest climate change impact, the area in Europe with summer conditions suitable for biomass sorghum is expected to increase significantly (see Figure 30 and Figure 32).

Figure 31 Biomass potentials for oil crops grown as summer intermediates in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.

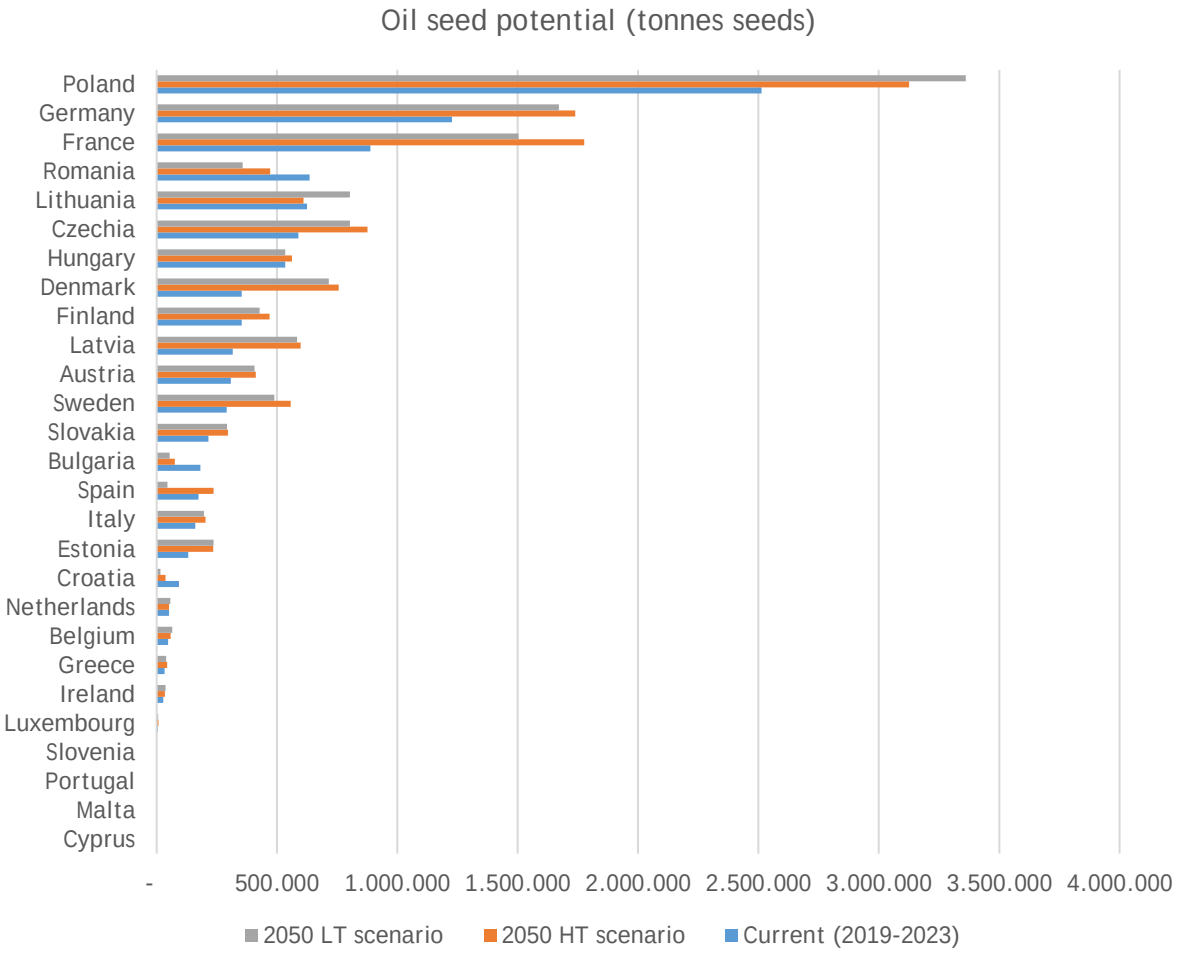
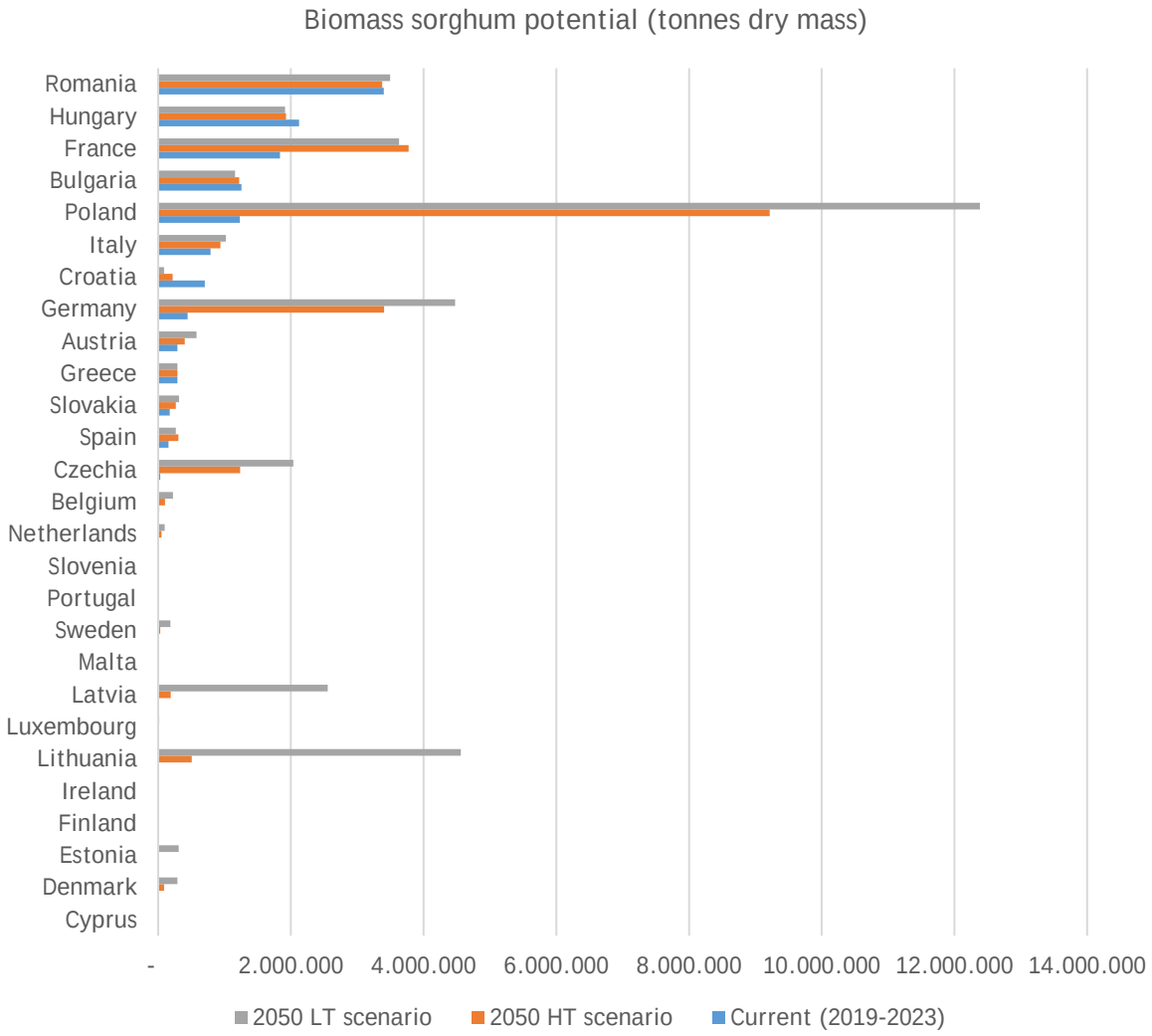


Figure 32 Biomass potentials for biomass sorghum grown as summer intermediate in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.



Countries with the largest intermediate oil crop potential in summer are mostly located in central EU. Towards 2050, the intermediate oil crop potential will particularly grow towards the north and east of the EU-27 (see Figure 31 and Figure 34).

Another important change concerns the optimal crop selection, with a shift from camelina to white mustard towards 2050. This shift is because for White mustard both the suitable area and the yield increases strongly under the influence of climate change. Because of this White mustard becomes a more preferable crop towards 2050, while in the current climate Camelina is still the best option (see Figure 33).

For biomass sorghum the current biomass potential is very modest and mostly concentrated in Eastern EU-27 countries like Bulgaria, Romania, Hungary, Poland and also in parts of France and Northern Italy (Figure 32). For this crop, there is also a very large increase in production potential expected in many countries towards 2050, especially in the Central and North-eastern countries of EU-27 (Figure 32).

Despite the higher selectivity and more limited land availability of biomass sorghum compared to oil crops, its production potential in mass units of biomass is significantly higher, particularly by 2050. This is directly linked to the much higher yields of lignocellulosic crops.

However, when considering biomass availability for biofuel production, lignocellulosic crops and oil crops cannot be compared on the same basis, as they follow fundamentally different conversion pathways. Oil crops, typically containing around 40% oil, undergo oil extraction prior to fuel processing. In practice, extraction performance depends on the characteristics of the specific oilseed feedstock, particularly crushing efficiency, which is reported in the literature to range approximately from 70% to 100% (Veljković, et al., 2022). For the purpose of this analysis, a 100% crushing efficiency was assumed for all seeds as a simplification. In contrast, lignocellulosic crops require conversion of the entire biomass, for example through thermochemical routes such as gasification followed by Fischer-Tropsch synthesis. These routes generally achieve biofuel mass yields of only 15-20 wt%, corresponding to energy yields of approximately 36-48% for drop-in fuels. Consequently, direct comparison of biofuel potential at the EU level requires a conversion-based approach rather than simply comparing biomass mass or land availability. To determine which option, oil crops or biomass sorghum, is more advantageous, an assessment at the regional level is required, as crop performance varies significantly between regions and sometimes even at the farm level. Such an evaluation must consider not only biomass productivity, but also the entire value chain, including conversion pathways and economics. The results presented here do not include this economic optimisation but provide a robust indication of the magnitude of the potential for intermediate crops.

Figure 33 Biomass potentials per oil crop type grown as summer intermediate in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.

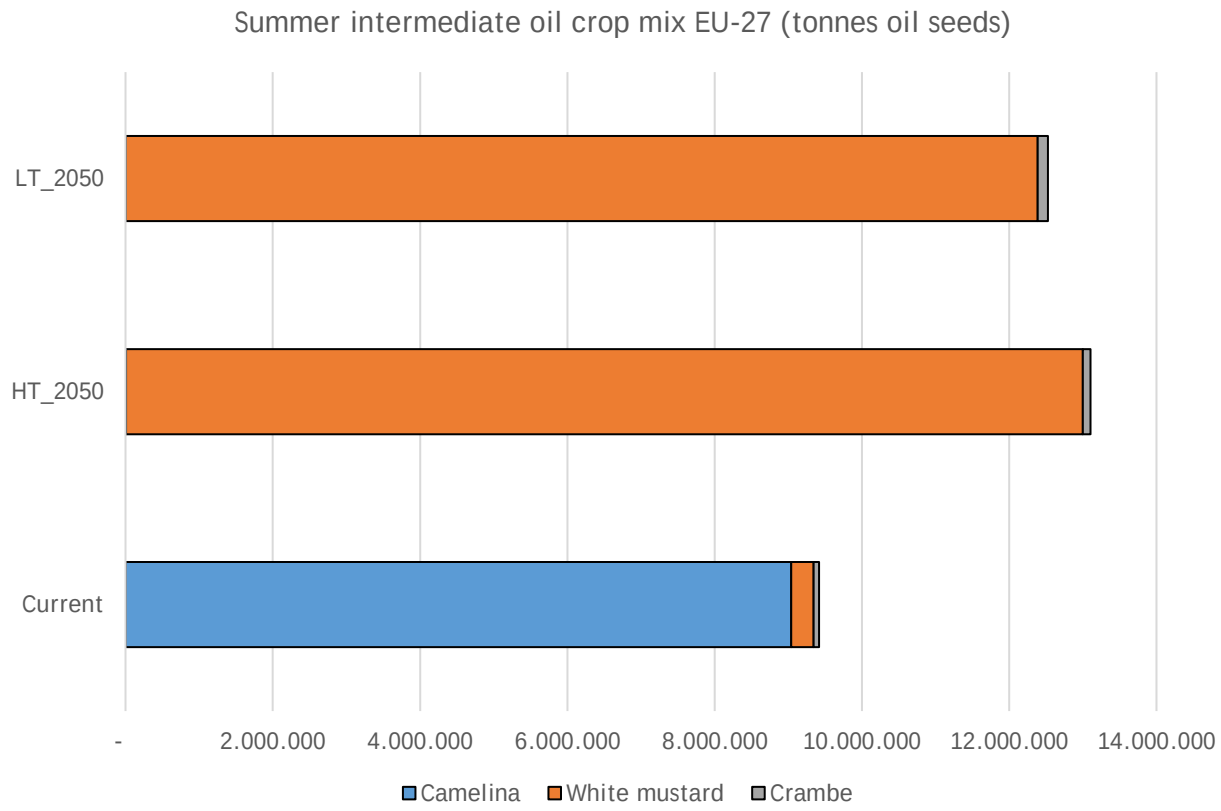


Figure 34 Regional potential (NUTS-3) for oil crops (tonnes seeds) as summer intermediates in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.

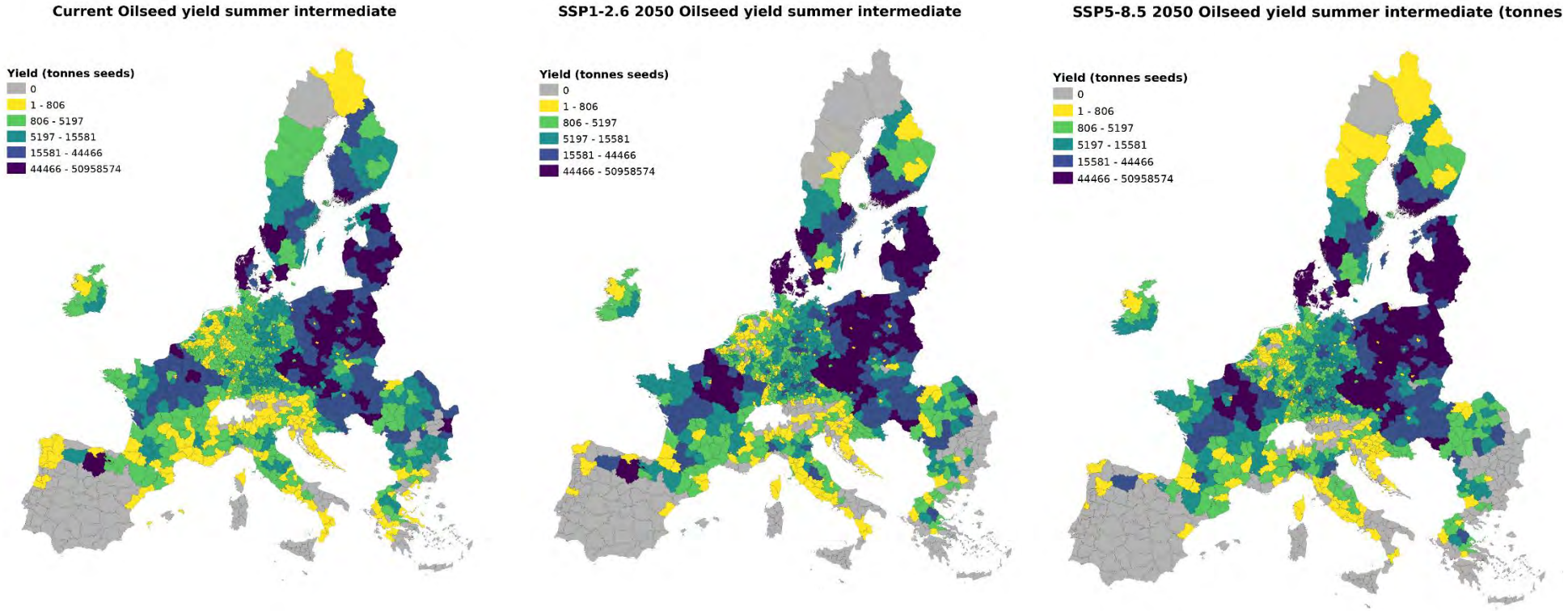
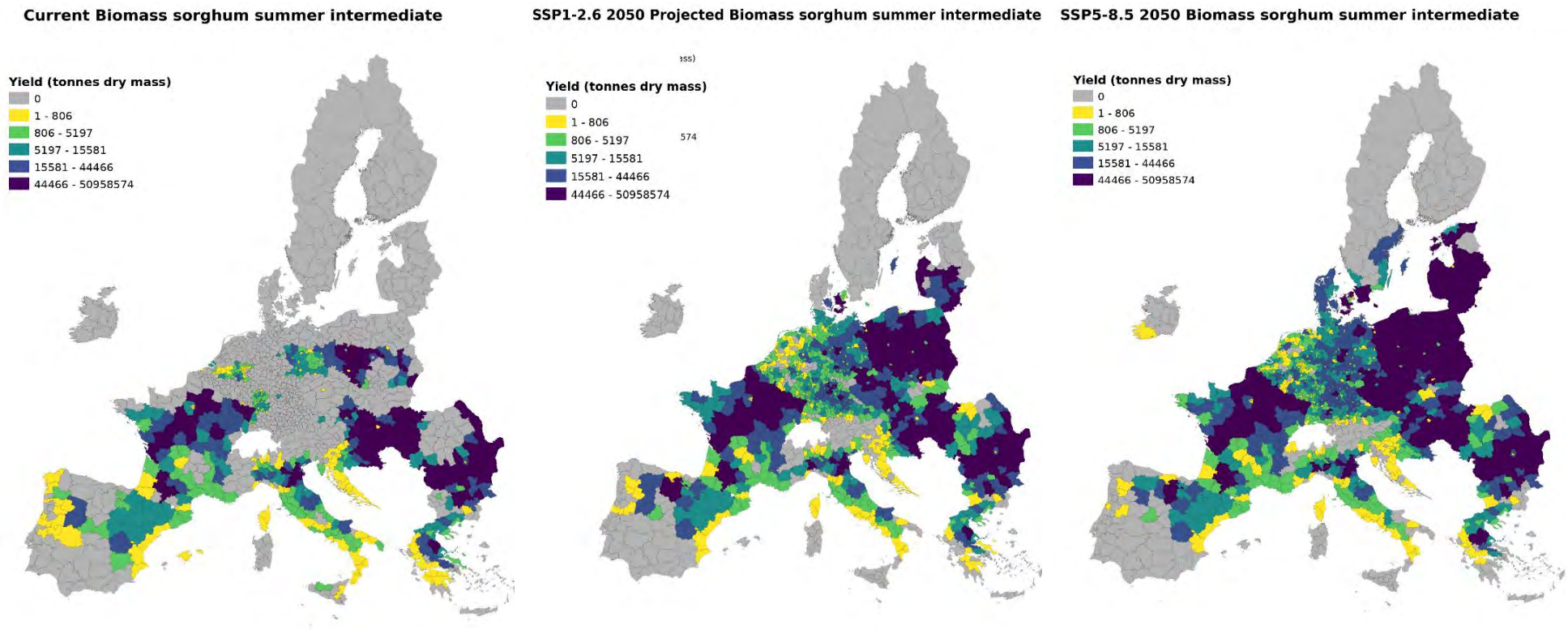


Figure 35 Regional potential (NUTS-3) for Biomass sorghum (tonnes dry mass) as summer intermediate in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.



6.3. POTENTIALS FOR INTERMEDIATE CROPS GROWN IN WINTER

6.3.1. Land availability in winter

As was already explained in the former section, the land availability for intermediate crops is an interplay of a number of spatially specific factors. This also applies for the intermediate crop land potential in winter. Land availability for intermediate crops in winter is determined by:

1. presence of a fallow period in winter in the rotational cropping systems of conventional (mostly) food crops,
2. presence of non-productive cover or intermediate crops in winter as these can also be exchanged by productive intermediate crops,
3. length of the winter fallow period which can either be fallow with no soil coverage or with a non-productive cover or intermediate crop,
4. availability of a suitable intermediate crop in every region that can perform its full growth cycle in the winter fallow period available
5. future climate that determines the local weather parameters enabling the growth of intermediate crops in water limited cropping systems in different locations, including the length of the cropping period a crop needs
6. future land use (crop mix) expectations that may influence the availability of rotational winter fallow periods to incorporate the intermediate crop.

From the former land availability evaluation (Table 15 in Chapter 5), it is clear that the unused land for main crop production in winter amounts to more than 40% of the arable land area in the EU. However, from the analysis it is calculated and concluded that currently only 703,245 hectares (2% of total land unproductively used arable land in winter) meets the intermediate crops growth criteria and can really be used to grow intermediate crops (see Table 20).

Table 20 Land available (hectares) and suitable to grow at least one intermediate crop in winter in EU-27. The results are given only for oil crops as according to the analysis, Biomass sorghum is not suitable to be produced during the winter months.

Country	Current scenario (average 2019-2023)	2050 HT scenario	2050 LT scenario
EU-27	703,245	512,597	824,489

The strong mismatch between the fallow land availability and the eventual intermediate crop land available is more strongly related to the length of the fallow period and the number of days needed for an intermediate crop to grow rather for the general climate suitability (see Figure 36). In the winter period, intermediate crops need many more days to mature than in summer. For example, under the current climatic conditions, the average number of growing degree days across EU-27 is 236 days for Camelina and 188 days for Crambe in winter. In the summer, this reduces to 91 days for Camelina and 118 days for Crambe. Under climate change, the number of growing days in winter may decline in several regions, although the opposite may also occur. See for further details on this aspect Chapter 7.

In the current scenario, the effect of climate constraints, particularly low temperatures, is as limiting in the North and Alpine region as the effect of the short fallow periods (see Figure 36). This is most pronounced in the case of Crambe. However, under influence of climate change towards 2050, the climate limitation effect decreases, but the limitation of fallow land length remains.

The results show that the land potential for intermediate crops will increase towards 2050 only under the LT scenario, as a result of the more pronounced climate change, while it will decline under the HT scenario. Specifically, in the LT scenario, the area available for winter intermediates will increase by 17%, while in the HT scenario, there will be a decline by nearly 27%. This decline is mainly driven by a stronger reduction in arable land and a shift in main crop production towards a higher share of winter crops.

If the land availability for winter intermediates is compared between countries (see Figure 37), the largest potential is found in the South of Europe, particularly in France, Spain, Greece and Italy. These are all countries with mild winters. Notable is that in France the potential in the LT scenario (with the most extreme climate change) will experience a more than doubling of the potential as compared to the current as well as to the HT scenario. This is mostly an interplay of shifts in land use and the climate change increasing the land suitable for oil crops in winter. In Spain, Portugal and Italy, an opposite trend is seen where with climate change, the land suitable for winter intermediates decreases. In Poland, Germany, and Bulgaria, the current potential for winter intermediate crops is still modest, but the land availability will grow strongly. This is not necessarily caused by climate change only, but also related to changes in the crop mix expected as part of the land use change scenarios of BAU and SA (see Chapter 5).

Figure 36 Area (ha) climatically suitable and area (ha) where climate and rotation match with LGS needs of oil intermediate winter crops (for detailed data see Appendix 7).

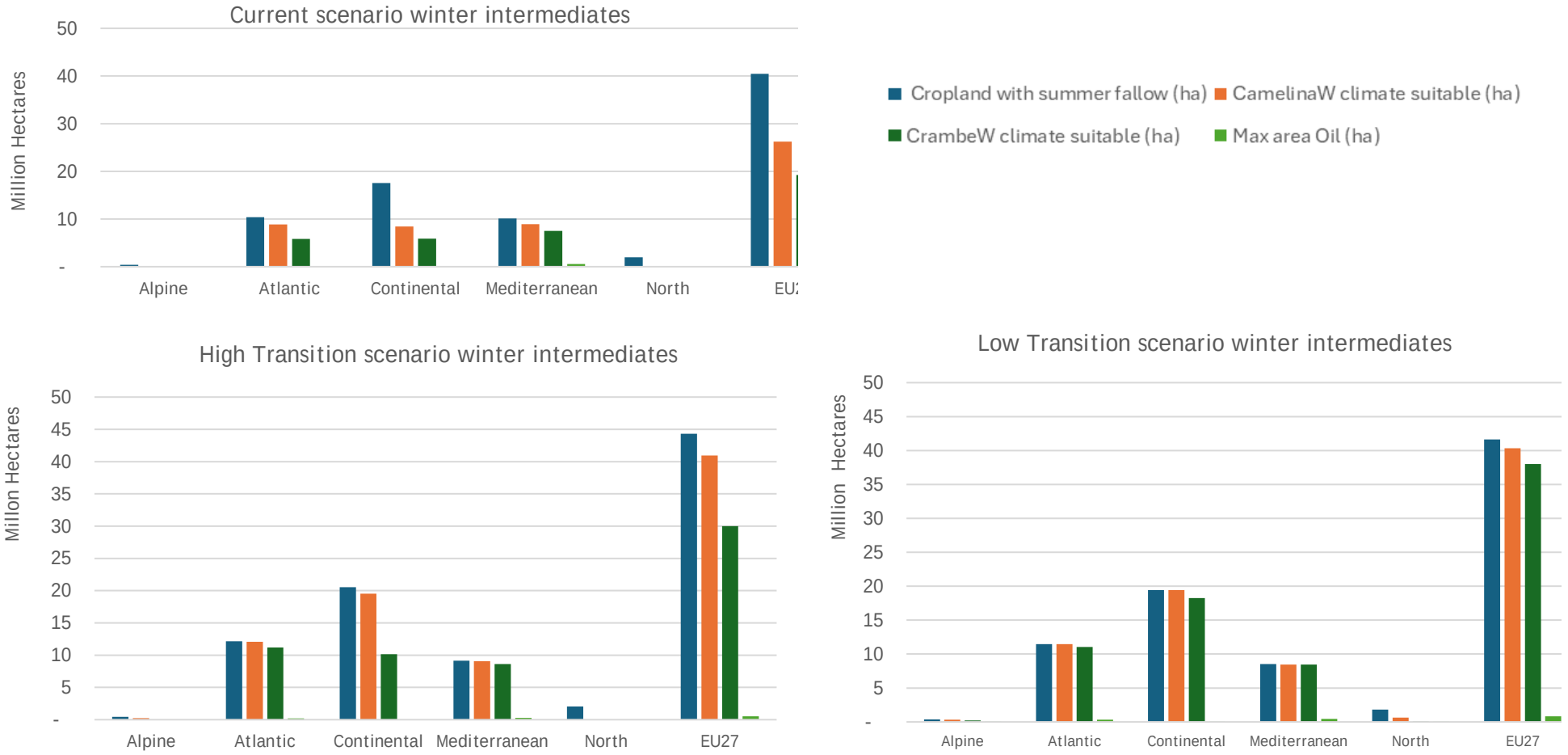


Figure 37 Land availability (in hectares) for winter intermediate crops in current, HT and LT scenarios for 2050.

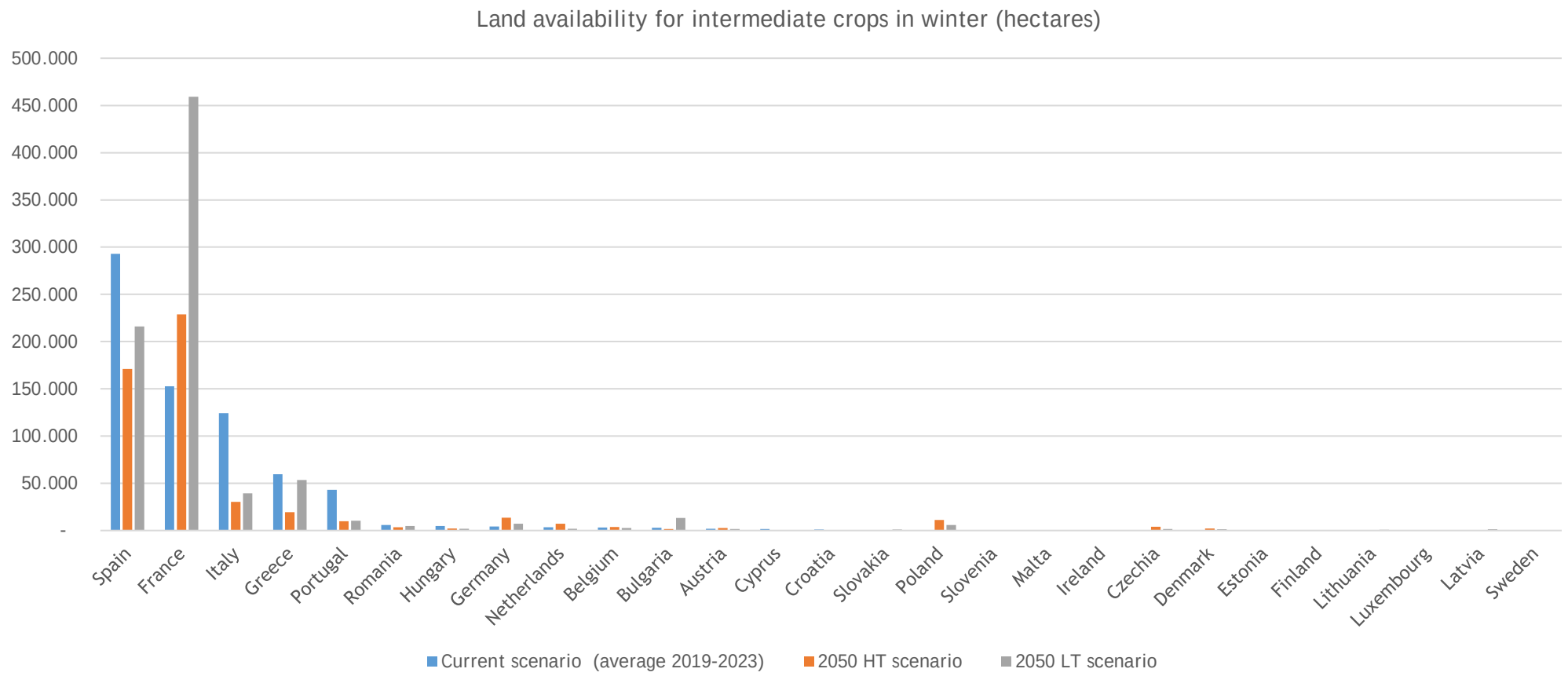
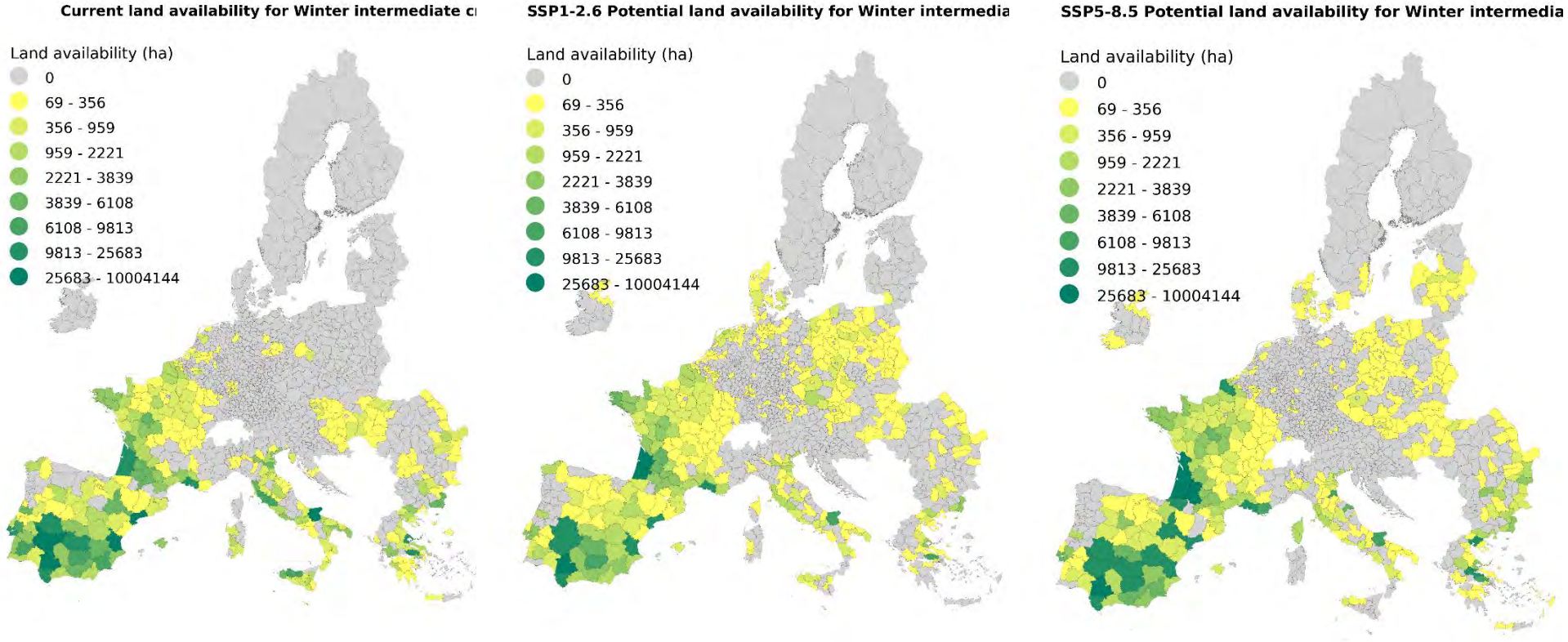


Figure 38 Regional land availability for winter intermediate crops in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.



6.3.2. Biomass availability in winter

The total biomass potential from intermediate crops in winter amounts to 0.97 million tonnes of oil seeds under current conditions. This can grow to over 1 million tonnes in 2050 for the LT scenario, but declines to 0.75 million tonnes for the HT scenario (see Table 21). This shows that the intermediate winter crop potential is only a modest amount compared to the summer intermediate potential (amounting only 10%, 4% and 6% in the current, 2050 HT and 2050 LT scenarios respectively).

However, this modest amount should be interpreted with caution because matching the growing degree days a crop needs to the length of the fallow period is very sensitive. Small changes in the threshold settings on both the side of the plant needs and the classification of land in fallow periods can lead to big differences. Therefore, it is logical to also review how small threshold changes influence the final potential. This is therefore analysed in the sensitivity analysis presented in Chapter 7.

When looking at the regional distribution of intermediate winter crops potential, in Figure 39, it becomes clear that for the current climate, the largest potential is in the Mediterranean area, but with climate change towards 2050, a shift towards central EU, especially France takes place.

Table 21 Biomass potentials for oil crops (tonnes oil seeds) grown as winter intermediates. The results are given only for oil crops as according to the analysis, Biomass sorghum is not suitable to be produced during the winter months.

	Current (2019-2023) scenario	2050 HT scenario	2050 LT scenario
Oil crops mix			
Oil crops land (hectares)	703,245	512,597	824,489
Share of available fallow land in winter	1.7%	1.2%	2.0%
Oil crops (tonnes of seeds)	974,067	753,295	1,043,225
Oil crops (Mtoe)	0.34	0.26	0.36
Biofuel potential (Mtoe)	0.31	0.23	0.32

The oil crop mix also changes in time under influence of climate change (see Figure 40). In the current climate, the majority of potential (57%) comes from Crambe, which generally yields a bit more per hectare. For the future climate conditions, especially in the LT scenario, the potential of Camelina will grow at the expense of Crambe (see Figure 40).

Figure 39 Biomass potentials for oil crops grown as winter intermediates in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.

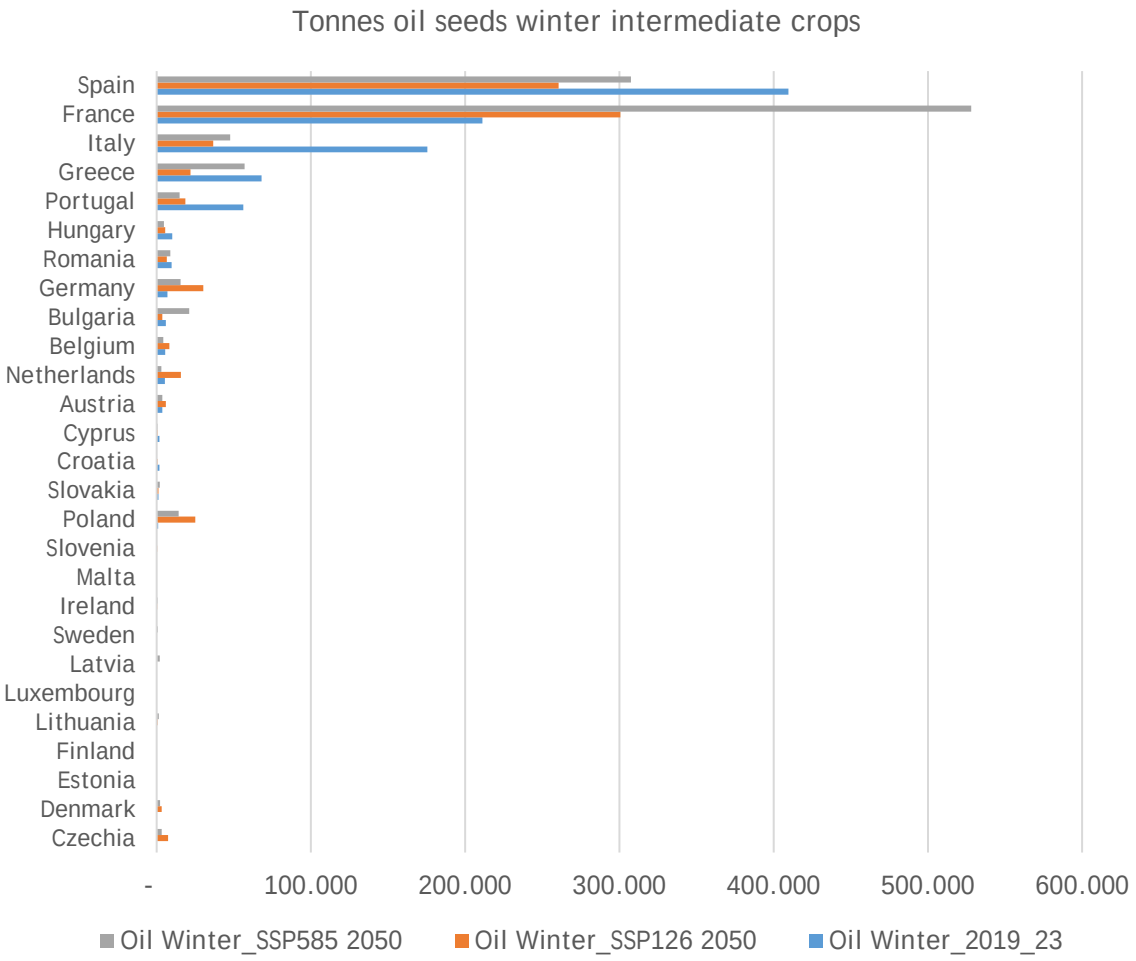


Figure 40 Biomass potentials per oil crop type grown as winter intermediate in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.

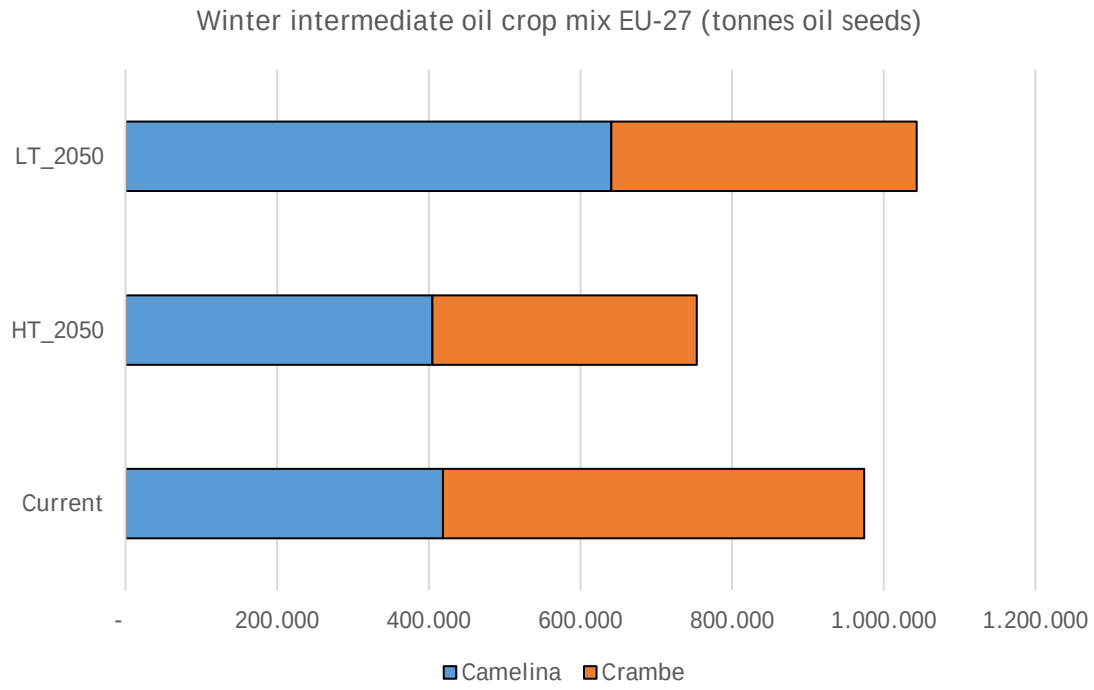
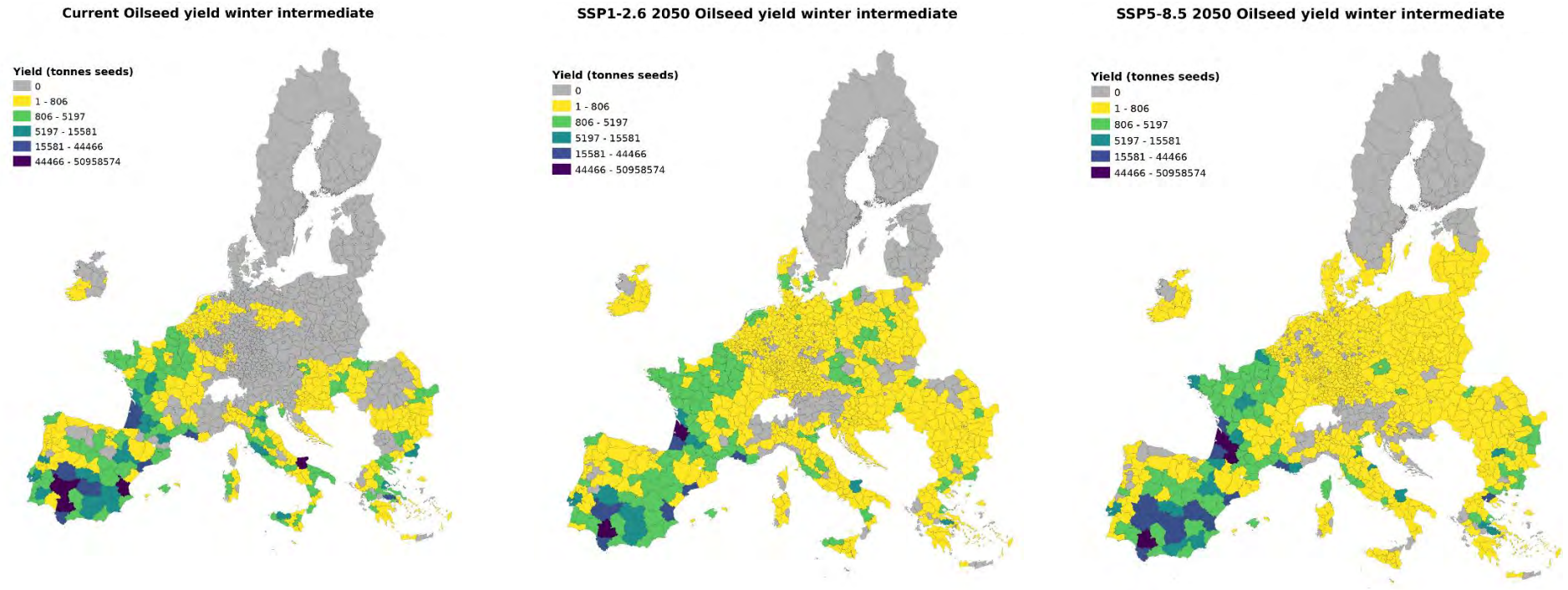


Figure 41 Regional potential (NUTS-3) for oil crops (tonnes seeds) as winter intermediates in current, HT (SSP1-2.6) and LT (SP5-8.5) scenarios for 2050.



7. SENSITIVITY ANALYSIS - ALTERNATIVE SCENARIOS

7.1. INTRODUCTION

From the discussion of land availability and associated biomass potentials in Chapter 6, it became clear that there is often a mismatch between the number of growing days an intermediate crop needs to perform all its growth stages and the length of the period that arable land is not being used for the production of the main crop. This mismatch can be reduced through technological innovation, for example by breeding short season crop varieties. Such breeding efforts may target the intermediate crop, the main crop, or both.

Furthermore, it was already shown that the number of growing degree days an intermediate crop needs can decline under the influence of climate change. This was one of the reasons why biomass potentials changed between 2023 and 2050 and were also different between the HT and LT scenarios. This reduction in growing degree day requirements may also apply to main crops, an aspect that has not yet been addressed but can be further explored in the sensitivity analysis.

In the light of these observations it was decided to focus the sensitivity analysis on the following:

1. Investigate if and how the length of growing degree days of the main crop may change under the influence of climate change towards 2050. A reduction in the growing degree days may lead to an increase in the length of the fallow period increasing the opportunities to grow intermediate crops.

2. Investigate how sensitive the change in land availability for intermediate crops is in relation to shortening the growing degree days requirements. To assess this, the thresholds used to match crop-specific growing degree day needs with fallow land duration classes are broadened by 5%, 10% and 20%. The resulting effect on biomass potential of this widening of thresholds will inform crop breeding and variety selection options to improve intermediate crop potentials with technological innovations. It should be noted, however, that the development of crop varieties with shorter growing periods may affect crop yields; such yield impacts were not considered in this assessment.

7.2. CLIMATE CHANGE EFFECTS ON GROWING DEGREE LENGTH OF MAIN CROP

7.2.1. Methodology

The version 4 of the Global Agro-Ecological Zoning (GAEZ) was developed by FAO in collaboration with IIASA to estimate sustainable crop production levels for historical, current and future climatic conditions for the whole world (Fischer, et al., 2021). It includes a special module that provides agro-climatic actual, attainable and potential yields for more than 300 crop/land utilisation types (e.g. rain-fed/water limited and irrigated conditions) assessed under different input and management assumptions and for current and future climate SSP1-2.6 and SSP5-8.5 scenarios.

From this GAEZ V4 database, the following data for the EU-27 territory[1] were extracted:

- Length of the growing period (LGP) which refers to the number of days during the year when temperature regime and moisture supply are suitable to crop growth and development. More specifically, it is the number of days when the average temperature is above 5ºC and there is no water stress for crops. This implies that the average daily evapotranspiration (ET_a) equals or exceeds the water requirement (ET_m). This is a general factor calculated taking specific reference crops per location. The GAEZ data was downloaded for current, and 2050 conditions for SSP1-2.6 and SSP5-8.5 IPCC climate change scenarios. From the downloaded data, weighted averages at NUTS-3 level were calculated.

- Average length of the crop growth cycles of three reference crops which are most common in the EU-27: Barley, wheat and rapeseed. With the downloaded data for every NUTS-3 region, the average length of the crop growth cycle per crop was calculated for the current and 2050 conditions for the SSP1-2.6 and SSP5-8.5 IPCC climate change scenarios.

With the downloaded and processed data the change in crop growth cycle length between current and 2050 of the main crops was determined as follows (example for SSP1-2.6):

Change in days available in growing season = Change in Length of Growing Season (LGS in days) - Change in Average Length of Crop Growth Cycle (LGC in days) for the 3 main crops in EU-27 e.g. wheat, barley and grain maize) between current and 2050 climate change scenarios in SSP1-2.6 and SSP8-5.8 →

$$(LGS_{SSP1\text{-}2.6} - LGS_{current}) - (LGC_{3crops\_SSP1\text{-}2.6} - LGC_{3crops\_current})$$

Applying this calculation provides an estimate of the number of days with which the growing season length is shortened (or increased) which creates more (or less days) for intermediate crops to grow. The results of this calculation are summarized at country level in Table 22.

Table 22 Average per country of extra number of days available for growing intermediate crops, because of the shortening of the LGS of the main crop. The results show the change in days in the LGS between 2020 and 2050 in SSP1-2.6 and SSP5-8.5 climate scenarios. A positive value means extra days are available for intermediate crops/a negative figure means a reduction in days for growing intermediate crops.

Country	Average of Extra_LGS_SSP1-2.6	Average of Extra_LGS_SSP5-8.5
Austria	-1	2
Belgium	34	42
Bulgaria	4	-9
Cyprus	-6	-31
Czechia	1	-4
Germany	8	12

[1] GAEZ data is available at a spatial resolution of 0.5° x 0.5° latitude by longitude grids (i.e., about 55 km at the equator). This data was extracted and further processed into average crop factors for NUTS-3 regions.

Country	Average of Extra_LGS_SSP1-2.6	Average of Extra_LGS_SSP5-8.5
Denmark	8	3
Estonia	4	7
Greece	1	-9
Spain	-6	-20
Finland	5	10
France	21	6
Croatia	10	7
Hungary	-18	-16
Ireland	19	24
Italy	13	14
Lithuania	6	10
Luxembourg	6	-10
Latvia	9	8
Malta	-22	-12
Netherlands	41	52
Poland	11	14
Portugal	-23	-27
Romania	3	-10
Sweden	8	7
Slovenia	4	15
Slovakia	-13	-15
EU-27	9	8

Source: GAEZ V4 data (Fischer et al., 2021) and own analysis

On average in the EU-27, an additional period of 9 days (HT) and 8 days (LT) may become available for growing intermediate crops between 2020 and 2050. However, this represents an average calculated over the 27 EU member states and not a weighted average according to arable land area. There are regions where the increase in extra days is very large, such as in central Atlantic (Belgium, Netherlands, Ireland, France) but there are also regions in Central and South where the opposite is seen. This pattern is more pronounced in the LT scenario. The changes in the North and Central parts of EU are more related to changes in temperature, while towards the South the decrease in water availability leads more regions to water stress. In the next section, it is presented how these expected changes affect the potential for intermediate crops.

7.2.2. Sensitivity Results: Biomass Potentials

The change in the growing season length of the main crop affects intermediate crop growth opportunities in several ways depending on the region. Table 23 shows that on average in EU27, it will lead to an increase in the intermediate crop potential only in winter, especially in the HT scenario.

Table 23 Summary of changes in intermediate crop potentials in 2050 caused by changes in the growing season length of main crops under two climate change scenarios (SSP1-2.6= HT and SSP5-8.5=LT).

Summary	HT_2050	HT sensitivity	% Change HT	LT_2050	LT sensitivity	% Change LT
Oil crops summer	13,229,277	12,582,117	-5%	12,697,486	12,327,685	-3%
Ligno cellulosic crops summer	27,553,648	27,299,088	-1%	39,893,834	36,711,569	-8%
Oil crops winter	753,295	1,955,574	160%	1,043,225	1,295,228	24%

The summer intermediate oil crops will not benefit in most regions from a change in the growing season length of the main crop. This is primarily because increased temperatures under climate change only shorten the growing season if sufficient water is available. In many regions, higher temperatures go together with lower water availability, which leads to higher evapotranspiration. This effect is stronger in the LT scenario with the most extreme climate change (SSP5-8.5). At national level, in most countries both intermediate oil and ligno crops in summer will not benefit from the change in growth season of the main crop. There are a few exceptions like in Poland, France, Germany, Lithuania, Latvia and Denmark but only for Biomass sorghum and only in one of the scenarios (see Figure 42 and Figure 44).

In winter, however, some countries do experience increases in intermediate oil crop potential due to changes in the growing-season length of the main crop. This applies to Atlantic countries like the Netherlands, Belgium and western France and only in the HT scenario characterised by mild climate change (SSP1-2.6). In the LT scenario, for which strong climate change (SSP5-8.5) is considered, the gains in intermediate crop potentials are more limited. Climate change leads to more extreme temperatures and water deficit in certain regions. For the main crop, this stress can lead to an increase in growing season length.

The effect on the lignocellulosic intermediate crop potential at country level is also diverse. More significant increases are observed in the HT scenario, primarily in Lithuania, France, Germany and Poland. In all other countries, there is either no effect or a decreasing effect in the HT scenario. In the LT scenario, the changes in the growing season length of the main crop lead in some countries to an increase (Latvia, Denmark) and also to a decrease (France, Romania, Hungary, Croatia, Bulgaria, Slovakia Austria, Greece) in the intermediate crop potential (see Figure 44).

Figure 42 Summary of changes in biomass potentials from intermediate oil crops in summer caused by changes in the growing season length of main crops under two climate change scenarios (SSP1-2.6=HT and SSP5-8.5=LT). The change in growing season length is indicated with 'SEN' in the legend.

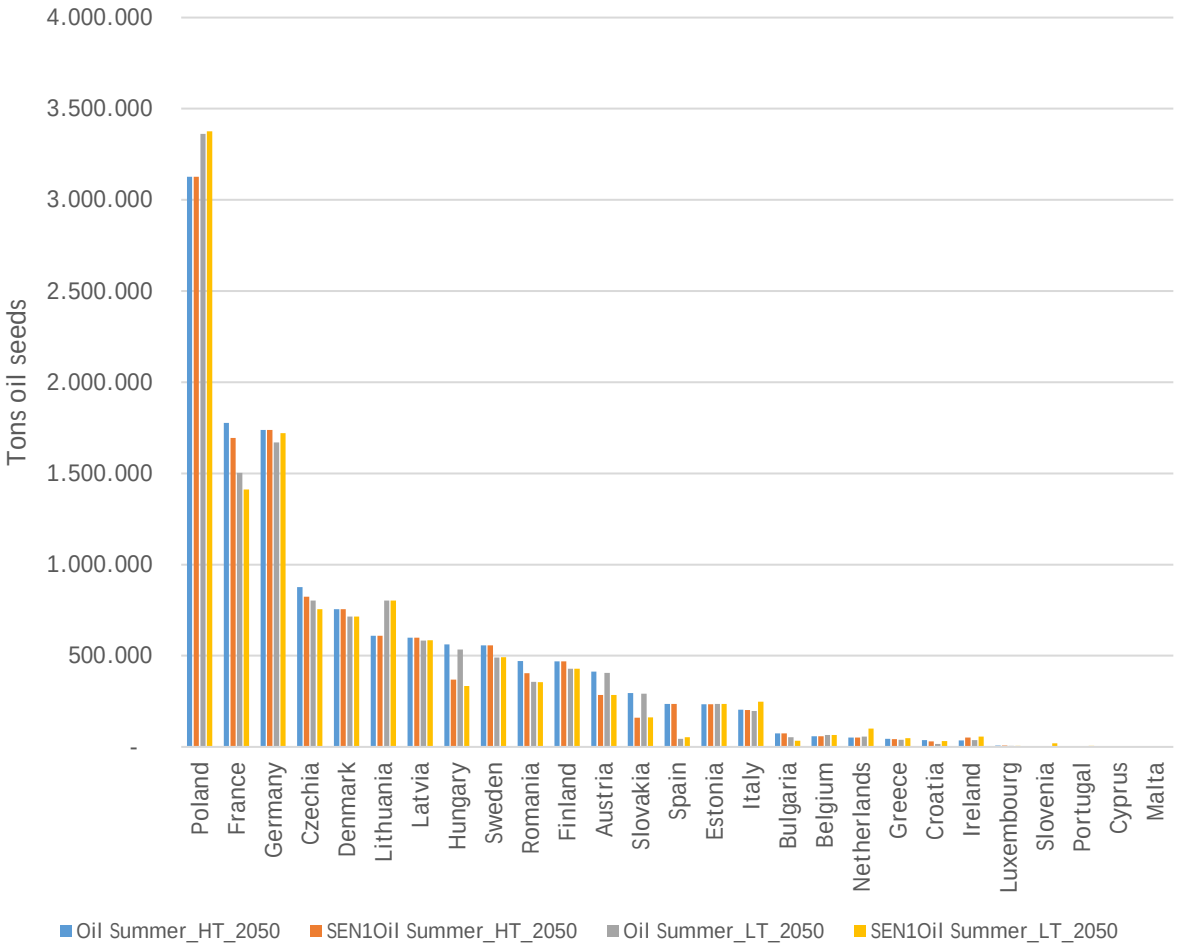


Figure 43 Summary of changes in biomass potentials (tonnes seeds) from intermediate oil crops in winter caused by changes in the growing season length of main crops in two climate change scenarios (SSP1-2.6=HT and SSP5-8.5=LT).

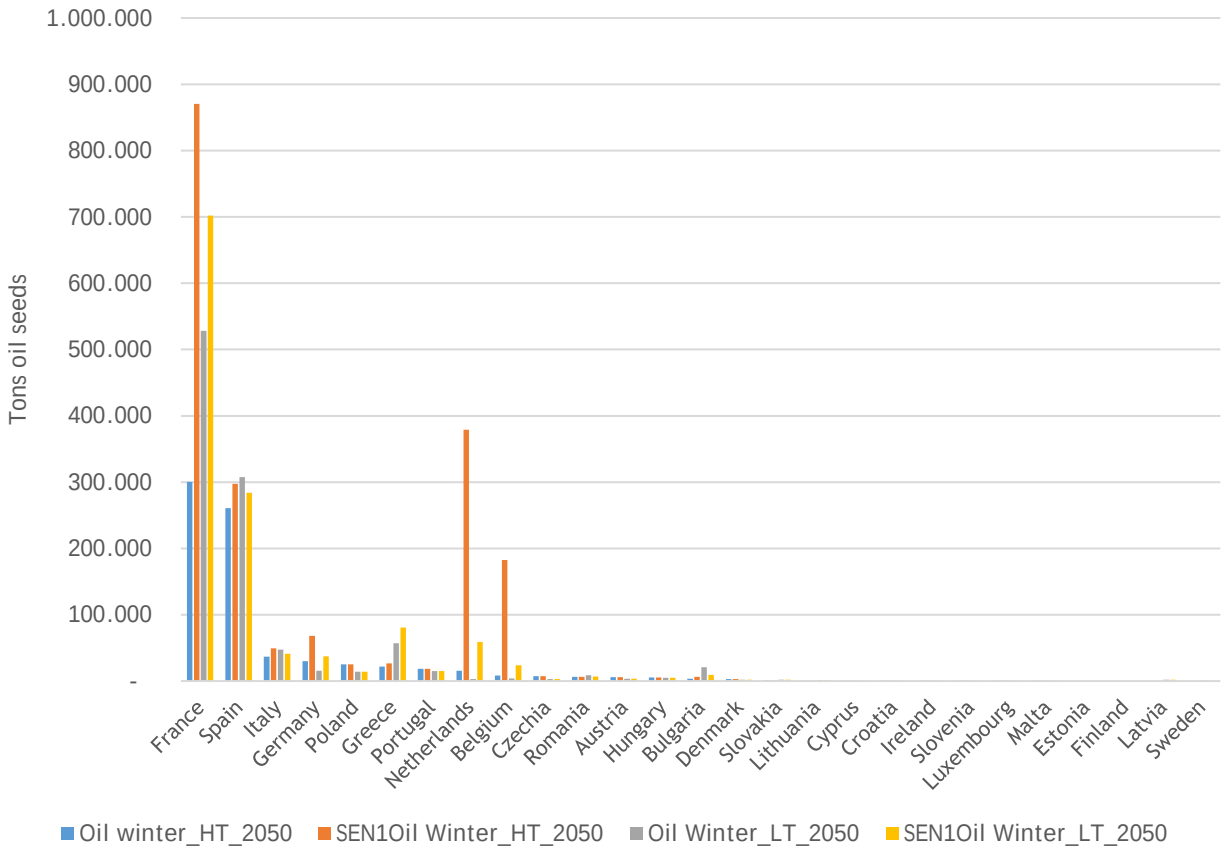
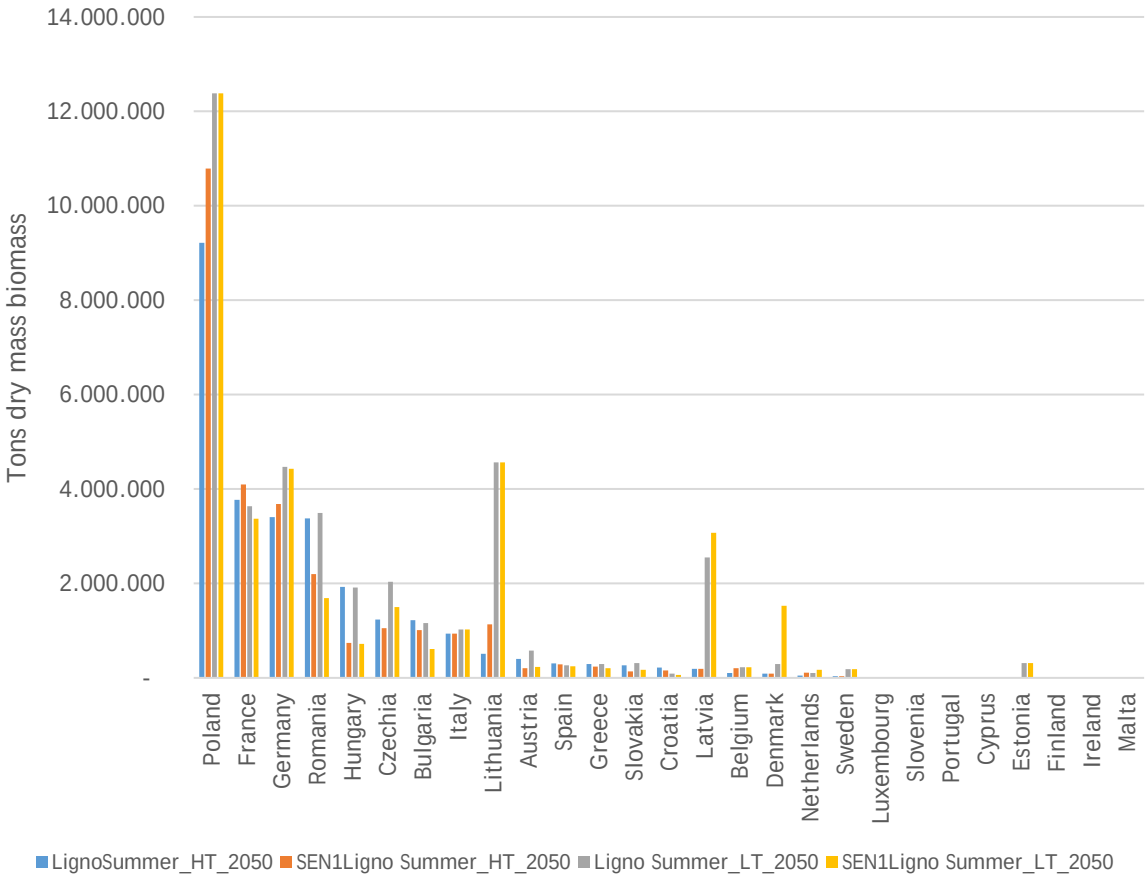


Figure 44 Summary of changes in biomass potentials (tonnes dry mass) from intermediate Biomass sorghum (summer) caused by changes in the growing season length of main crops in two climate change scenarios (SSP1-2.6=HT and SSP5-8.5=LT).



7.3. GROWING LENGTH FOR INTERMEDIATE CROPS: REDUCTION THROUGH TECHNOLOGICAL INNOVATION

The second sensitivity analysis focuses on the options to shorten the growing season length needs of the intermediate crop. Such changes in growing season length are typically expected to be derived from crop breeding innovations. The central question here is what level of shortening in the growing season length would be effective to significantly increase the intermediate crop potential. For this reason, decreases of 5%, 10% and 20% in the growing season length were tested. The results at EU-27 level of this sensitivity analysis are presented in Table 24 and Figure 45.

For intermediate oil crops, the largest benefits in biomass potentials through breeding for shorter season can be achieved for those grown as winter intermediates. For example, the 2050 base case potentials can grow from around 1 million tonnes oil seeds in 2050 to almost 6.5 million tonnes oilseeds in 2050, as a result of a 20% reduction in the growing season length. This implies that with this 20% reduction, intermediate crops can be grown on 8.5% of the winter fallow land, instead of 1.2% calculated for the base case. If the reduction is 5%, it only reaches a very modest increase in both LT and HT scenarios. The largest gains in oil seed potentials in winter through breeding can be reached in countries like France, Germany, and the Netherlands (see Figure 46).

Breeding for shorter growing-season length (GSL) in oil crops used as intermediates during summer does not lead to a strong additional gains in biomass potential (see Figure 45*Figure* 45). Overall, there could be an additional gain of 3% and 3.3% in the HT and LT scenarios respectively caused by a shortening of the GSL by 5%. Further reductions in GSL of 10% or 20% do not lead to meaningful additional increases in potential. Differences between countries are also observed. The largest relative gains in intermediate summer oil crop potential from a 5% reduction in GSL are projected for Slovenia, Portugal, the Netherlands, Ireland, Croatia, Greece, Italy, Bulgaria, and Romania. In absolute terms, the largest increases occur in Italy (an additional 68,747 tonnes), Germany (54,705 tonnes), Romania (48,980 tonnes), the Netherlands (47,224 tonnes), and Hungary (31,546 tonnes). Overall, shortening the GSL by 5% could result in an additional potential of nearly 400,000 tonnes of oilseeds across the analysed regions.

If we look at Biomass sorghum as a summer intermediate, there could be an absolute gain through breeding for short season varieties. This especially applies to the HT scenario where a decrease of 5% in GSL will increase the potential by 34 million tons dm, a 10% decrease leads to an extra 37 million tons dm and a 20% increase to an extra 41 million tons dm. The largest increases in Biomass sorghum potentials through breeding for shorter season needs can be reached in countries Poland, Germany, Lithuania, Czechia, France, Austria, Denmark Croatia, Latvia, Romania and Hungary (see Figure 47).

Table 24 Relative changes in biomass potentials from intermediate crops caused by breeding for shorter season crops (with 5%, 10% and 20% reduction in growing season length (GSL) length) in two climate change scenarios (SSP1-2.6=HT and SSP5-8.5=LT).

		Extra biomass potential relative to 2050 base potential		
	2050 base potential (tonnes)	5% decrease in GSL	10% decrease in GSL	20% decrease in GSL
HT scenario - summer oil intermediate crop	13,229,277	3.0%	3.1%	3.1%
LT scenario-summer oil intermediate crop	12,697,486	3.3%	3.3%	3.3%
HT scenario-winter oil intermediate crop	753,295	32.8%	173.5%	752.2%
LT scenario-winter oil intermediate crop	1,043,225	49.2%	132.1%	501.0%
HT scenario summer-lignocellulosic intermediate	27,553,648	125.3%	132.5%	148.6%
LT scenario summer-lignocellulosic intermediate	39,893,834	89.4%	92.1%	93.6%

Figure 45 Summary of absolute changes in intermediate crop potentials caused by breeding for shorter season crops (with 5%, 10% and 20% reduction in the growing season length (GSL)) in two climate change scenarios (SSP1-2.6=HT and SSP5-8.5=LT).

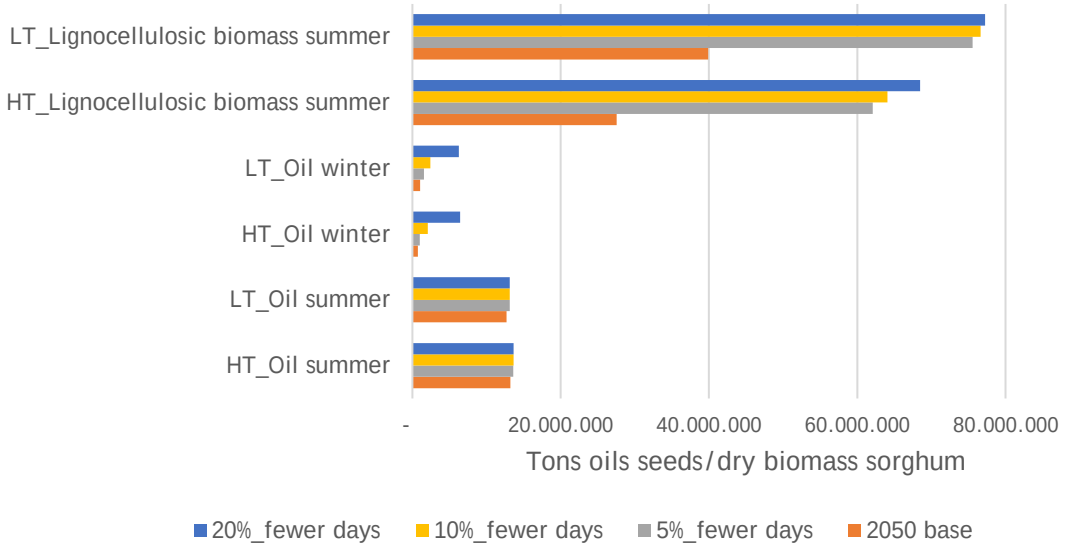


Figure 46 Country summary of absolute changes in winter intermediate crop potentials caused by breeding for shorter season crops (with 5%, 10% and 20% fewer days in the growing season length (GSL)) in HT scenario (SSP1-2.6).

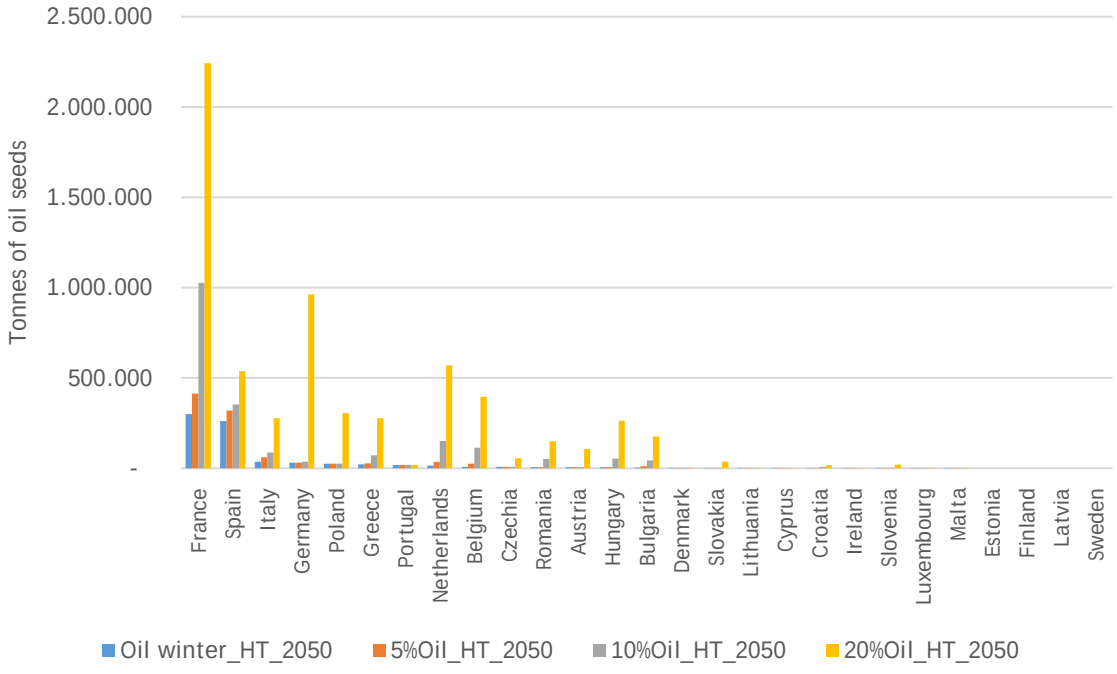
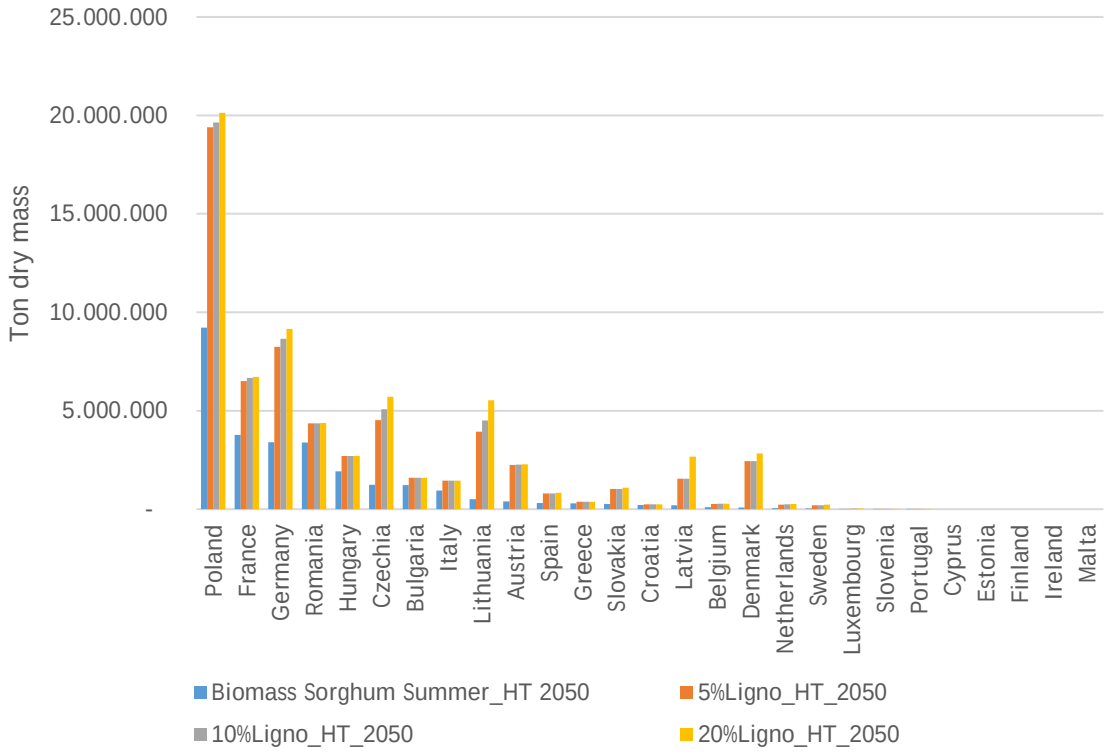


Figure 47 Country summary of absolute changes in biomass potentials for intermediate lignocellulosic crop (Biomass sorghum) in summer caused by breeding for shorter season crops (with 5%, 10% and 20% fewer days in the growing season length (GSL)) in HT scenario (SSP1-2.6=HT).



8. CONCLUSIONS AND RECOMMENDATIONS

This study provides, for the first time, insights into the availability of intermediate crops through dedicated modelling of their growth across the different conventional crop rotation schemes in the EU-27, both under current conditions and towards 2050. It also identifies the optimal spatial distribution of intermediate crops at the regional level taking account of rotational crop practices in arable landscapes in the EU27. Using high resolution cropping data, crop growth simulation models and developing multiple scenarios, the study evaluates intermediate crop potential today and by 2050 under varying climate change and land-use change assumptions, each representing different levels of energy and decarbonisation transition. The analysis focuses on assessing yield potential during the crop production stage. Limitations or crop-specific advantages related to downstream feedstock processing were not considered. The conclusions arising from the final results can be summarised as following:

Intermediate crop climatic suitability

The dedicated screening analysis demonstrated that intermediate crops do not perform uniformly across all European climate zones, therefore, a prioritisation approach based on each crop's phenological characteristics and region-specific weather conditions is required.

- In Northern Europe, colder climatic conditions limit the establishment of lignocellulosic intermediate crops. Within oil crops, only Camelina, Crambe, and White Mustard show suitable performance, particularly when cultivated during the summer period.

- In Central Europe, agroclimatic conditions support the integration of the broadest range of intermediate crops, making this region the most flexible for deployment across both summer and winter rotations.

- In contrast, Mediterranean regions, similar to Northern Europe, face important climatic constraints, particularly heat and drought, which restrict the feasible options largely to Camelina and Crambe grown during winter.

Intermediate crop sustainability and management practices

Beyond climatic suitability, selecting intermediate crops with neutral or positive environmental impact is essential. Most intermediate crops, particularly oil crops such as Camelina and Crambe, offer clear benefits for soil health by acting as cover crops that reduce erosion, while their root systems contribute additional organic carbon to the soil. Furthermore, intermediate crops such as Camelina, Carinata, and Crambe help prevent nutrient leaching to groundwater, thereby improving nitrogen retention within crop rotations.

Biodiversity impacts are also an important consideration when deploying new crops. Field trials and broader agronomic experience indicate that most intermediate crops have a neutral to even positive effect on biodiversity, owing to their low pesticide requirements and the additional floral resources they provide for pollinators and insects, particularly valuable during periods when flowering in agricultural landscapes is typically scarce.

Finally, the water footprint of most intermediate crops is relatively low compared with conventional crops. Oil crops, and to a lesser extent lignocellulosic intermediate crops, can generally be cultivated under rainfed conditions across

Europe, as the crop screening and final selection of crops in this study confirms, making them a sustainable option for integration into biofuel value chains.

Intermediate crops availability potential and deployment drivers

I. Intermediate crops during the summer period:

The potential of intermediate crops by 2050, based on the simulation of the different scenarios, ranges from 12.7 to 13.2 Mt, equivalent to 4.0-4.2 Mtoe of advanced drop-in biofuel when assuming that only oil crops are cultivated across the EU-27. For example, this volume would meet around 20-25% of the projected sustainable aviation fuel (SAF) demand under the ReFuelEU Aviation mandate by 2050 (EC, 2024), (S&P Global, 2025). Among the different oil crop options, white mustard is by far the most widely selected crop due to its higher yielding performance. If lignocellulosic crops are assumed instead, the availability increases to 27.5-39.9 Mt of dry biomass, corresponding to 4.6-6.7 Mtoe of biofuel potential.

Despite the broader adaptability of oil crops to diverse environments and their higher conversion yields to biofuels, the significantly higher biomass productivity of lignocellulosic crops (approximately ten times greater than oil crops) makes them somewhat stronger contributors in terms of total biofuel potential, certainly in the context of expected climate change effects towards 2050.

However, the optimal selection of crop types must be region-specific and should incorporate the economics of the entire value chain. While lignocellulosic biomass offers higher biomass output and potentially lower upstream production costs, it follows a more complex and more expensive conversion pathway. In addition, process technologies for producing advanced biofuels through oil crops are already commercial which allows oil crops to be deployed at a more rapid rate.

II. Intermediate crops during the winter period:

Under winter conditions, the potential contribution of intermediate crops by 2050 is limited, adding only marginally to the summer potential. The estimated winter availability is 0.7-1.0 Mt of oil seeds, corresponding to 0.3-0.4 Mtoe of advanced biofuel. This contribution arises exclusively from oil crops, as lignocellulosic intermediate crops cannot be cultivated during the winter months.

Intermediate crops availability, deployment drivers and constraints

Although intermediate crops can serve as important feedstocks for advanced biofuel deployment, certain limitations prevent them from achieving their full technical potential. For oil crops, for example, 25% of the available fallow land can be utilised in summer and only 2% in winter. In both cases, the main limitation is the long growing period required by intermediate crops, which in some cases prevents them from fitting efficiently within existing crop rotation cycles and available fallow periods. However, these limitations are highly sensitive to changes in management practices, crop breeding improvements, or shifts in rotation design. Therefore, the results and associated limitations should be interpreted with caution.

Drivers for change and the need for technological improvements

Beyond the yield increases through technological innovation already incorporated in the base scenario modelling, the results show that reducing the number of growing days required by intermediate crops or increasing the length of the fallow period are important strategies for improving their deployability.

Sensitivity simulations explored scenarios such as (i) extending fallow periods through climate-driven changes in the growth duration of primary crops, and (ii) reducing intermediate crop growing periods through targeted breeding efforts. These simulations demonstrate the substantial influence such technological developments can have. In particular, the development of shorter-season intermediate crop varieties could increase the biomass potential of winter crops by up to a factor of seven, making their production volumes highly relevant. Similar improvements could benefit summer intermediate lignocellulosic crops, where even small reductions in growing-day requirements (e.g., 5%) can result in significant increases in potential. Overall, this highlights the importance of continued research and development aimed at improving intermediate crop characteristics, as this could sustainably enhance their contribution to the decarbonisation of the EU transport sector.

9. GLOSSARY AND ABBREVIATIONS

"Intermediate crops, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained". The term 'double cropping' may also be used to indicate this cropping system.

Main crop or cash crop is the crop grown with the purpose of selling the product on the market and in most of the farm lands in the EU this involves a food or feed crop. The rotation of crops is usually organised around the main cash crops because they provide the most important economic returns.

Annual crop completes its life cycle within a single growing season or within a year. The large majority of the food and feed produced on cropping land comes from annual crops such as cereals, potatoes, sugar beet, oil seed rape, sunflower, grain maize etc.

Perennial crop is a cultivated plant that lives longer than two years without the need for replanting each year. These crops can provide yields yearly, but there are also examples of perennials that provide multiple yields in the growing seasons (e.g. ryegrass).

Rotational crop refers to a practice on arable land of alternating crops grown on a specific field in a planned pattern or sequence in successive crop years, so that crops of the same species are not grown without interruption on the same field. In a rotation, the crops are normally changed annually, but they can also be multi-annual. If the same crop is grown continuously, the term monoculture can be used to describe the phenomenon.

Cover cropping: Cover crops are grown to provide vegetative cover between rows of main crops in orchards and vineyards, or in the period between two main arable crops to prevent erosion and minimize the risk of surface runoff by improving the infiltration. They may also function as catch crops, which scavenge the remaining nitrogen after the main crop is harvested, thereby reducing nutrient losses from leaching. They are temporary crops that may be cut and removed or incorporated into the soil[2].

Green manure crops are crops that are grown to substitute, partially or totally, mineral-nitrogen (N) fertilisers. Green manure consists of an herbaceous cover crop which can be either a legume, a non-legume or a mix, grown in alternance to main crop/cash crops, that is not harvested, and it is typically killed, chemically or mechanically, ahead of cash crop planting. The practice of incorporating crops into the soil to provide nutrient is defined as "green manuring".

Intercropping is a farming method that involves cultivating two or more crop species (i.e., crop mixture cropping) or genotypes (i.e., cultivar mixture cropping) in the same area and coexisting for a time so that they interact agronomically[3]. In this situation, the intercrop is grown amidst a main crop or in between the planting rows of that main crop[4]. 'Relay cropping' is a form of intercropping where a crop is sown into another, standing crop.

[2] Cover and catch crops GENERAL - IMAP - EC Public Wiki
[3] Intercropping GENERAL - IMAP - EC Public Wiki
[4] Soilcare project glossary. Available online: https://www.soilcare-project.eu/resources/glossary

Fallowing refers to the farming practice in which arable land included in the crop rotation system is left to recover, at least for an entire crop year, whether worked (e.g., ploughed) or not and with no intention to produce a harvest.

Spring crop or summer annual crops are sown/germinate in spring or early summer, grow over summer and are harvested in late summer or autumn. Spring/summer annual crops are typically sown in late winter to spring, once the risk of frost has passed and soil temperatures are adequate for germination. In Southern Europe, sowing generally begins earlier, often from late February to April, depending on altitude and local climate. In Central and Northern Europe, sowing usually takes place from April to May, as spring temperatures rise more gradually. Harvesting occurs earlier in the south, typically from June to August, while in Central and Northern Europe, it is usually from late July to September, depending on the crop and local conditions. The longer growing season in the north can benefit some crops, though it may also expose them to late-season weather risks.

Winter annual crops are sown/germinate in late summer or autumn and are harvested the following spring or summer after they have produced seeds or die. Winter annual crops are typically sown in autumn, specifically early of the season in Central and Northern Europe and later in Southern Europe. For example, winter cereals in Central and Northern Europe are usually sown from early September to late October, allowing sufficient time for establishment before winter. In contrast, in Southern Europe, sowing can be delayed by a month or more, often extending until early December, depending on local climate conditions. Harvesting follows the opposite pattern. It generally occurs later in Central and Northern Europe, from late June to early August, depending on the location. In Southern Europe, harvesting can begin as early as the end of May and may extend through late June, thanks to the earlier onset of warm and dry conditions.

Soil biodiversity, as defined by ESDAC building on the definition of soil biodiversity of the Convention on Biological Diversity, is '*the variety of life belowground. The concept is conventionally used in a genetic sense and denotes the number of distinct species (richness) and their proportional abundance (evenness) present in a system, but may be extended to encompass phenotypic (expressed), functional, structural or trophic diversity. The total biomass belowground generally equals or exceeds that aboveground, whilst the biodiversity in the soil always exceeds that on the associated surface by orders of magnitude, particularly at the microbial scale.*'[5]

Canopy structure refers to the arrangement and organization of plant elements, such as leaves and branches, within a vegetative canopy, which influences the development of turbulent flow and momentum transport in that environment (Smith and Hinckley, 1995).

[5] Soil Biodiversity - ESDAC - European Commission

Abbreviation	Explanation
BAU	Business as Usual
CAP	Common Agricultural Policy
CHELSA	Climatologies at high resolution for the earth's land surface areas
EGD	European Green Deal
ESDAC	European Soil Data Centre
ET	Evapotranspiration
ETa	Average daily evapotranspiration
ETm	Evapotranspiration minimum
F2F	Farm to Fork
FAO	Food and Agriculture Organization
GAEC	Good agricultural and environmental conditions
GDD	Growing degree days
GIS	Geographic Information System
GWP	Global warming potential
HI	Harvest index
HRL	High resolution layer
HT	High Transition
IPCC	Intergovernmental Panel on Climate Change
KF	Killing Frost
KPI	Key Performance Indicator
LGP	Length of the growing period
LT	Low Transition
NUTS	Nomenclature of territorial units for statistics
RED	Renewable Energy Directive
SA	Sustainable agriculture
SOC	Soil organic carbon
SSP	Shared socioeconomic pathway
TRL	Technology readiness level
WP	Water productivity
WUE	Water use efficiency

10. REFERENCES

1. Abdalla, M. et al., 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology.*

2. Bisselink, B. et al., 2020. ***Climate change and Europe's water resources,*** s.l.: JRC.

3. Bufe, C. & Korevaar, H., 2018. *Evaluation of additional crops for Dutch list of ecological focus area,* s.l.: WUR.

4. Cossel, M. V. et al., 2020. Bridging the Gap Between Biofuels and Biodiversity Through Monetizing Environmental Services of Miscanthus Cultivation. *Earth's Future.*

5. Dalton, J. C. et al., 2024. Impact of Drought Stress on Sorghum bicolor Yield, Deconstruction,and Microbial Conversion Determined in a Feedstocks-to-Fuels Pipeline. *ACS Sustainable Chem. Eng,* Volume 12.

6. Dees, M. & al., e., 2017. *A spatial data base on sustainable biomass cost-supply of lignocellulosic biomass in Europe—Methods & data sources.,* s.l.: S2BIOM.

7. EC, 2024. *Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuel,* Brussels: European Commission - Directorate-General for Research and Innovation.

8. Fischer, G. et al., 2021. *Global Agro-Ecological Zones v4 - Model documentation.* [Online]
Available at: https://openknowledge.fao.org/items/039f7ec9-98af-49e1-8d24-850122c69bef

9. Gawdiya, S., Sharma, R. K., Singh, H. & Kumar, D., 2025. Crop diversification as a cornerstone for sustainable agroecosystems: tackling biodiversity loss and global food system challenges. *Discover Applied Sciences.*

10. Gesch, R. & Archer, D., 2013. Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. *Industrial Crops and Products,* Volume 44.

11. Giller, K. E., Hijbeek, R., Andersson, J. A. & Sumberg, J., 2021. Regenerative Agriculture: An agronomic perspective.. *Outlook Agric..*

12. Grung, M. et al., 2015. Pesticide levels and environmental risk in aquatic environments in China — A review. *Environment International,* Volume 81.

13. Hossain, Z. et al., 2019. Plant establishment, yield and yield components of Brassicaceae oilseeds as potential biofuel feedstock. *Industrial Crops and Products,* Volume 141.

14. Hufnagel, J., Reckling, M. & Ewert, F., 2020. Diverse approaches to crop diversification in agricultural research. A review. *Agronomy for Sustainable Development.*

15. Johannssen, S. & Armitage, P., 2010. Agricultural practice and the effects of agricultural land-use on water quality.. *Frshwater Forum.*

16. JRC, 2019. [Online]

17. Available at: https://water.jrc.ec.europa.eu/portal/apps/storymaps/stories/9bf714ab8fec49b6b3a56cd601252b42

18. Kakabouki, I. et al., 2021. Introduction of alternative crops in the Mediterranean to satisfy EU Green Deal goals. A review. *Agronomy for Sustainable Development,* Volume 41.

19. Klebl, F., Feindt, P. H. & Piorr, A., 2024. Farmers' behavioural determinants of on-farm biodiversity management in Europe: a systematic review. *Agriculture and Human Values,* Volume 41.

20. McCalmont, J. P. et al., 2017. Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. *Glob Change Biol Bioenergy.*

21. Midler, E., Pagnon, J. & Hulot, J.-F., 2022. *Reducing European fertiliser and feed dependency through the CAP. IEEP Policy brief. Reducing European fertiliser and feed dependency through the CAP,* s.l.: Institute European Environmental Policy.

22. Ogle, S. M. et al., 2019. Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. *Sci..*

23. Pancaldi, F. & Trindade, L. M., 2020. Marginal Lands to Grow Novel Bio-Based Crops: A Plant Breeding Perspective. *Front Plant Sci..*

24. Panoutsou C & Manatis, K., 2021. *Sustainable biomass availability in the EU, to 2050,* Brussels: Concawe.

25. Potter, H. K., Yacout, D. M. M. & Henryson, K., 2023. Climate Assessment of Vegetable Oil and Biodiesel from Camelina Grown as an Intermediate Crop in Cereal-Based Crop Rotations in Cold Climate Regions. *Sustainability.*

26. Ramsar.org, 2023. *Wetlands and agriculture: impacts of farming practices and pathways to sustainability.* s.l.:s.n.

27. Schils, R. et al., 2018. Cereal yield gaps across Europe. *European Journal of Agronomy,* Volume 101.

28. Scott, D. A. et al., 2021. Yield, nitrogen, and water use benefits of diversifying crop rotations with specialty oilseeds. *Agriculture, Ecosystems & Environment,* Volume 317.

29. S&P Global, 2025. *Study on the potential evolution of Refining and Liquid Fuels production in Europe,* Brussels: Concawe.

30. VELDE, M. V. D. et al., 2025. *Policy relevant crop diversity monitoring based on Earth observation and farmers' declarations,* s.l.: JRC.

31. Verheijen, F., Jones, R., Rickson, R. & Smith, C., 2009. Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews,* Volume 94.

32. Volsi, B., Higashi, G. E., Bordin, I. & Telles, T. S., 2021. Production and profitability of diversified agricultural systems. *Acad. Bras. Ciênc.*

33. Vries, W. d. et al., 2021. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. *Science of the Total Environment,* Volume 786.

34. Wei, Q. et al., 2024. Nitrogen losses from soil as affected by water and fertilizer management under drip irrigation: Development, hotspots and future perspectives. *Agricultural Water Management,* Volume 296.

35. WMO, 2024 . [Online] Available at: https://wmo.int/publication-series/state-of-global-water-resources

36. Zegada-Lizarazu, W., Parenti, A. & Monti, A., 2021. Intercropping grasses and legumes can contribute to the development of advanced biofuels. *Biomass and Bioenergy,* Volume 149.

APPENDIX 1. OVERVIEW OF MAIN REFERENCE PROJECTS

- MAGIC (GA no. 727698) - aimed to help farmers to decide which industrial crops are suitable for marginal lands. Starting with the mapping of marginal land, the selection of suitable crops, investigating the breeding and land management practices for the crops and the development of cultivation and harvesting methods and machinery for these special requirements. Further, based on sustainability assessments, recommendations for policymakers for growing industrial crops on marginal land were given.

- MIDAS (GA no. 101082070) - Marginal agricultural land and climate-resilient and biodiversity-friendly industrial crops for innovative bio-based value chains. The focus is on developing and demonstrate innovative solutions to grow industrial crops on marginal agricultural land and build sustainable value chains for a wide range of bio-based products. The cropping systems tested include agro-forestry system and relay cropping.

- BIKE (GA No. 952872) - The aim of the project was to support EC and national governments in the planned revisions of the Recast Renewable energy Directive (REDII) by providing evidence for the market potential of low indirect land use risk value chains for biomass and biofuels made from it for transport in Europe. Focus was of chains based on intermediate crops and crops grown on degraded lands.

- CARINA - Three ways of production of Camelina and Ethiopian Mustard (Brassica Carinata) have been studied within the framework of the project. Both crops are being tested in double cropping systems as winter or summer intermediate crops, in intercropping systems with a companion crop, or as intermediate crops replacing fallow periods on marginal lands. A total of 158 field trials of these two oilseed crops were carried out in Bulgaria, Spain, France, Greece, Italy, Morocco, Poland, Serbia, and Tunisia.

- BECOOL Brazil-EU Cooperation for the Development of Advanced Lignocellulosic Biofuels (GA No. 744821) - In the project a range of research and demonstration activities across the entire lignocellulosic biomass value chain were carried out: from the production of non-food crops to biomass logistics and harvesting, the production of bioenergy intermediates and final products, and a full environmental and socio-economic assessment of their large-scale deployment. Carried out several field trials: perennial grasses on marginal lands and innovative rotation schemes where intermediate crops were included.

- 4CE-MED - A prima project (H2020) where camelina was investigated as cover cash cover crop for the Mediterranean region. CRES did field trials for four growing periods where camelina was cultivated with conventional crops.

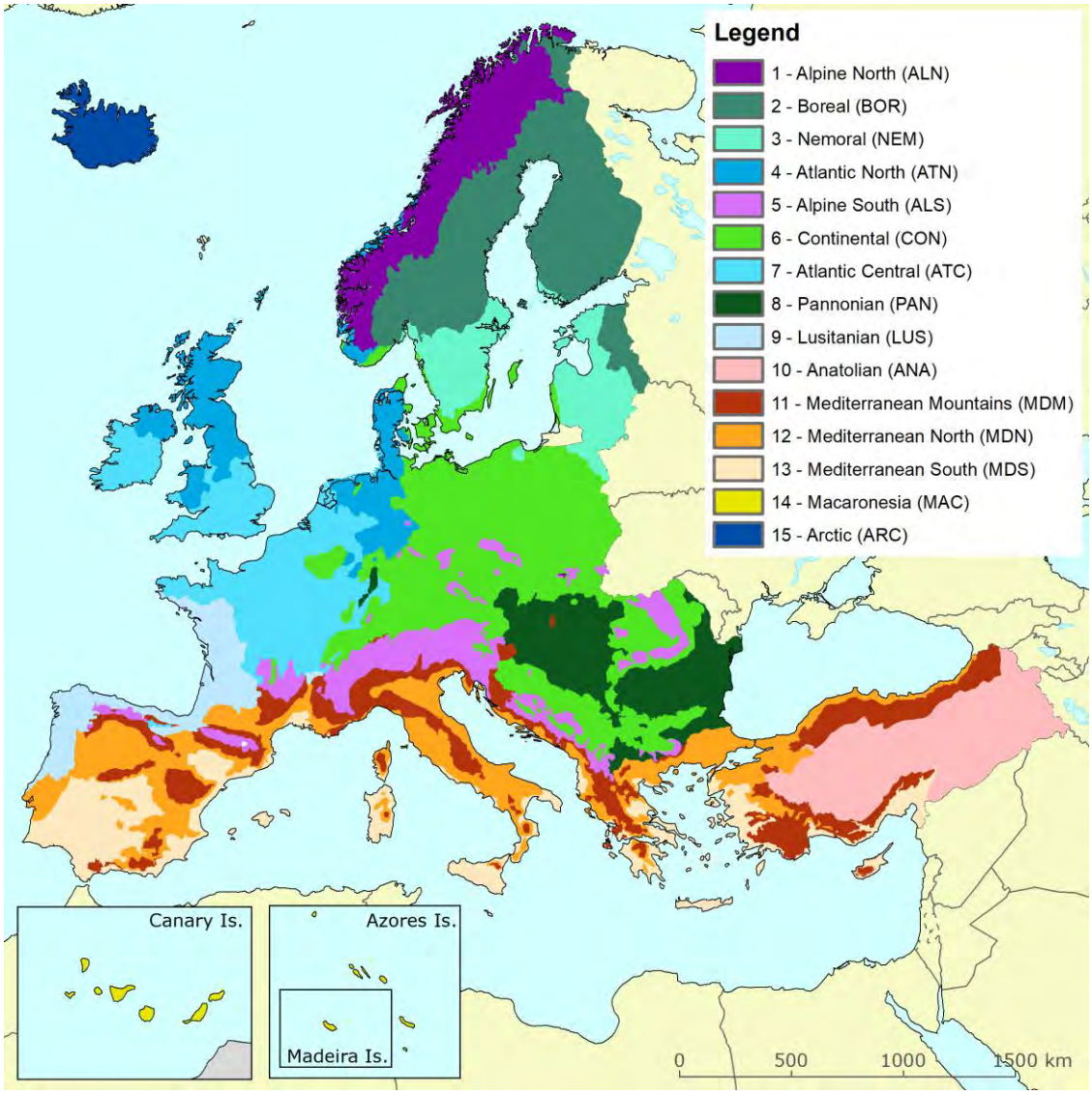
- PANACEA - A thematic network for non-food crops as feedstock for biobased products and bioenergy. In this project a long list of non-food crops had been investigated for Europe. CRES coordinated it.

- FIBRA - A thematic network for fiber crops and the organisation of biorefineries for biobased products and bioenergy. CRES coordinated it.

- COSMOS - A research project where crambe and camelina was studied as novel and cash oilseeds for biochemicals. CRES was WP leader and carried out for 4 growing seasons trials with camelina and crambe under innovative cropping systems.

  EUROBIOREF - A research project organising biorefineries from a wide variety of crops; oilseeds (camelina, crambe, castor, lesquerella, cuphea, sunflower, safflower) and lignocellulosic (willow, poplar, miscanthus, switchgrass, giant reed). CRES was the leader of innovative crops.

APPENDIX 2. ENVIRONMENTAL ZONES



Source: Environmental zones 2018 - version 1.0, June 2020 (europa.eu)

For this study the ENZ were clustered in three main climate zones as follows:

1) North: Alpine North, Boreal, Nemoral
2) Central: Atlantic North, Atlantic South, Lusitanian, Continental, Pannonian and Alpine south
3) Mediterranean: Mediterranean South, Mediterranean North and Mediterranean Mountains

A further split was made for evaluating the climate suitability and selecting the final suitable crops as follows:

1) North: Alpine North, Boreal, Nemoral
2a) Central - Atlantic: Atlantic North, Atlantic South, Lusitanian
2b) Central - Continental: Continental, Pannonian and Alpine south
3a) Mediterranean-North and Mountains: Mediterranean North and Mediterranean Mountains
3b) Mediterranean- South: Mediterranean South

APPENDIX 3. CHELSA CLIMATE CHANGE MODELLING AND DATA

Climate Change Modelling Methodology

CHELSA (Karger et al. 2017; Karger et al. 2018) provides very high resolution (30 arc sec, ~1km) global downscaled climate data for the period 1981-2010, but also climate future scenarios for the periods 2011-2040, 2041-2070 and 2071-2100.

CHELSA V2 is currently only available for a selected number of CMIP6 (Coupled Model Intercomparison Project Phase 6, the follow-up of CMIP5) scenarios, i.e. a selection of Global Climate Models (GCMs) and SSP (Shared Socioeconomic Pathways) combinations (more detailed information can be found here):

The GCM selection follows the models given for the Intersectoral Impact Model Intercomparion Project (ISIMIP), which are:

- GFDL-ESM4
- UKESM1-0-LL
- MPI-ESM1-2-HR
- IPSL-CM6A-LR
- MRI-ESM2-0

The selected scenarios are SSP1-2.6, SSP3-7.0 and SSP5-8.5, which are updates of scenario SSP1, SSP3 and SSP5 with an additional radiative forcing of 2.6, 7.0 and 8.5 W/m2 respectively by the year 2100. SSP126 is a remake of the optimistic scenario RCP2.6. This scenario assumes climate protection measures being taken (CO_2 emissions cut to net zero around 2075). SSP5-8.5 represents the upper boundary of the range of scenarios described in the literature. It's an update of CMIP5 scenario RCP8.5, with high fossil fuel emissions combined with socioeconomic reasons (CO_2 emissions triple by 2075).

The following climate data was downloaded for the 5 GCM models (listed above), i.e. 6 datasets:

- Daily mean/maximum/minimum air temperature at 2 meters from hourly ERA5 data for each month (TAS/TAS_{MAX}/TAS_{MIN})
- Annual precipitation amount (BIO12)
- The heat sum of all days above the 5°C temperature accumulated over 1 year (GGD 5°C)

Derived climatic parameters:

- Annual potential evapotranspiration for reference grass (ETo or PET), based on the Hargreaves method. The annual sum was derived from monthly ETo. Monthly ETo was derived from monthly air temperature data as follows: ETo = 0.0023 (T_{mean} + 17.8) (T_{max} - T_{min})$^{0.5}$ · 0.408 · K_{rad}, where K_{rad} is extra-terrestrial radiation.
- The aridity index (AI) or degree of dryness, defined as the annual precipitation amount (BIO12) divided by the annual potential evapotranspiration (ETo) → AI = BIO12/Eto. Note that the CHELSA data does not include ETo and AI data. Instead these parameters have been derived by own calculations for all 6 datasets.
- Monthly fraction of Soil Water Content (SWC) available for evapotranspiration processes (as percentage of Maximum Soil Water Content). It's a measure of soil stress and equals to the soil water stress coefficient (K_{soil}) as percentage. Here, the method of Trabucco et al. (2019) was followed to derive monthly SWC_fr (or excessive wetness) for the climatic data and 5

future scenarios. Finally, the monthly SWC_fr results are converted into total number of days with saturated soil.

The model described by Trabucco et al. (2019) uses spatially distributed values of monthly precipitation and monthly potential evapotranspiration, and returns monthly spatially-distributed values defining actual evapotranspiration, runoff and soil water content (SWC). The modelling is spatially explicit to represent varying climate conditions, while vegetation and soil properties are assumed as uniformly standard (characterized by crop coefficient equal to 1, rain interception coefficient equal to 0.15 and maximum SWC in the rooting zone equal to 350 mm). Within MIDAS EU project, the model of Trabucco et al. (2019) was implemented but for this study it was rerun based on the CHELSA data (current and future scenario). To achieve more realistic conditions of the initial SWC, we repeated the simulation several years, before deriving the monthly SWC _fr.

Downloaded data:

- Mean daily mean/max./min. air temp. + precipitation amount per month; BIO12 (annual precipitation amount), GGD 5°C (heat sum for all days above the 5°C temp. accumulated over 1 year)

- Derived parameters:

a. Aridity Index (AI) or degree of dryness, defined as annual precipitation divided by the annual reference evapotranspiration (PET). Monthly PET determined using Hargreaves method:

$$PET = 0.0023\ (T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5} \cdot 0.408 \cdot K_{rad}$$

b. Monthly fraction of Soil Water Content (SWC), following Trabucco et al. (2019). Monthly SWC_fr is converted to total number of days with saturated soil.

Results at Country Level

Table A.1 Change in temperature and precipitation in SSP1-2.6 and SSP5-8.5 as compared to the climatic historic scenario (2019-2023).

Countries	Average temperature change_SSP1-2.6 (C˚)	Average temperature change_SSP5-8.5 (C˚)
Austria	1.87	2.81
Belgium	1.59	2.31
Bulgaria	1.81	2.76
Cyprus	1.54	2.12
Czechia	1.84	2.75
Germany	1.74	2.55
Denmark	1.67	2.35
Estonia	2.00	3.16
Greece	1.68	2.44
Spain	1.48	2.27
Finland	1.87	3.07
France	1.70	2.41
Croatia	1.85	2.69
Hungary	1.86	2.82
Ireland	0.72	1.29
Italy	1.71	2.52
Lithuania	1.93	3.02
Luxembourg	1.70	2.47
Latvia	1.95	3.09
Malta	1.33	2.00
Netherlands	1.59	2.21
Poland	1.83	2.76
Portugal	1.43	2.25
Romania	1.88	2.82
Sweden	1.77	2.69
Slovenia	1.89	2.72
Slovakia	1.80	2.75
EU27	1.72	2.55

APPENDIX 4 INPUT DATA CROP SUITABILITY AND CROP GROWTH MODELLING

Table A.2 Parameters and factors used for the crop yield simulation in AquaCrop.

Crop name & winter or summer annual			Days of growing stages					Crop coefficient (Kc) stage				WUE	
	min_water requirement	min_start day	initial	development	Mid-season	late season	Min temp (basetemp)	kc_initial	kc_development	kc_midseason	kc_lateseason	water use efficiency	harvest_index
	mm	days	days	days	days	days	C°	stage 1	stage 2	stage 3	stage 4	g/l	%
Camelina (summer)	350	150	0.2	0.45	0.8	1	4	0.4	0.7	1.075	0.4	2.1	0.38
Sunflower	300	150	0.1	0.6	0.8	1.0	5	0.35	0.85	1.3	0.35	1.8	0.55
White Mustard	380	150	0.10	0.52	0.70	1.00	4	0.7a	1.2	1.38a	1.1a	0.9d	0.55e
Crambe (summer)	320	150	0.21	0.56	0.80	1.00	4	0.35	0.7	1.4	0.85	1.8	0.4
Carinata/Ethiopian mustard (summer)	360	150	0.1	0.5	0.6	1	4	0.7a	0.8	1.2b	0.95a	1.4	0.45
Castorbean	450	150	0.09	0.49	1.02	1.00	9	0.35	0.7	1.15c	1.5c	0.9	0.38
Safflower (summer)	300	150	0.2	0.5	0.8	1.0	5	0.35	1	1.2	0.5	1.44	0.46
Camelina (winter)	370	275	0.24	0.5	0.8	1	4	0.4	0.6	1.1	0.4	1.6	0.32
Crambe (winter)	350	275	0.21	0.56	0.80	1.00	5	0.35	0.7	1.1	0.6	1.7	0.38
Carinata/Ethiopian mustard (winter)	500	275	0.12	0.5	0.62	1	4	0.7a	0.7	1.05a	0.95a	0.9	0.35
Safflower (winter)	350	275	0.25	0.5	0.75	1	5	0.3	1	1.2	0.5	1.4	0.46
Biomass sorghum	210	150	0.05	0.59	0.90	1.00	8	0.64	0.98	1.45	1.22	5.6	0.96
Industrial Hemp	350	150	0.12	0.74	0.86	1.00	5	0.3	0.9	0.75	0.38	2.35	1

a Value for Brassica crops in general (Silva, A. L. B. R. d., Coolong, T., Dunn, L. & Carlson, S., 2022. *Water Use and Irrigation Management for Vegetables in Georgia: Brassica Crops,* s.l.: University of Georgia)
b Campbell, D. N. et al., 2015. Development of a regional specific crop coefficient (Kc) for castor (Ricinus communis L.) in Florida, USA by using the sap flow method. *Industrial Crops and Products,* Volume 74
c Campbell, D. N. et al., 2015. Development of a regional specific crop coefficient (Kc) for castor (Ricinus communis L.) in Florida, USA by using the sap flow method. *Industrial Crops and Products,* Volume 74
d Gesch, R. W. et al., 2024. Water use and water use efficiency of three Brassicaceae oilseeds under high- and low-yielding environments. Crop Science, 64(4)
e Jankowski, K. J., 2025. White mustard: Energy balance at different nitrogen management strategies. *Industrial Crops and Products,* Volume 225

APPENDIX 5. CROP FACTSHEETS

CAMELINA (Camelina sativa L., family Brassicaceae)

Description of the crop: Camelina is an annual winter and/or spring oilseed crop with plant height varying from 30 to 120 cm. Its stems, when it is grown at high densities, are unbranched and woody at the maturity. It has long leaves (2-8 cm long and 2-10 mm width). At the flowering camelina develops flowers with pale yellow colour that produce fruits that contains small seeds, orange in colour. The seeds are very small and 1000 seeds weight from 0.8 to 2 gr, noting that there is no seed dormancy in camelina [1].

Origin and research in Europe: Camelina is native to southeast Europe and southwest Asia and it is naturally widespread in Europe. It is well adapted to temperate and cold semi-arid climate areas. Although it is a winter crop it can also be grown as spring crop in Europe. It used to be grown in Northern and Eastern Europe until 1940s when it was replaced by rapeseed [2]. It was reintroduced in Europe in last two decades especially through research in a number of EU projects (ITAKA, ICON, COSMOS, BIO3A, MAGIC, 4CEMED, etc.). In the majority of these research activities emphasis was placed on the cultivation of camelina on marginal and/or contaminated lands (e.g., projects IASIS and CARINA that are currently ongoing).

Climate preferences: In general, camelina species are best adapted to temperate to cool semi-arid climates. Compared to other oilseed crops, like rapeseed and sunflower, camelina shows better performance in semi-arid regions due to its drought and frost tolerance (Figure A.1). Camelina can survive conditions of dry soil, low rainfall (100-200 mm of annual rainfalls) and frost (killing frost <-20^{0}C). Due to its short growth season (90 to 120 days) or a temperature sum of 1200 hours it is very suitable as an intermediate crop. There are two limiting climate factors that rule out some regions for growth of Camelina. When used as a summer crop heat-stress can be limiting if it occurs in the last growth phase when seed are ripening and filling with oil. It leads to a serious yield depression. Too much rain in the last growth phase will also adversely affect the ripening of the seeds and will make harvesting a problem.

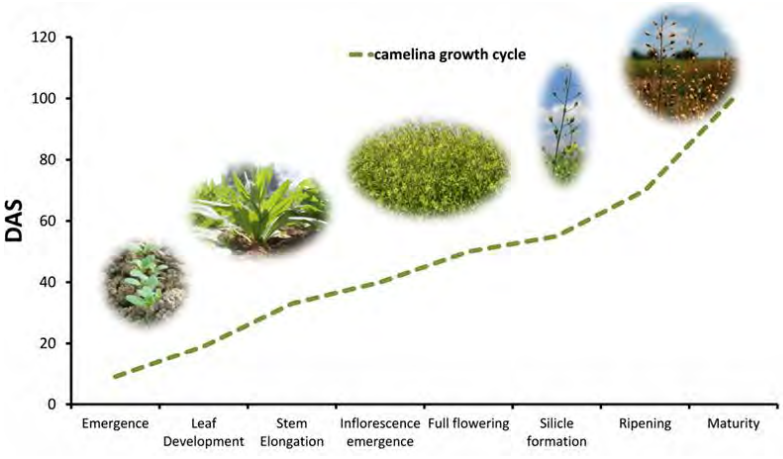
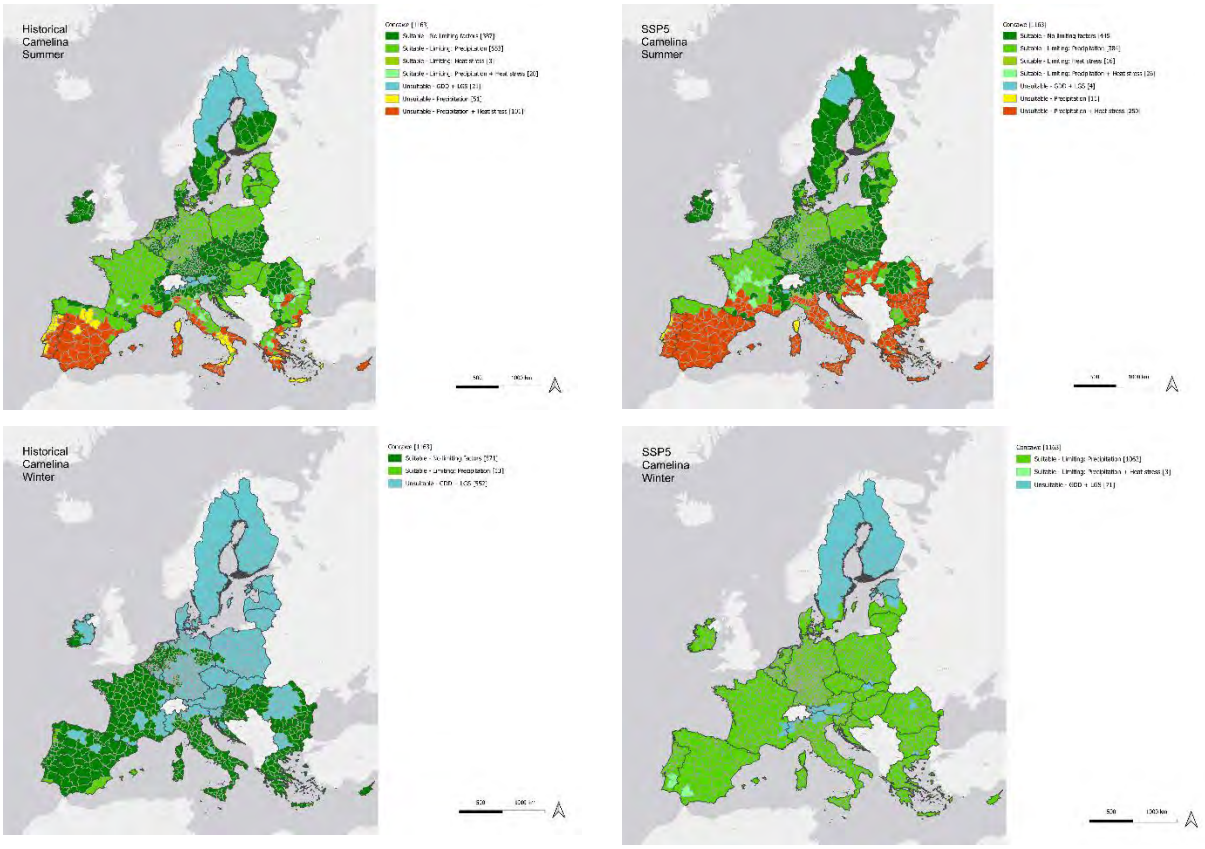


Figure A.1 Camelina growing stages in relation to DAS (days after sowing)

Table A.3. Overview of climate suitability factors determining suitability for Camelina grown as winter and summer crop (sources: See Appendix 4).

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 °C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	90	1200	4 °C	< -10 °C	YES	>=100 mm	1000 mm
Winter crop	150	1400	4 °C	< -15 °C	YES	>=100 mm	1000 mm

Figure A.2 Climate suitability for Camelina grown as a summer crop (left maps) and as a winter (cover) crop (right maps). Top maps refer to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).



Soil preferences: In general, Camelina grows very well on well-drained light (sandy), medium (loamy) and heavy (clay) soils. It can be grown well in nutritionally poor soils. It is reported as crop with increased resistance to salinity (up to 4 dSm ^{1}) ([3],[4]). Thus, it is considered as an oilseed that can be grown on marginal lands.

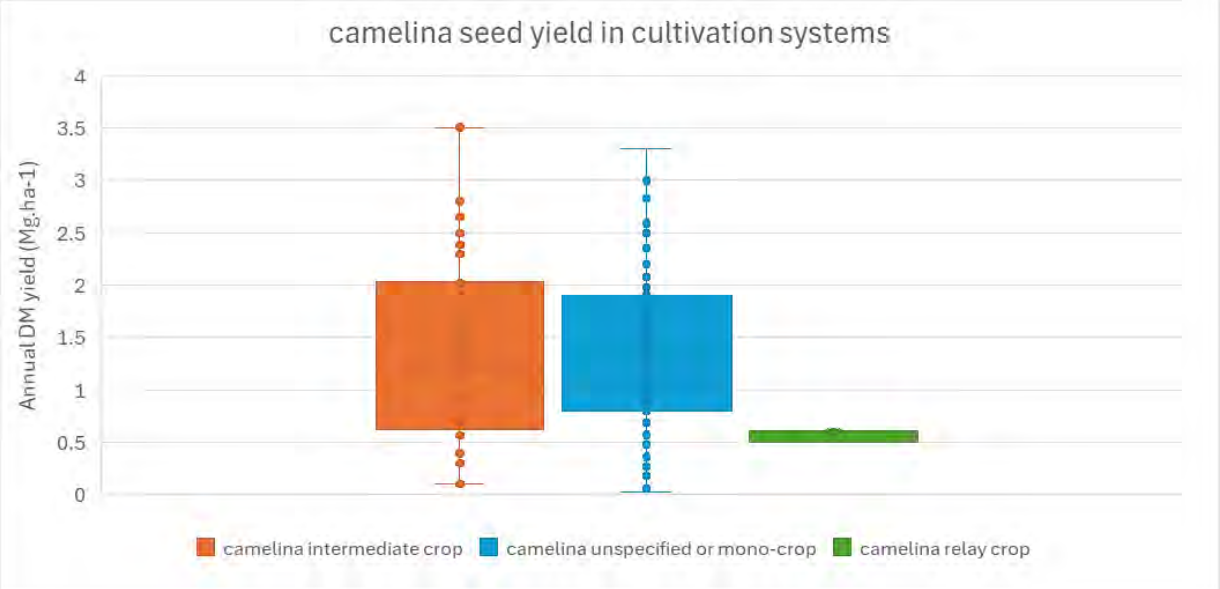
Soil preparation and sowing: Minimal seedbed preparation is needed to establish camelina. Although there is no registered herbicide for camelina when needed it is recommended to apply pendimethalin as pre-emergence herbicide. It is recommended to apply 6 to 8 kg seeds per ha at sowing [5]. The proposed distances between the rows can vary between 15 to 20 cm. The soil depth at sowing should not be more than 2 cm [6]. As winter cover crop, the proposed sowing date is similar to that of winter cereals which depends on the location. When it is grown as spring crop, the sowing should be done immediately after the winter period. In 4CE-MED project, it was found that the sowing as a winter crop in the Mediterranean region could be done from late November till the beginning of March but the best results were recorded when the sowing was done at the same time that each Mediterranean country used to sow the winter cereals.

Figure A.3: Camelina on marginal land in northern Greece; winter cover crops with 1.30 t/ha seed yields

Water and fertilization: Camelina has low nutritional requirements. 60 kg N/ha is enough to cover the nitrogen needs of the crop, while higher doses of nitrogen fertilization can increase the lodging problems and decrease the oil content of the seeds (experience derived from ITAKA, ICON, COSMOS, BIO3A, MAGIC, 4CEMED, etc.). The recommended fertilization is: 60 to 80 kg N/ha, 30-40 kg P/ha, 40-50 kg K/ha. P & K are applied with the basic fertilization, while for N only the 30% is applied then and the rest when the plants are in the rosette stage. The crop is considered to have a high tolerance to drought so irrigation is not needed. Furthermore, when grown as winter cover crop, water shortage is not an issue. Camelina does suffer from heat stress at prolonged periods with temperatures above 32˚C in the seed maturing phase ([7],[8]). This makes growth of Camelina as a summer crop in the Mediterranean more challenging, certainly under the potential influence of climate change (see Figure A.2)

Varieties: In the COSMOS project a high number of new varieties were developed by Smart Earth Camelina (Canada; former Linnaeus Company). These were tested and compared on screening trials located in Greece, Italy, Poland and Canada with very promising results and seed yields that in some sites exceeded the 2 t/ha. At the same time, the Camelina Company in Spain (CCE, https://camelinacompany.es/en/) developed and tested (for the projects ITAKA, BIO4A, 4CE-MED, CARINA) a large number of varieties (Alba, CCE44, CCE117, etc.) with very good results on marginal lands (in the majority of the reported case studies yields around 1.5 t/ha are reported). University of Poznan has developed several varieties that are being tested now in CARINA project with yields around 1.5 t/ha (varieties: Luna, Olivia, Lenka). In Untwist project (www.untwist.eu) camelina is being studied as drought resilience crop to provide a mechanistic understanding of successful adaptation strategies to drought and heat stress that can be applied in additional crops to increase their resilience to climate change. For this purpose, a large variety of camelina genotypes both from Europe and Canada are being used.

Figure A.4 Published seed yield levels in camelina grown as a summer or winter crop based on 51 references (see literature list - at the end of the factsheet). Intermediate crop: camelina was part of a rotation in the field experiments; mono-crop: camelina was cultivated as a single crop in the field experiment; unspecified: cultivation type (rotation or not) was not explicit in the experimental design; relay-crop: camelina was sown into a standing crop.



Seed Yields: In COSMOS project, the mean seed yields that have been recorded so far are 2 t/ha (varied from 1 to 3 t/ha) depending on the country (Greece, Italy, Poland and Netherlands) and the specific climatic conditions of each growing period. In ITAKA project, the reported yields in Spain varied from 0.5 to 2.5 t/ha. In 4CE-MED, the seed yields varied from 0.7 to 2.2 t/ha among the participated Mediterranean partners and the highest yields were recorded in the EU Mediterranean countries (Italy, Spain and Greece) compared to other Mediterranean countries such as, Morocco, Tunisia and Algeria.

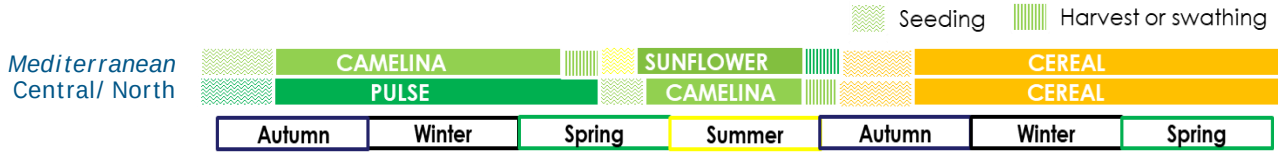
This is also confirmed by a literature review of seed yields of which the results are presented in Figure A.4. On average, spring camelina reaches slightly lower yields then winter camelina. So, the average yield level ranges between 0.7 to 2.0 t/ha. By considering an average oil seed yield of 36-47% the oil yields varied from 0.25 to 0.94 t/ha [9].

Diseases and insects: Camelina is considered a pest and disease resistant crop compared to other oilseed crops [5]. It is highly resistant to blackleg (Leptosphaeria maculans), which is a major disease of canola and other Brassica crops. Few insects appear to cause damage to camelina and thus the use of insect control measures is rarely reported.

Harvesting time and options for use as intermediate crop: When camelina is grown as winter crop the harvesting can be organised from mid-May to early June, while when is grown as spring crop (central and north Europe, see Figure A.5) the harvesting can be done by the beginning of August.

Camelina can comply with Annex IX of RED definition for 'intermediate crop' because it can be added to existing rotations as a winter cover crop or as a summer crop. When established as a summer crop (like sunflower, sorghum) in Central/North Europe, no-till sowing machines can be used in order to avoid the soil preparation (plowing, harrowing, etc.) and to speed up the establishment of the second crop. The latter can also be done when established as a winter crop, but in that situation, the time available between harvest of former crop and establishment of Camelina is longer and therefore not necessary. From a soil health perspective however, it is recommended to apply no-till sowing systems. In Figure A.5, the rotation schemes are presented that were tested in 4CE-MED project and work very well for the Mediterranean region (as winter crop) and France (as both winter and spring crop).

Figure A.5 Rotations including Camelina as winter and summer crop tested in 4CE-MED project (https://4cemed.eu/).



Harvesting and storage: Camelina can be harvested with unmodified combines and is usually direct-combined standing but can be swathed and then combined with similar seed yields [10]. The harvesting should start when 75% of silicles are dried. Mature pods are dark tan or brown [11]. The combine settings should be similar to those used for rapeseed or alfalfa seed, but the combine fan speed should be reduced to minimize seed losses. Small-opening combine screens designed for alfalfa seed are effective in separating camelina seed and hulls. Unlike other members of the mustard family, camelina pods hold their seeds tightly, and seed shattering is not generally a problem. Most camelina cultivars are resistant to shattering.

Uses: Camelina seeds are considered as low ILUC feedstock as it has been proved to grow well on different types of marginal lands as well as cover or intermediate crop by adding it to existing rotation schemes without affecting the yields of the main food crops (see figure above with the proposed rotations). This implies camelina can be used for advanced biofuel production. The seed meal (after the oil extraction) has high protein content (28-32%) and can be used as animal feed (high percentage to omega-3). Camelina oil is a source of medium-chain fatty acids (MCFA, C10-C14) and these types of fatty acids are currently mostly imported to the EU (e.g., imported coconut oil and palm kernel). These fatty acids are used by the oleochemical industry for the production of surfactants and detergents, lubricants and other products.

Environmental impacts: The performance of camelina in terms of the main environmental aspects is presented in the table below.

Environmental aspects	Color score	Explanation
1a) Soil structure		Camelina intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting. However, establishment of crop can be done with no-till sowing.

Environmental aspects	Color score	Explanation
1b) Soil organic carbon		Camelina serves as a cover crop which protects the soil against erosion. Camelina crop residues are an additional soil carbon input in a rotation [12].
1c) Soil biodiversity		Pesticide and herbicide application is either not required or very limited because Camelina is a pest and disease resistant crop [5]. Problems may occur however, when the sowing rate is either too low or too high. Based on field trial experience in several projects ITAKA, BIO4A, 4CE-MED, CARINA) it is recommended to apply a sowing rate between 6 to 10 kilos seeds per ha and at this sowing density herbicides applications can be avoided.
2a) Risk for leaching & losses to ground and surface water		Camelina as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. Nitrogen and other nutrient requirements are very low compared to other oil crops [12], [13].
2b) Risk for loss from spraying pesticides, herbicides		Pesticide and herbicide application is either not required or very limited because Camelina is a pest and disease resistant crop [5].
3) Water quantity		Compared to other oilseed crops, like rapeseed, camelina shows better performance in semi-arid regions due to its drought tolerance [15]. Camelina can produce good yield even if precipitation reaches only 200 mm in GS.
4a) Habitat quality		Nutrient input requirements are very low in Camelina as compared to a conventional crop like wheat. No need to apply pesticides and herbicides because it is very disease and pest resistant. As a cover crop Camelina also prevents leaching of nutrients in winter [13].
4b) Species viability contribution		Camelina provides food to pollinators in periods in early spring or over summer when it flowers [12]. When used as an intermediate crop it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Camelina is not invasive. It is native to southeast Europe and southwest Asia and it is naturally widespread in Europe [16].

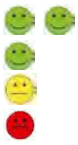
The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: The TRL of camelina is already at 7. Firstly, Camelina can be grown successfully in practically the whole of the EU. Currently, it is grown at 2000 to 3000 ha annually in Spain by CCE for seed production. There is a growing interest from the oil companies (e.g., BP, ENI, Shell etc.) for camelina as source for low ILUC biofuels. In Greece camelina has been selected as crop for an Eco-scheme in CAP aimed at the use of resilient and adapted species and varieties. This is due to resistance to dry thermal conditions. Since input needs are low and the crop has a pollination function its interest to be part of Eco-schemes may also widen to other countries. Recently, the seed company named Smart Earth Camelina (www.smartearthcamelina.ca) was bought by Bayer. It implies that the seeds propagation is expected to be elevated.

Figure A.6. Factor scores for Camelina Sativa determining the TRL scoring.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	N	C	S		
					



TRL >7, industrial production already available at commercial scale
5≤TRL≤ 7, production available at demo scale
3<TRL< 5, from research to production development
TRL< 3, only basic research data available

References for factsheet

[1] https://extension.oregonstate.edu/sites/extd8/files/documents/em8953.pdf (Oregon State University)

[2] Krzyżaniak, M. et al., 2019. Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. *Industrial Crops and Products,* Volume 138.

[3] Jovičić, D., Jocković, J., Marjanović Jeromela, A., Zanetti, F., Mastroberardino, R., Nikolić, Z., & Ovuka, J. (2025). Salinity stress tolerance in camelina: A focus on the germination stage for crop improvement. Industrial Crops and Products, 227, 120773. https://doi.org/10.1016/j.indcrop.2025.120773

[4] Heydarian, Z. et al., 2018. Changes in gene expression in Camelina sativa roots and vegetative tissues in response to salinity stress. Scientific Reports.

[5] Berti M, Gesch R, Eynck C, Anderson J. 2016. Camelina uses, genetics, genomics, production, and management. Industrial Crops and Products 94 (2016) 690–710.

[6] McVay, K., Lamb, P., 2008. Camelina Production in Montana. Montana State University Extension, Bozeman, MT

[7] Nadakuduti, S. S. et al., 2023. Heat stress during seed development leads to impaired physiological function and plasticity in seed oil accumulation in Camelina sativa. Frontiers in Plant Science.

[8] Carmo-Silva, A. E. & Salvucci, M. E., 2012. The temperature response of CO2 assimilation, photochemical activities and Rubisco activation in Camelina sativa, a potential bioenergy crop with limited capacity for acclimation to heat stress. Planta, Volume 236.

[9] Luo, Z. et al., 2019. Genetic Diversity and Population Structure of a Camelina sativa Spring Panel. Front. Plant Sci., Volume 10.

[10] Gesch, R.W., 2014. Influence of genotype and sowing date on camelina growth and yield in the north central US. Ind. Crops Prod. 54, 209-215.

[11] Sintim, H.Y., Zheljazkov, V.D., Obour, A.K., Garcia y Garcia, A., Foulke, T.K., 2016. Evaluating agronomic responses of camelina to seeding date under rain-fed Conditions. Agron. J. 108, 349-357

[12] Karlsson Potter, H., Yacout, D. M. M., & Henryson, K. (2023). Climate Assessment of Vegetable Oil and Biodiesel from Camelina Grown as an Intermediate Crop in Cereal-Based Crop Rotations in Cold Climate Regions. Sustainability, 15(16), 12574. https://doi.org/10.3390/su151612574 [wisdomlib.org], [mdpi.com]

[13] Kakabouki, I. et al., 2021. Introduction of alternative crops in the Mediterranean to satisfy EU Green Deal goals. A review. Agronomy for Sustainable Development, Volume 41.

[14] Dusica, J. et al., 2025. Salinity stress tolerance in camelina: A focus on the germination stage for. Industrial Crops & Products.

[15] Krzyżaniak, M. et al., 2019. Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. Industrial Crops and Products, Volume 138.

[16] Larsson, M. (2013). Cultivation and processing of Linum usitatissimum and Camelina sativa in southern Scandinavia during the Roman Iron Age Vegetation History and Archaeobotany, 22, 509-520. https://doi.org/10.1007/s00334-013-0413-3 [link.springer.com]

References list for Figure A.4 - Yields

Agarwal et al. (2013) In: Roberto Matteo, Eleonora Pagnotta, Luisa Ugolini, Laura Righetti, Silvia Tavarini, Luca Lazzeri, Chapter 27 - Camelina sativa (Cranz.) from minor crop to potential breakthrough. Editor(s): Muhammad Farooq, Kadambot H.M. Siddique, Neglected and Underutilized Crops, Academic Press, 2023, Pages 781-801, ISBN 9780323905374, https://doi.org/10.1016/B978-0-323-90537-4.00025-9.
Wittenberg, A., Anderson, J.V., Berti, M.T. (2020). Crop growth and productivity of winter camelina in response to sowing date in the northwestern Corn Belt of the USA, Industrial Crops and Products, Volume 158,113036, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2020.113036.
Alexopoulou, E., Chirstou, M. and Eleftheriadis, I. (2018). D1.5 - Handbook with fact sheets of the existing resource-efficient industrial crops. Horizon 2020 project, grant agreement No. 727698.
Angelini et al. (2020) in: Matteo et al. (2023)
Angelini, L. G., Abou Chehade, L., Foschi, L., & Tavarini, S. (2020). Performance and Potentiality of Camelina (Camelina sativa L. Crantz) Genotypes in Response to Sowing Date under Mediterranean Environment. Agronomy, 10(12), 1929. https://doi.org/10.3390/agronomy10121929
Avola et al. (2021) in: Matteo et al. (2023)
Berti et al. (2011), Solis et al. (2013); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690-710
Borah et al. (2021) in: Matteo et al. (2023)
Campbell et al. (2013) in: Matteo et al. (2023)
Eberle, C., Scott, D.A., Forcella, F., Gesch, R.W., Weyers, S., Johnson, J.M.F. et al. (2024) Planting date impact on flowering, pollinator visitation and yield of mass flowering oilseed

crops in the Northern Corn Belt. Agricultural and Forest Entomology, 26(4), 534-545. Available from: https://doi.org/10.1111/afe.12644
Factsheets MAGIC Handbook updated, received from Efi on 31-3-2022
Zanetti, F., Pietro Peroni, Elena Pagani, Moritz von Cossel, Beatrice Elisabeth Greiner, Michał Krzyżaniak, Mariusz J. Stolarski, Iris Lewandowski, Efthymia Alexopoulou, Walter Stefanoni, Luigi Pari, Erika Facciolla, Andrea Monti (2024). The opportunities and potential of camelina in marginal land in Europe. Industrial Crops and Products, Volume 211, 2024, 118224, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2024.118224.
Gehringer et al. (2006); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Gesch et al. (2015, 2014), Berti et al. (2015); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Gesch et al. (2019) in: Matteo et al. (2023)
Hossain Z., Johnson E.N., Wang L., Blackshaw R.E., Cutforth H., Gan Y. (2019). Plant establishment, yield and yield components of Brassicaceae oilseeds as potential biofuel feedstock. Industrial Crops and Products, 141, art. no. 111800. DOI: 10.1016/j.indcrop.2019.111800
Hunsaker et al. (2013); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Jankowski et al. (2019) in: Matteo et al. (2023)
Jarecki (2021) in: Matteo et al. (2023)
Javaid et al. (2021) in: Matteo et al. (2023)
Johnson et al. (2010); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710 (table 6). https://harvest.usask.ca/server/api/core/bitstreams/5e24ce98-15e7-455c-861d-f83536efd628/content
Katar et al. (2012); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Leclère et al. (2021) in: Matteo et al. (2023)
Liu, R., Wells, M.S. & Garcia y Garcia, A. (2020). Relay and sequential cropping corn with winter oilseed crops in northern climates. Nutr Cycl Agroecosyst 116, 195–203 (2020). https://doi.org/10.1007/s10705-019-10036-x
Leclère, M. Loyce, C. & Jeuffroy, M.H. (2018). Growing camelina as a second crop in France: A participatory design approach to produce actionable knowledge. European Journal of Agronomy, Volume 101, 2018, Pages 78-89, ISSN 1161-0301, https://doi.org/10.1016/j.eja.2018.08.006.
Berti, M. Samarappuli, D. Johnson, B.L. Gesch, R.W. (2017). Integrating winter camelina into maize and soybean cropping systems. Industrial Crops and Products, Volume 107, 2017, Pages 595-601, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2017.06.014.
Masella et al. (2014); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Ceriani, M., Giuliana D'Imporzano, Patrizia De Nisi, Martina Ghidoli, Irene Rapone, Salvatore Pilu, Fabrizio Adani (2024). Improving biodiesel sustainability by double-cropping oilseed and oil-less seed cake recovery: A field approach in northern Italy, Energy Conversion and Management: X, Volume 24, 2024, 100821, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2024.100821.
Matteo et al. (2020) in: Matteo et al. (2023)
Matteo et al. (2020). Camelina (Camelina sativa L. Crantz) under low-input management systems in northern Italy: Yields, chemical characterization and environmental sustainability. Italian Journal of Agronomy 2020; volume 15:1519
Krzyżaniak, M., Mariusz J. Stolarski, Józef Tworkowski, Debra Puttick, Christina Eynck, Dariusz Załuski, Jacek Kwiatkowski (2019). Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. Industrial Crops and Products, Volume 138, 2019, 111443, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2019.06.006.

Monti et al., 2022. D4.5. – Report on "Comparative studies on selected industrial crops grown on large scale fields on marginal land". D4.5 of the EU-MAGIC project.
Pavlista et al. (2016), Aiken et al. (2015); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Pavlista et al. (2016), Chen et al. (2015); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Gesch, R.W. & D.W. Archer (2013). Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food, Industrial Crops and Products, Volume 44, 2013, Pages 718-725, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2012.05.023.
Gesch, R.W., Y.A. Mohammed, M.K. Walia, B.S. Hulke, J.V. Anderson (2022). Double-cropping oilseed sunflower after winter camelina, Industrial Crops and Products, Volume 181, 2022, 114811, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2022.114811.
Reinhardt, J., Hilgert, P. and Von Cossel, M. (2022), Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe – a review. Biofuels, Bioprod. Bioref., 16: 609-622. https://doi.org/10.1002/bbb.2314
Reinhardt, J., Hilgert, P., & von Cossel, M. (2021). A review of industrial crop yield performances on unfavorable soil types. Agronomy, 11(12). https://doi.org/10.3390/AGRONOMY11122382
Reinhardt, J., Hilgert, P., & von Cossel, M. (2022). Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe – a review. Biofuels, Bioproducts and Biorefining, 16(2), 609-622. https://doi.org/10.1002/BBB.2314
Rode (2002); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Royo-Esnal & Valencia-Gredilla (2018) in: Matteo et al. (2023)
Sagirova et al. (2020) in: Matteo et al. (2023)
Schillinger (2019) in: Matteo et al. (2023)
Scordia, D. (2022). D4.4 – Identification of low-input practices for the cultivation of the selected industrial crops on marginal land facing natural constraints (First). D4.4 of the EU-MAGIC project. Zenodo. https://doi.org/10.5281/zenodo.7576224
Sintim et al. (2016); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Solis et al. (2013) in: Matteo et al. (2023)
Stefanoni et al. (2020) in: Matteo et al. (2023)
Toncea (2014), Toncea et al. (2013); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710
Vollmann et al. (2007); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710 (table 6). https://www.sciencedirect.com/science/article/pii/S0926669007000702
Waraich et al. (2020) in: Matteo et al. (2023)
Schillinger, W.F. (2019). Camelina: Long-term cropping systems research in a dry Mediterranean climate, Field Crops Research, Volume 235, 2019, Pages 87-94, ISSN 0378-4290, https://doi.org/10.1016/j.fcr.2019.02.023.
Zanetti et al. (2017) in: Matteo et al. (2023)
Zhang et al. (2021) in: Matteo et al. (2023)
Zubr (1997); in: M. Berti et al. / Industrial Crops and Products 94 (2016) 690–710

CRAMBE (Crambe abyssinica L., family Brassicaceae)

Description of the crop: Crambe is an annual spring oilseed crop with plant height varying from 50 to 120 cm. Like camelina, crambe has a rather small cropping cycle between 85 to 105 days. Usually, flowering is starting 52 days from planting [1]. From the end of flowering to the maturing, two weeks are required. Usually, its stems are straight when it is cultivated at high densities. Its leaves have an oval shape. The flowers are small and white with four free sepals and are arranged in racemes [2]. Although the flowers are mostly self-pollinated, some cases of cross-pollination have been observed. High temperatures during flowering have a negative effect on seed set. The fruit is a capsule, initially pale green but becoming yellow with maturity, when it also becomes covered with a well-defined network of small ridges. The weight of 1000 seeds vary from 6 to 10 gr [3]. The crop at several stages of growth is presented in Figure A.7, while in Figure A.8 the main growing stages are outlined.

Origin and research in Europe: Crambe origins from eastern Africa and domesticated in the Mediterranean region. Besides its African origin, over the last century it has been tested and cultivated in north Europe, former USSR, Canada and USA. In the late 1940s, Crambe had been cultivated in a total area of 25,000 ha (Poland, Finland and former USSR) [4]. Breeding research works have been carried out in Europe, Canada and USA.

Figure A.7 View of crambe from 2-leaves stage till the harvesting time (source: COSMOS project by CRES).

Crambe has been studied in several EU research projects namely Crops2Industry (www.cres.gr/cropsindustry), ICON (https://cordis.europa.eu/project/id/211400), EUROBIOREF (www.eurobioref.org), COSMOS project (www.cosmos-h2020.eu), MAGIC project (www.magic-h2020.eu), PANACEA project (https://panacea-crops.net/). Currently, crambe is being studied in as a promising industrial crop for marginal lands [MIDAS (www.midas-bioeconomy.eu)] and contaminated ones [IASIS project (www.iasis-soil.eu)].

Climate preferences: A temperature range of 15-25°C is required over the main vegetative period. Crambe is well adapted to broad range of climates and adapted to marginal land areas with mild winters and hot and dry summers (see Table A.4 and Figure A.9). It has adapted to colder and drier areas. In Northern Europe, it can be grown as a spring crop if sown once the risk of frost has passed. In the Mediterranean region, although it can be possibly cultivated both as a winter and spring crop, it is recommended the sowing to be postponed till the second part of February. In the Atlantic and Continental zone, Crambe can be grown both as winter and as spring crop (see Figure A.9). It has a tap root. Under stress conditions, such as drought, plants may develop long tap roots, which later become conical. Figure A.9 also shows that under climate change influence, it can be expected that the area suitable for crambe grown as a winter cover crop will increase towards the North and East of Europe.

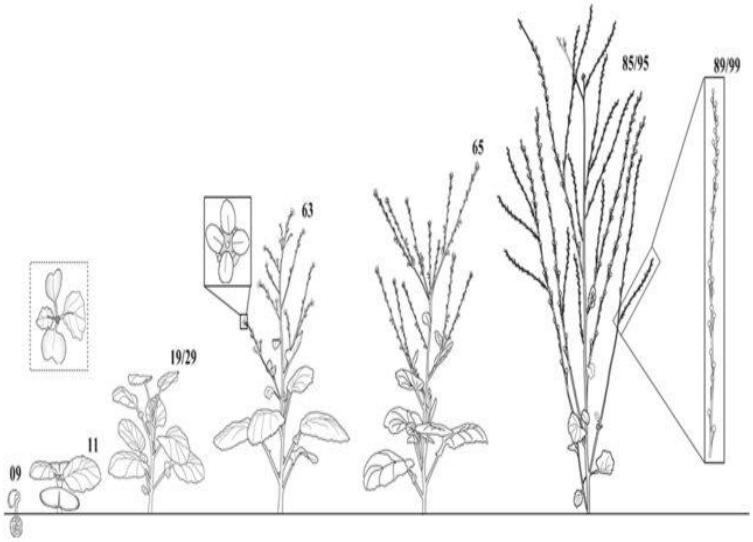
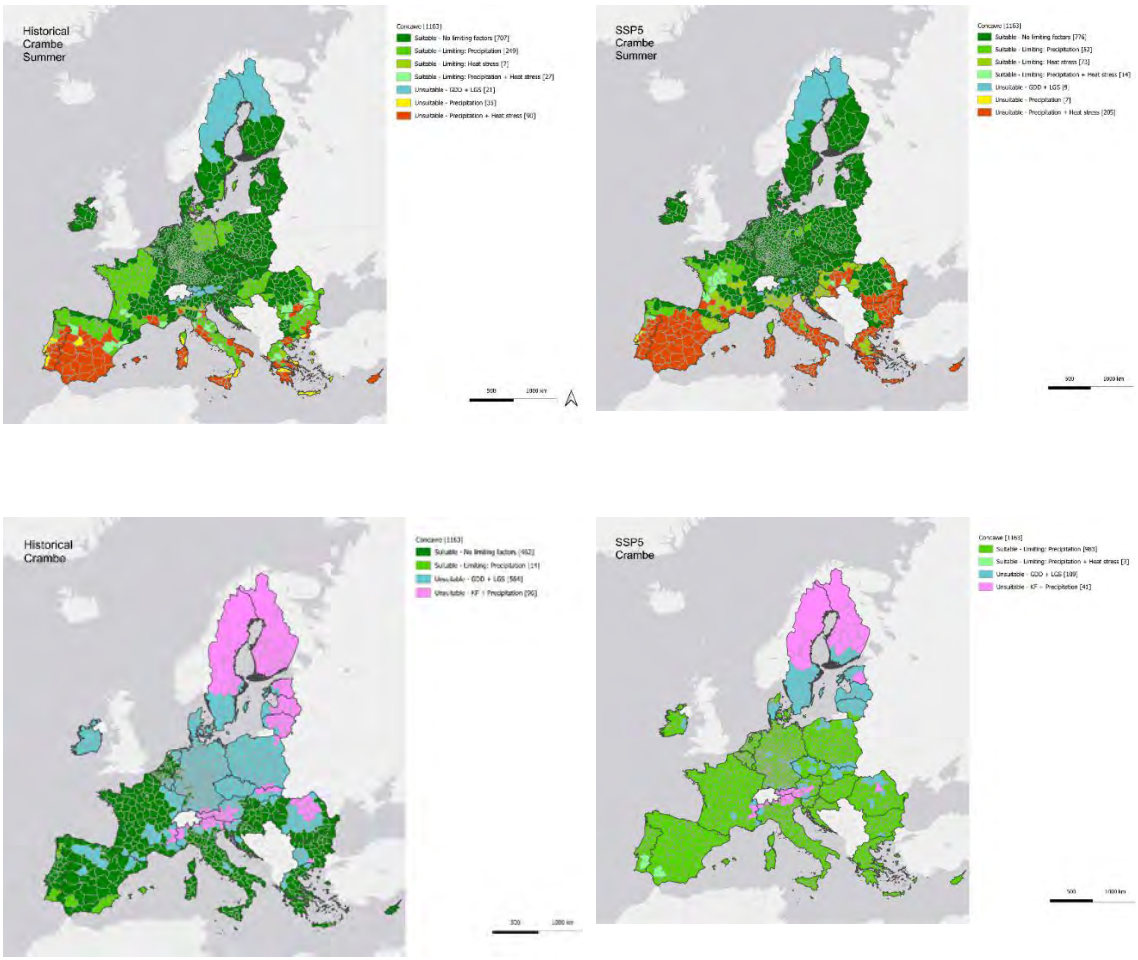


Figure A.8 View of growing stages of crambe [5].

Table A.4 Overview of climate suitability factors determining suitability for Crambe grown as winter and summer crop. (source: See Appendix 4).

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 ºC in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	110	1200	4 °C	< -10 °C	YES	>=100 mm	1000 mm
Winter crop	150	1400	4 °C	< -15 °C	YES	>=100 mm	1000 mm

Figure A.9 Climate suitability for Crambe grown as a summer crop (left maps) and as a winter (cover) crop (right maps). Top maps refer to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).



Soil preferences: Crambe can grow on a variety of soil types with pH 5.0 to 7.8 [6]. The highest yields have been obtained on sandy loams, similar to those regions where it is found growing naturally. Soils that are heavy clays, sandy as well as soils with an impacted layer that restricts the root growth are unsuitable for crambe [7]. The tolerance of Crambe to saline soils is less than barley but greater or similar to wheat (Francois and Kleiman, 1990). It is highly tolerant to heavy metals and is accumulator of Pb and Zn [8].

Soil preparation and sowing: The seedbed for Crambe should be firm in order to place seed at a uniform and shallow depth. Seedlings are easily damaged by drifting soil. Seed should be sown 1.5-2.5 cm deep, but up to 4 cm is acceptable in loose soil, or to ensure the seed is sown into moist soil [9]. A seed bed temperature around 10°C is preferable at sowing. At least 100 seeds per m^2 should be seeded (15 kg seeds per ha) in order to achieve density of 75 plants per m^2. Crambe seeds should be sown at a rate of 10-25 kg/ha on a well-prepared, fine and firm seedbed, no deeper than 2 cm [9]. In COSMOS project two densities are being compared 125 and 250 seeds per m^2 with narrow rows (12.5 and 25 cm, respectively). In the same project, different sowing densities have been tested.

Water and fertilization need: Based on the experiences with field trials with Crambe in all EU projects (COSMOS, Crops2Industry, ICON, EUROBIOREF, COSMOS, MAGIC project, PANACEA, MIDAS and IASIS) it can be concluded that although its drought resistance strongly depends on the cultivated variety, crambe can be considered as drought tolerant crop. Crambe has similar fertilizer requirements with camelina. There is no need for irrigation even when it is grown in the Mediterranean area.

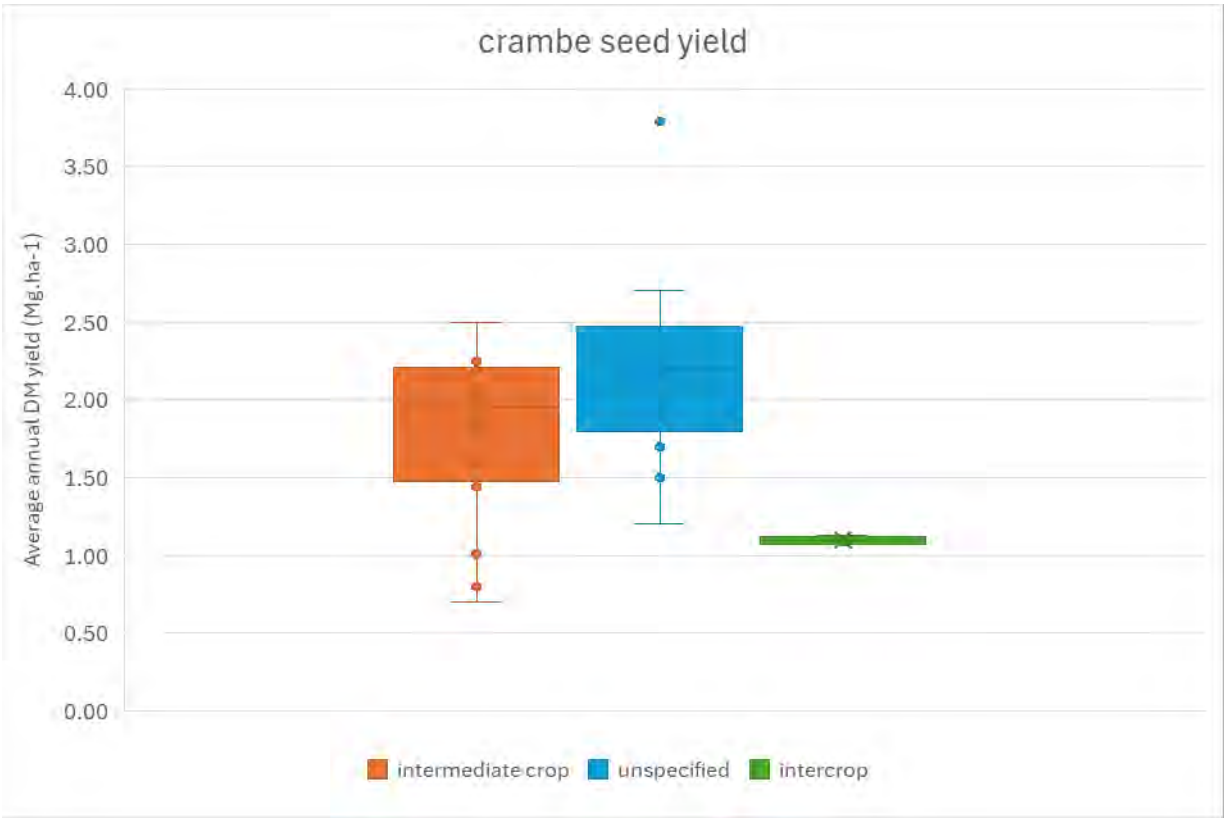
Varieties: Although some breeding programmes for the crop have been carried out, the number of crambe varieties available for commercial production is limited. In EUROBIOREF project, the tested variety was Galactica (Figure), while in COSMOS project, additional varieties are being compared with Galactica, which are: PRi9104-71, PRi9104-101, Elst2007-2, Elst2007-3, Elst2007-7, Elst2007-8, Elst2007-9, Elst2007-16 and Nebula that had been provided by Wageningen Research (WR) Institute. In MIDAS and IASIS projects, the variety tested is Galactica as well as five mutants that had been developed by WR.

Figure A.10 Crambe trial ready to be harvested (source: CRES; Greece).

Seed Yields: Crambe seed yields vary widely between 1 and 3 t seeds/ha under varying environmental situations and countries. In Brazil, a production of 1-1.5 t/ha it has been reported. In COSMOS project the mean seed yields were 2.3 t/ha (varied from 0.6 to 3.1 t/ha) depending on the site (Greece, Italy, Netherlands, Poland) and specific climatic conditions. Its oil content varies from 36-43% [10]. In dehulled seeds, the oil content could be up to 54%, while it is quite lower (25-33%) in non-dehulled. A literature review showed a yield range for crambe as an intermediate crop of between 1.5 to 2.3 t/ha and by considering that the mean oil content of crambe seeds is around 40% the expected oil yields can vary from 0.6-0.9 t_{oil}/ha [11].

The content of erucic acid on the seed oils varies from 55 to 60% [4]. On a dry basis, the whole crambe seed contained 33.9% oil, 25.2% protein, and 12.3% crude fiber. Crambe meats were high in oil 47.6% and protein 31.6% and low in crude fiber at 5.0%. Crambe hulls were low in oil 1.2% and protein 8.8% and high in crude fiber 42.6% [4].

Figure A.11 Published seed yield levels in Crambe grown as a spring or winter crop based on 11 references (see literature list at the end of the factsheet). Intermediate crop: crambe was part of a rotation in the field experiments; unspecified: cultivation type (rotation or not) was not explicit in the experimental design; relay-crop: Crambe was sown into a standing crop.



Diseases and insects: Crambe was successfully commercialized, because of its inherent ability to compete with weeds, ward off insects, and escape diseases without help from pesticides. Seedlings may be attacked by flea beetle (Phylltrea cruciferae). Also pollen beetle (Meligethes aeneus) may attack young flower buds; a yield response has been observed where bee friendly insecticides were used. Crambe has been found to be susceptible to Alternaria and Sclerotinia, though well-timed fungicide applications at the mid-flowering stage can increase the yield (up to 1 t/ha) and may also improve the oil content. Fungicide dressed seed may also be beneficial. Plants are generally susceptible to the same pests and diseases as those of oilseed rape including beet cyst nematode (Heterodera schachtii) [12], [13].

Crambe as intermediate crop: When Crambe is grown as winter crop, the harvesting can be organised from mid-May to early June, while when is grown as summer crop (central and north Europe), the harvesting can be done by the beginning of August.

Harvesting time and options for use as intermediate crop: Crambe can be harvested with unmodified combines and is usually direct-combined standing but can be swathed. Timely harvest is important to avoid high shattering losses. Crambe is physiologically mature when 50 percent of the seeds have turned brown. At maturity, the appearance of the plant may vary from leaves turning yellow and drop

while in others the plant (stems and leaves) remains green. Usually, the crop is ready to be harvested when: a) the majority of leaves have been fallen, b) the upper part of the stem is yellow and c) when at least 75 per cent of the capsules have turned yellow (Figure A.12). This usually takes 90-100 days after planting.

Figure A.12 View of Crambe trial in Poland (Source: COSMOS project; UMW).

Uses: Initially crambe oil gained attention due to its high percentage in erucic acid (higher than rapeseed) which had significant value in industrial uses, specifically the plastics industry [14]. Crambe oil withstands high temperatures and remains liquid at low temperatures which makes it a good quality lubricant and transfer oil. Because it is a very effective lubricant and much more biodegradable than mineral oils, this oil may be used alone or as an additive in the textile, steel and shipping industries. Crambe appears to be a promising crop because of the many possible uses of its seeds (pharmaceuticals, detergents, cosmetic, ceramides, nylon and perfumes etc.). Crambe (and camelina) has been selected by COSMOS project as a source of medium-chain fatty acids (MCFA, C10-C14). In Europe, currently, these fatty acids are obtained by the imported coconut oil and palm kernel. These FA are used by the oleochemical industry for the production of surfactants and detergents, lubricants, plasticisers and other products. Not only are the prices for these FA higher than those for the more common LCFA such as palmitic, stearic and oleic acid, but their prices are also much more volatile. Crambe seeds are crushed to extract oil. After pressing or extracting the oil, pressed cake or extracted oil meal are obtained, which may be useful as a feedstuff for cattle, and to a very little extent for pigs [15].

Environmental impacts: The performance of Crambe in terms of the main environmental aspects is presented in the table below.

Environmental aspects	Color score	Explanation
1a) Soil structure		Crambe intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting. However, establishment of crop can be done with no-till sowing.
1b) Soil organic carbon		Crambe serves as a cover crop which protects the soil against erosion. Crambe crop residues are an additional soil carbon input in a rotation [16], [17].
1c) Soil biodiversity		By following the correct cultivation protocol herbicides and pesticides are not needed [12], [13].
2a) Risk for leaching to ground and surface water		Crambe as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. Nitrogen and other nutrient requirements are very low compared to other oil crops [16], [17], [different EU projects: COSMOS, Crops2Industry, ICON, EUROBIOREF, COSMOS, MAGIC project, PANACEA, MIDAS and IASIS)].

2b) Risk for loss from spraying pesticides, herbicides		As it mentioned in 1c, crambe by applying the proper cultivation protocol the pesticides application can be avoided, while the reported pesticides problems are quite limited [12], [13]).
3) Water quantity		Compared to other oilseed crops, like rapeseed crambe shows better performance in semi-arid regions due to its drought tolerance [9].
4a) Habitat quality		Nutrient input requirements are very low in crambe as compared to a conventional crop like wheat. No need to apply pesticides and herbicides because it is very disease and pest resistant [12], [13]. As a cover crop crambe also prevents leaching of nutrients in winter [16], [17].
4b) Species viability contribution		Like with Camelina, Crambe also provides food to pollinators in periods from early spring to early summer when it flowers [18]. When used as an intermediate crop it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Crambe is not invasive. Crambe origins from eastern Africa and domesticated in the Mediterranean region.

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: Crambe can be grown successfully in Central and South Europe. There is a growing interest from the oil companies for crambe as source for low ILUC biofuels. The seeds availability is key on Crambe cultivation. Currently, only Galactica variety is available by Wageningen Research Institute, and there is a company named PBC enterprises in UK that sells, among others, crambe seeds (www.pbcenterprises.co.uk).

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		

	TRL >7, industrial production already available at commercial scale
	5≤TRL≤7, production available at demo scale
	3<TRL<5, from research to production development
	TRL<=3, only basic research data available

References for factsheet

[1] https://www.hort.purdue.edu/newcrop/duke_energy/Crambe_abyssinica.html

[2] Mastebroek, M. D., Wallenburg, S. C. & van Soest, L. J. M., 1994. Variation for agronomic characteristics in crambe (Crambe abyssinica Hochst. ex Fries). Ind. Crops Products, Volume 2.

[3] Falasca L. S., Lamas M C, Carballo S M, Anschau. 2010. Crambe abyssinica: An almost unknown crop with a promissory future to produce biodiesel in Argentina. International Journal of Hydrogen Energy, Vol. 35, 5808-5812.

[4] Oplinger, E. S. et al., 1991. Crambe in Alternative Field Crops, s.l.: University of Wisconsin.

[5] Sória-Teixeira, L. et al., 2024. Phenological coding of Crambe abyssinica Hochst. according to the BBCH system. Annals of Applied Biology, Volume 184.

[6] Duke, J. A., 1983. Handbook of Energy Crops. NewCROPS web site, Purdue University

[7] Oplinger, E. S., Oelke, E. A., Kaminski, A. R., Putnam, D. H., Teynor, T. M., Doll, J. D., Kelling, K. A., Durgan, B. R., & Noetzel, D. M. (1991). Crambe. University of Wisconsin-Madison, University of Minnesota & North Dakota State University, Alternative Field Crops Manual. [corn.aae.wisc.edu]

[8] Jin Hu, Zhaohui Deng, Bin Wang, Yuan Zhi, Bingxue Pei, Guangyu Zhang, Mingdan Luo, Banglian Huang, Wenhua Wu, Bangquan Huang (2015). Influence of Heavy Metals on Seed Germination and Early Seedling Growth in Crambe abyssinica, a Potential Industrial Oil Crop for Phytoremediation". American Journal of Plant Sciences, Vol.6 No.1, 2015

[9] Samarappuli, D.; Zanetti, F.; Berzuini, S.; Berti, M.T. Crambe (*Crambe abyssinica* Hochst): A Non-Food Oilseed Crop with Great Potential: A Review. *Agronomy* 2020, *10*, 1380. https://doi.org/10.3390/agronomy10091380

[10] Prakhova, T.Y., Odrin, I.V. Photosynthesis Parameters and Productivity of *Crambe abyssinica* when Using Growth Regulators. *Russ. Agricult. Sci.* 50, 371–376 (2024). https://doi.org/10.3103/S106836742470037X

[11] https://www.feedipedia.org/node

[12] Nyvall, R. F. (1989). Field Crop Diseases Handbook (2nd ed.). Springer US. ISBN (electronic): 978-1-4757-5221-2 → Chapter 6: Diseases of Crambe

[13] Samarappuli, D., Zanetti, F., Berzuini, S., & Berti, M. T. (2020). Crambe (Crambe abyssinica Hochst): A Non-Food Oilseed Crop with Great Potential—A Review. Agronomy, 10(9), 1380. https://doi.org/10.3390/agronomy10091380

[14] Castleman G, Pymer S, Greenwood C. Potential for Crambe (C. abyssinica) In Mallee/Wimmera of Australia. In: Proceedings 10th international rapeseed congress. Camberra, Australia; 1999.

[15] Kampf, D., Böhme, H., 2001. Feeding value of crambe by-products. Animal nutrition - resources and future developments, workshop on Sustainable Animal Production, 15-16 June 2000, EXPO 2000, Hannover, German

[16] SARE Outreach. (2025). *Cover Crops at Work: Covering the Soil to Prevent Erosion.* Sustainable Agriculture Research and Education. [sare.org]

[17] Field Crop News. (2025). *Cover crop benefits for soil and cropping systems.* Ontario Ministry of Agriculture.

[18] https://globalpollenproject.org/Taxon/Brassicaceae/Crambe

References for yield data in figure A.11 - Yields

De Marins, A. C., Secco, D., Ruffato, G. G., Bassegio, D., Tiruneh, G. A., & Reichert, J. M. (2024). Soil chemical properties affecting grain yield and oil content of crambe biofuel crop. Soil Science Society of America Journal, 88, 1891-1908. https://doi.org/10.1002/saj2.20741
Vasconcelos, U. A. A., Dias, L. A. dos S., Corrêa, T. R., Rosmaninho, L. B. de C., Silva, D. R. M. da, & Zaidan, I. R. (2020). Estimates of genetic parameters and path analysis of crambe: An important oil plant for biofuel production. Acta Scientiarum. Agronomy, 42(1), e42490. https://doi.org/10.4025/actasciagron.v42i1.42490
Secco, D., Doglas Bassegio, Bruna de Villa, Araceli Ciotti de Marins, Luiz Antônio Zanão Junior, Tiago Roque Benetoli da Silva, Samuel Nelson Melegari de Souza (2021). Crambe oil yield and soil physical properties responses to no-tillage, cover crops and chiseling, Industrial Crops and Products, Volume 161, 2021, 113174, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2020.113174.
Berzuini, S., Federica Zanetti, Myrsini Christou, Efthymia Alexopoulou, Michał Krzyżaniak, Mariusz J. Stolarski, Federico Ferioli, Andrea Monti (2021). Optimization of agricultural practices for crambe in Europe. Industrial Crops and Products, Volume 171, 2021, 113880, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2021.113880.
De Oliveira, GB, David, AMSD, Soares, LM, Figueiredo, JC, Fernandes, IPS, AF de Oliveira, Gevaldo Barbosa David, Andreia Marcia Santos de Souza Soares, Larissa Medeiros Figueiredo, Josiane Cantuaria Fernandes, Ilmair Pereira Silva (2023). Burndown herbicides in Crambe abyssinica crops: seed yield and quality.REVISTA CIENCIA AGRONOMICA. 1408-2020, 0045-6888,1806-6690. 2023. DOI 10.5935/1806-6690.20230018. https://www.scielo.br/j/rca/a/ksGZLP4fWjtjLXH5bBDQnCf/?format=pdf&lang=en
Krzysztof J. Jankowski, Artur Szatkowski, Adam Okorski, The effect of sowing date and sowing density on the yield and quality of crambe seeds. A case study in north-eastern Poland, European Journal of Agronomy, Volume 152, 2024, 127010, ISSN 1161-0301, https://doi.org/10.1016/j.eja.2023.127010. (https://www.sciencedirect.com/science/article/pii/S1161030123002782)
Eberle, C., Scott, D.A., Forcella, F., Gesch, R.W., Weyers, S., Johnson, J.M.F. et al. (2024) Planting date impact on flowering, pollinator visitation and yield of mass flowering oilseed crops in the Northern Corn Belt. Agricultural and Forest Entomology, 26(4), 534-545. Available from: https://doi.org/10.1111/afe.12644
Ramires, M.F., Weiler, D.A., de Souza, E.L. et al. Intercropping with oilseeds enhances greenhouse gas mitigation during the initial establishment phase of tung trees. Agroforest Syst 99, 57 (2025). https://doi.org/10.1007/s10457-025-01158-z
Krzysztof J.J., Mateusz Sokólski, Artur Szatkowski, Marcin Kozak (2022). Crambe - Energy efficiency of biomass production and mineral fertilization. A case study in Poland. Industrial Crops and Products, Volume 182, 2022,114918, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2022.114918.
Scott, D.A., Carrie Eberle, Russ W. Gesch, Sharon Schneider, Sharon Weyers, Jane M.F. Johnson (2021). Yield, nitrogen, and water use benefits of diversifying crop rotations with specialty oilseeds. Agriculture, Ecosystems & Environment, Volume 317, 2021, 107472, ISSN 0167-8809, https://doi.org/10.1016/j.agee.2021.107472.
Volsi B, Higashi GE, Bordin I, Telles TS. Production and profitability of diversified agricultural systems. An Acad Bras Cienc. 2021 May 31;93(2): e20191330. doi: 10.1590/0001-3765202120191330. PMID: 34076037.

Sunflower (Helianthus annus L., family Asteraceae)

Description of the crop: Sunflower is an annual oilseed crop with an erect stem (1-3 m high). It has a tap root that can exploit moisture down to 1.5 m. Its stems have branches and each one produce one composite head on the top. The cultivated types have one head on the top. Its leaves can be 4 to 20 cm and 3-15 wide. The "flower head" of sunflower contains two types of flowers; the outer ones that look like petals, they called ray flowers and they are sterile. The inner flowers called disk flowers and are those that produce the seeds.

Origin and area of its cultivation: Sunflower is native of North America. In 18th century, it became a popular cultivated crop in Russia, where the area of its cultivation in the beginning of the 19th century came up to 900,000 ha [1]. At the end of 18th century, the crop came back to North America and became popular again. Currently, sunflower is an important oilseed crop that is cultivated worldwide. The top three sunflower producers at world level are Ukraine, Russia and the European Union. The sunflower annual production in Europe (Eurostat, 2023 data) is around 10 million tonnes and the harvested area was 4.5 million hectares (2.2 t/ha).

Figure A.13 View of sunflower from emergence to the harvesting time (source: CRES).

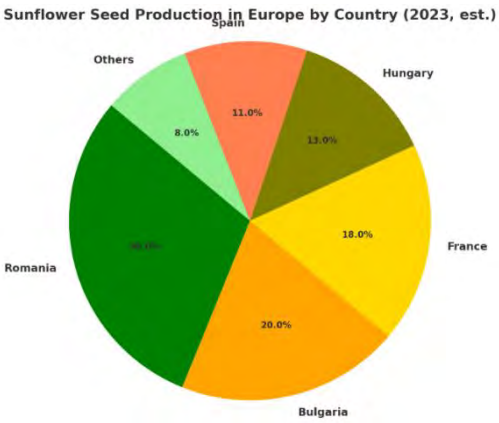


Figure A.14 View of sunflower from emergence to the harvesting time (source: CRES).

Climate preferences: Sunflower C3 crop is an oil crop with a short growth season ranging between 90 days for early maturing varieties to 160 days for late maturing varieties [2]. The plant has some higher temperature requirements for optimal growth than Camelina as the base temperature is at 5 °C, and it grows best in a temperature range between 20-25 °C [3]. It is however able to adapt to very warm climate. Tolerance to drought is also high for this crop as it will produce moderate yields even at 300 mm of rain but 500-750 mm are required for better yields. Sunflowers are full sun plants that only thrive in environments in which they are provided six or more hours of direct sunshine per day [4]. It is a crop which, compared to other crops, performs well under drought conditions; this is probably the main reason for the crop's popularity in the marginal areas of South Africa but also southern Europe.

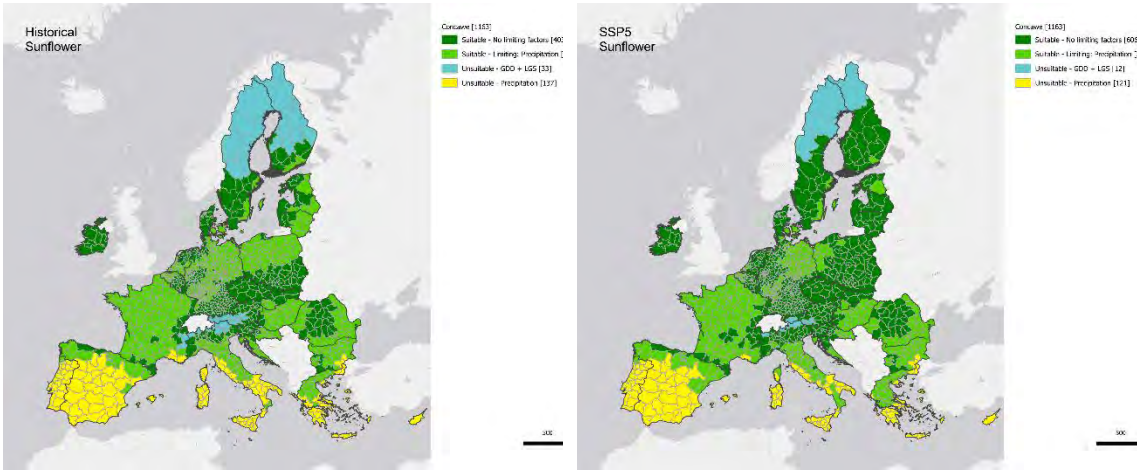
Soil preferences: The hardiness of the sunflower makes it an adaptable plant that is able to survive in almost any soil conditions, except those that are water-logged. Sunflowers thrive in neutral soils, but they also tolerate slightly acidic to slightly alkaline soils (pH range from 6.0 to 7.5) [5].

Soil preparation and sowing: Several tillage systems have been used with some success in specific environments. The final plant density should be 20,000 to 30,000 plants per ha. When the crop is going to be cultivated on marginal dry lands, lower densities are recommended, while higher densities can be applied in areas with adequate soil moisture [6]. Usually, the distance between the rows varies between 0.75 to 1 m. The soil depth at sowing should be between 3 and 5 cm. The soil temperature at sowing should be higher than 10 ºC [6].

Table A.5 Overview of climate suitability factors determining suitability for Sunflower grown as winter and summer crop. (source: See Appendix 4).

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 °C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	90	1200	5 °C	< 0 °C	NO	>=200 mm	-

Figure A.15 Climate suitability for Sunflower grown as a summer crop (left maps) and as a winter (cover) crop (right maps). Top maps refer to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).



Water and fertilization need: Sunflowers belong to a group of particularly drought-tolerant plants [7]. As long as they receive enough water during establishment when they are developing their root system, sunflowers are able to withstand periods of drought and heat. A critical time for water stress is the period 20 days before and 20 days after flowering. If stress is likely during this period, irrigation will increase the yield and the oil contents [7]. The protein percentage, however, will decrease. The demand of a sunflower crop for soil macronutrients is lower compared to traditional crops like corn and potato. Medium to high levels of macronutrients are usually required for good plant growth. The extensive tubular root system makes this plant a heavy feeder, although it is important not to over fertilize sunflowers, which can cause weak stems. The fertilization needs of sunflower are quite similar to those of wheat. A 1 t/ha Sunflower crop will need approximately 40 kg/ha N, 60 kg/ha P and 30 kg/ha K. It is claimed that the fertilization required for sunflower ranges: N - 50 to 90 kg/ha, P - 40 to 60 kg/ha, N - 60 to 100 kg/ha [3], [7].

Varieties: The research that was carried out initially in Russia and later in USA resulted in high number of varieties and hybrids with high yields. Nowadays, most of the farmers that grow sunflower, use seeds of hybrids [9]. The hybrids are characterized by higher yields and resistance to pathogens. Moreover, hybrids have been produced that perform well under dryland conditions and produce seeds rich in oleic acid that is appropriate for biodiesel production [9].

Seed Yields: Sunflower is in the top-three oilseed crops for Europe. In 2023, the total seed production was around 10 million tonnes and the average seed yields productivity was 2.2 t/ha. Sunflower is a common crop, grown in the majority of countries in the EU. The national yield averages between (2000-2020) reported by Eurostat for this crop range EU range between 0.85 to 2.65 t seeds/ha. Seed oil content can range, depending on the hybrids between 38% and 42% [3]. So, if we take a 40% oil content as an example, the oil yield per hectare would range between 0.34 to 1.1 t_{oil} per hectare.

Figure A.16 Sunflower seed yield in EU countries for the period 2020-2024 (average of 20 countries). Source: Eurostat.

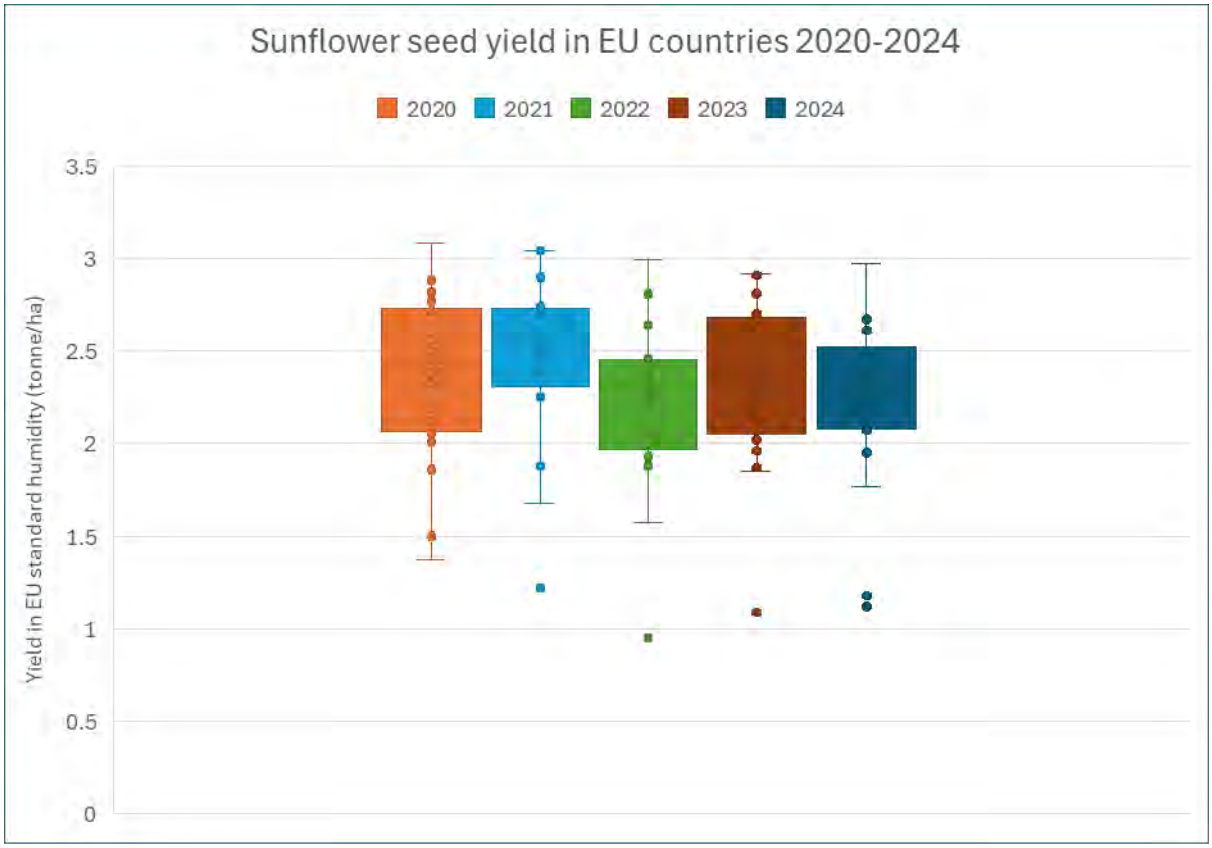
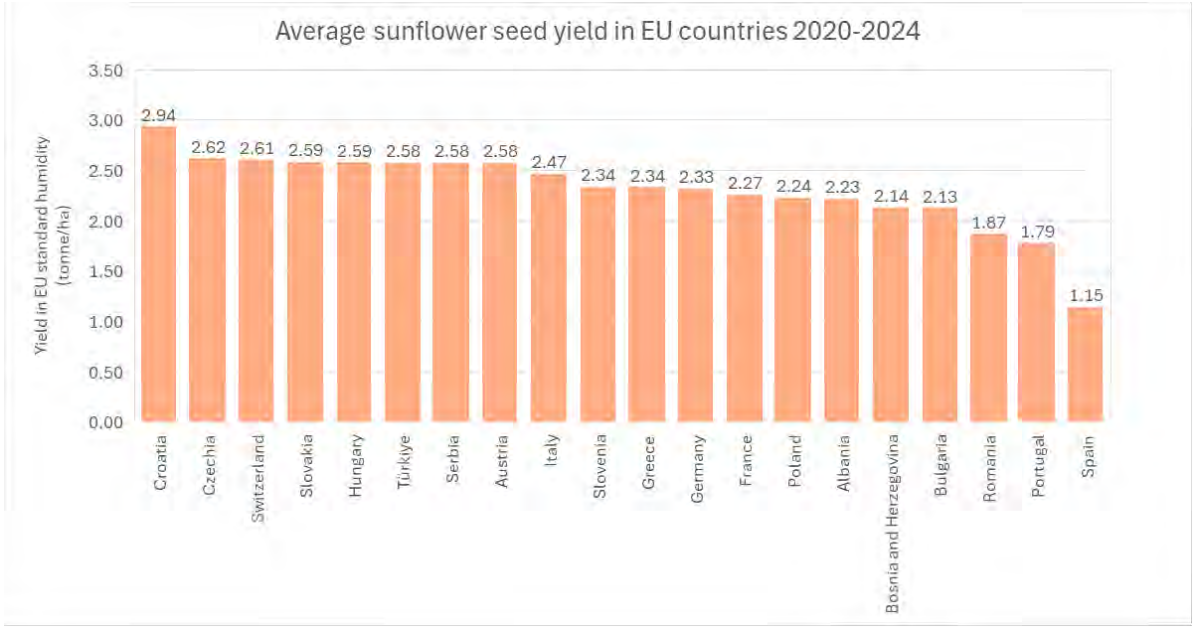


Figure A.17 EU-average sunflower seed yield over the period 2020-2024. Source: Eurostat.



Diseases and insects: Disease and pest pressure is high in sunflower [3]. One of the main sunflower diseases is Fusarium that is found largely in soil and plants. Sunflower is also susceptible to downy mildew. One major threat to sunflower crops is broomrape that is a parasite that attacks the root of the sunflower and causes extensive damage to sunflower crops. The pesticide and herbicides application levels in sunflower are therefore high. Birds can also be a problem because they sit on the heads and pick the seeds out. New hybrids have been developed with overhanging head at maturity (more difficult for the birds to hang onto).

Harvesting time and options for use as intermediate crop: Sunflower is a spring/summer crop than can follow winter crops if these are harvested within May. There are short cycles sunflower hybrids that can follow a winter annual crop (June to September) and can provide satisfactory seed yields when the rainfall is around 150 to 200 mm (with emphasis at the early stages of growth) otherwise it should be irrigated (2-3 times).

Harvesting and storage: Sunflower is an annual plant which will ripen and dry off without the need for chemical desiccation. A sunflower crop is physiologically mature when the majority of the heads have turned yellow, and are facing down (at this stage, harvesting will still be some weeks away). It can be harvested at a moisture content of 15%, but it is better to wait and harvest at 9% moisture, unless you have the capacity to dry grain on farm [10]. Harvest can be done with a conventional header and front, but sunflower trays (1 – 2 m trays or pans) must be fitted to the front (bolted to the header cutter bar) to avoid shattering losses. Sunflower reels and head snatchers reduce the amount of plant material entering the header. Heads should be largely intact when they come out the back of the machine, with any small centre seeds still present [10].

Uses: Sunflower is one of the most important oilseed crops that have been cultivated worldwide for several applications. The main use of sunflower is the oil production. Its oil has lower percentage in saturated fatty acids compared to other vegetable oils. After the oil extraction, the seed meal can be used for animal feeding. Regardless of the method of sunflower meal manufacture, the meal can serve as the sole source of supplemental protein in diets for beef or dairy cattle. The whole seed is being used as snack food. Sunflower seed oil is also being used for biodiesel production. In Europe, two are the main oilseed crops that are being used for biodiesel and these are rapeseed in Central and North Europe and Sunflower in the Mediterranean region.

Environmental impacts: The performance of sunflower in terms of the main environmental aspects is presented in the table below.

Environmental aspects	Color score	Explanation
1a) Soil structure		Sunflower is an intermediate crop that requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting. When is grown after camelina, it can be sown without ploughing and with no-till sowing machinery.
1b) Soil organic carbon		Sunflower can provide protection against soil erosion. However, the plant has long stems and does not provide a very dense coverage [3].
1c) Soil biodiversity		Pesticide and herbicide application is needed since disease and pest pressure is high in sunflower [3].

Environmental aspects	Color score	Explanation
2a) Risk for leaching to ground and surface water		Sunflower as a cover crop prevents some loss of nutrients through soil erosion and leaching in the soil as compared to fallow land even though the soil cover is limited. Nitrogen and other nutrient requirements are moderate compared to other oil crops (e.g., rapeseed) [10].
2b) Risk for loss from spraying pesticides, herbicides		Pesticide and herbicide application is needed since disease and pest pressure is high in sunflower [3].
3) Water quantity		Compared to other spring crops, like corn and cotton, sunflower shows better performance in semi-arid regions due to its drought tolerance [7]. However, it will do worse compared to Camelina, Crambe and Carinata/Ethiopian mustard.
4a) Habitat quality		Nutrient input requirements are moderate, but pesticide and herbicide requirements are high [6].
4b) Species viability contribution		Sunflower provides food to pollinators and birds in summer when it flowers [9]. When used as an intermediate crop, it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Sunflower is not invasive. It is originated from North America and came to Europe in the 16th century.

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: The crop is fully mechanized and large-scale commercial production is found all over Europe, except for the North.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

	TRL >7, industrial production already available at commercial scale
	5≤TRL≤7, production available at demo scale
	3<TRL<5, from research to production development
	TRL<=3, only basic research data available

References for factsheet

[1] https://www.sunflowernsa.com/all-about/history

[2] Fernández-Luqueño, F. et al., 2014. An Introduction to the Sunflower Crop. In: Sunflowers. s.l.: Nova Science Publishers, Inc.

[3] Puttha, R. et al., 2023. Exploring the Potential of Sunflowers: Agronomy, Applications, and Opportunities within Bio-Circular-Green Economy. Horticulturae, 9(10).

[4] https://florasense.com/blogs/sunlight-requirements-for-growing-sunflowers/

[5] https://www.holmesseed.com/growers-guidebook/growing-guides/sunflower-growing-guide

[6] Steer,B.t., Coaldrake, P.d., Pearson, C.J., Canty, C.P. (1986). Effects of nitrogen supply and population density on plant development and yield components of irrigated sunflower (Helianthus annuus L.), Field Crops Research, Volume 13, Pages 99-115, ISSN 0378-4290, https://doi.org/10.1016/0378-4290(86)90014-6.

[7] Earley, A., Nolting, K., Donovan, L. Burke, J (2024). Trait variation and performance across varying levels of drought stress in cultivated sunflower (*Helianthus annuus* L.). *AoB PLANTS*, Volume 16, Issue 4, July 2024, plae031, https://doi.org/10.1093/aobpla/plae031

[8] Hussain, F., Khan, F., Ahmad, J., Huo, H., Jiang, T. et al. (2025). Sunflower (*Helianthus annuus* L.) Hybrids: Strategic Crossbreeding Techniques to Efficiently Enhance Yield and Oil Quality. *Phyton-International Journal of Experimental Botany*, *94(10)*, 3231-3249. https://doi.org/10.32604/phyton.2025.069654

[9] Fernández-Martínez, J. Pérez-Vich, B.,Velasco, F. (2015) Sunflower Broomrape (Orobanche cumana Wallr.), Editor(s): Enrique Martínez-Force, Nurhan Turgut Dunford, Joaquín J. Salas, Sunflower, AOCS Press, Pages 129-155, ISBN 9781893997943, https://doi.org/10.1016/B978-1-893997-94-3.50011-8.

[10] https://grdc.com.au/__data/assets/pdf_file/0026/370619/GrowNote-Sunflower-North-12-Harvest.pdf

White mustard (Sinapis Alba L., Brassicaceae)

Description of the crop: Sinapis alba, the white mustard, is an annual crop of the Brassicaceae family. Brassica alba (syn. B. hirta), commonly referred to as white or yellow mustard, is believed to have originated in the Mediterranean basin. This annual herbaceous plant can attain a height of approximately 70 centimetres. Its leaves are stalkless, pinnate, and bear resemblance to those of Sinapis arvensis. Seeds are spherical, yellowish, and measure 1.5-3 mm. The yellow flowers exhibit a cruciform arrangement with four petals and four alternating sepals. The siliquae (seed pods) measure between 2.0 and 4.2 cm in length. Sinapis alba is classified as a long-day plant, initiating flowering once photoperiod thresholds are exceeded.

Origin and area of its cultivation: White mustard is native to the Mediterranean region. Its area of cultivation in Europe varies from 20,000 to 30,000 ha and is found in Germany, France, Hungary, Czech Republic, Slovakia, Romania and Poland [1].

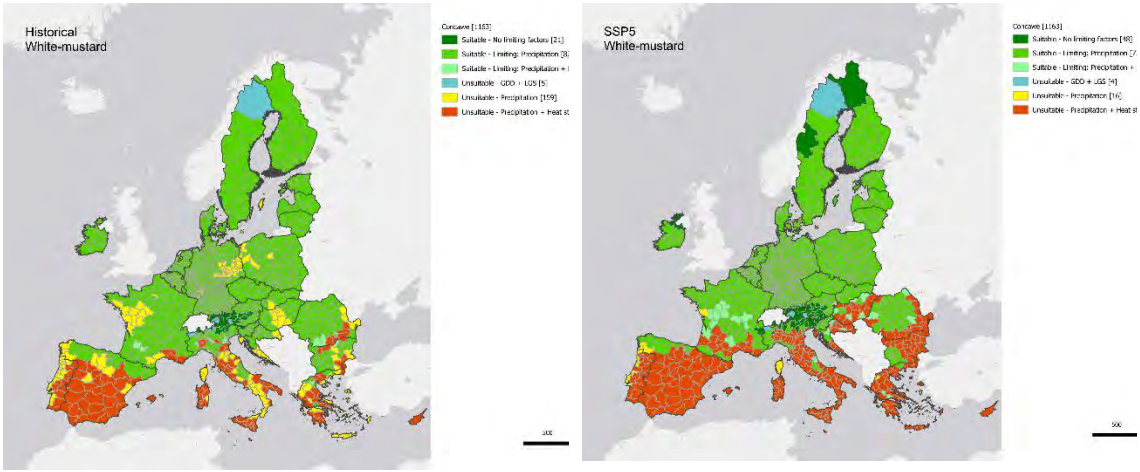
Varieties: There are varieties available in the market provided by a number of companies such as: Saaten-Union, Semences de France, KWS, Danko, Agrolution or AGROSEM, COOPs or Organic Suppliers, etc.

Climate preferences: Mustard thrives in temperate climates and is well-adapted to short growing seasons and arid conditions, which enhance seed quality. Optimal growth is achieved in well-aerated soils with near-neutral pH, although the crop tolerates both alkaline and mildly saline soils [2]. Yellow mustard varieties typically mature in 80-85 days, whereas brown and oriental varieties require 90-95 days [2].

Table A.6 Overview of climate suitability factors determining suitability for White Mustard grown as summer crop. (source: See Appendix 4).

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32*C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	60	860	4 °C	< -2 °C	YES	>=100 mm	-

Figure A.18 Climate suitability for White Mustard grown as a summer crop. Left map refers to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).

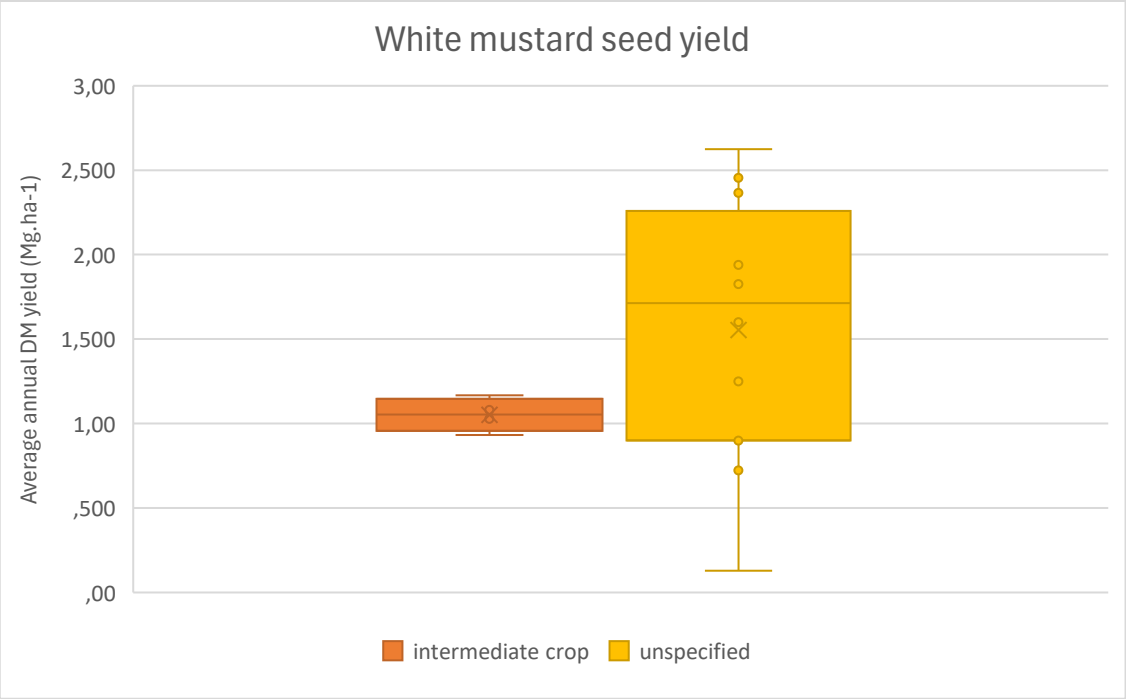


Soil preferences: White mustard can be cultivated in a wide range of pH from 4.5 to 8.2. The optimum to soils for the cultivation are light well-drained [3], but it may be grown on a wide range of soils from light to heavy, growing best on relatively heavy sandy loamy soils. It is not suited to very wet soils. Sinapis alba grows best where the annual precipitation varies from 35 to 179 cm, and the annual temperature ranges from 5.6 to 24.9 °C [3].

We can say that white mustard (Sinapis alba) shows measurable sensitivity to salinity during germination and early seedling growth, with its tolerance varying by genotype and strong reductions at higher NaCl levels, while agronomy guides describe it as tolerant of slightly saline soils; growth can also be constrained on soils with low organic matter/low fertility, where reduced nutrient supply and water-holding conditions are associated with poorer plant development [4].

Yields: Average commercial yields are around 1,000 kg/ha for yellow mustard and 1,500 kg/ha for brown. Studies have shown that the yields increase while increasing the plant density but not proportionally (When 40 plants are grown, grain yield is only slightly lower than when the number of plants is doubled (80 plants), denoting a minimum difference). The literature review provided a few references for yields when White Mustard is cultivated as an intermediate crop, with an average seed yield of 0.9-1.2 t/ha. Unspecified cropping system yields ranged between 0.8 and 2.3 t/ha. The average oil content was reported to be 47% [5]. This implies an oil range of between 0.4-1.1 t_{oil}/ha.

Figure A.19 Published seed yield levels for white mustard, based on 6 references (see literature list at the end of this factsheet).



Soil preparation and sowing: The recommended seed dose is 8 kg/ha at the beginning before sowing. 100 kg/ha of nitrogen are required to achieve the optimum yields [6]. The space among the plants should be at 15 cm on the row and between rows at 20 cm and a depth of 1.5 to 2.5 cm into a firm, moist seedbed with projected plant population of over 300,000 per ha to get significant yields [6]. The sowing should be done shallowly in a moist, firm seedbed. The seed density is approximately 6 kg/ha for brown mustard and 10-12 kg/ha for yellow mustard. Five weeks post-emergence, the plants enter the budding stage, followed by flowering after 10 days [6]. Good soil moisture during flowering prolongs the blooming period and enhances yield [6].

Harvesting time and options for use as intermediate crop: It can be sown the same time like Crambe in Europe, when it is grown as summer crop. It has a longer cycle than Crambe and thus a following crop is challenging. It should be considered as part of a rotation cycle. When white mustard is grown as intermediate crop the sowing should be done by mid-March and the harvesting time 120 days later.

Harvesting & Storage: In Europe, mustard is generally harvested using direct combine methods, whereas Canadian practices often involve swathing to expedite drying [7]. White mustard should be harvested once the foliage begins to yellow and the seed pods display browning. Brown and oriental varieties, which are more susceptible to shattering, require harvesting when 75% of the seeds reach their mature colour [7].

Harvesting techniques range from manual methods using sickles to mechanized approaches via combine harvesters. Seeds can be manually extracted or collected by placing inflorescences in paper bags until maturation, after which a light shake releases the majority of seeds. Modern combine harvesters have largely replaced manual cutting. To limit wind-related seed loss, swath rollers are employed to compress the swath. During combine threshing, a low cylinder speed is

recommended to minimize pod breakage, and threshing should only be performed when seed moisture is below 9.5%.

Figure A.20 View of White mustard [8].

Post-harvest is essential to maintain seed oil quality by preventing lipid degradation. Seeds are dried, either via sun exposure or hot-air convection, to a moisture content below 9%, ensuring optimal conditions for oil extraction. For optimal storage, seed moisture content must be reduced below 10%, and drying temperatures must not exceed 52°C to preserve enzymatic activity essential for flavour compound development [8]. For long-term storage, seeds should be kept at temperatures below 18°C with proper aeration to prevent microbial spoilage and pest infestation.

Uses: Mustard (Sinapis alba, Brassica juncea, etc.) has historically used in culinary traditions and medicine across the Mediterranean basin. The leaves, seeds, and oils from mustard plants are widely utilized for nutritional and flavouring purposes.

Beyond its culinary and medicinal roles, mustard has demonstrated considerable value in industrial processes, ecological applications, and sustainable agriculture. Mustard oil, when is oxidized forms “blown oil,” becomes viscous and is employed in leather processing to enhance softness and pliability by reintroducing fats removed during tanning. The oil cake, a by-product of oil extraction, serves as a nutrient-rich cattle feed and organic manure. Additionally, mustard seed oil is utilized in soap production, as a lubricant, and occasionally as an illuminant.

Brassica species, including mustard, are significant in integrated pest management due to their glucosinolate content [9]. Upon enzymatic hydrolysis, glucosinolates degrade into compounds such as isothiocyanates and nitriles, which exhibit antimicrobial and nematocidal properties. This makes mustard an effective biofumigant, capable of suppressing soil-borne pathogens, fungi, and nematodes, and contributes to environmentally sustainable agricultural practices [9].

Mustard oil has been explored for its potential in repelling domestic animals, including cats and dogs. This, along with its soil-enhancing properties and bioactive profile, underscores mustard's versatility across sectors, from agriculture to industry and environmental health.

Phytoremediation: Sinapis alba is a promising hyperaccumulator for certain toxic elements, particularly thallium, and can contribute significantly to sustainable environmental clean-up efforts. Sinapis alba can be cultivated in wide range of edaphoclimatic conditions, has a very short cultivation cycle, so it produces high biomass quickly, ideal for phytoextraction. It also shows strong tolerance to pollutants. The crop tolerates moderate to high levels of heavy metals. It is effective in in remediating soils contaminated with mining and industrial waste.

Environmental impacts: The performance of white mustard in terms of the main environmental aspects is presented in the table below.

Environmental aspects	Color score	Explanation
1a) Soil structure		Sinapis alba as intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting. However, establishment of crop can be done with no-till sowing.
1b) Soil organic carbon		Sinapis alba serves as a cover crop which protects the soil against erosion [2].
1c) Soil biodiversity		Low requirements in terms of herbicides but in terms of pesticides (due to its similarities with rapeseed) some applications are needed [9].
2a) Risk for leaching to ground and surface water		Sinapis alba as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. It has quite lower nitrogen needs (50 to 80 kg/ha) compared to rapeseed and wheat.
2b) Risk for loss from spraying pesticides, herbicides		Pesticide and Herbicide application is not usually required, while pesticides could be required deepening on the site and the prevailing climatic conditions per cultivation site [9].
3) Water quantity		Compared to other oilseed crops, like rapeseed, white mustard shows better performance in semi-arid regions due to its high drought tolerance [10].
4a) Habitat quality		Nutrient input requirements are very low in white mustard as compared to a conventional crop like wheat. Some pesticides are needed. As a cover crop it also prevents leaching of nutrients.
4b) Species viability contribution		Sinapis alba provides food to pollinators in periods in early spring when it flowers [2]. When used as an intermediate crop it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Sinapis alba is a widely naturalized species in Europe. It is not considered invasive or a serious environmental weed [1].

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect

	No effect
	Low to medium adverse effect
	High adverse effect

TRL: The TRL is quite high since it is a well-established crop in Europe (White mustard is widely used across Europe, particularly in France, Germany and the Netherlands, as a cover crop to reduce nitrogen leaching and improve soil structure).

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

TRL >7, industrial production already available at commercial scale

5<=TRL=>7, production available at demo scale

3<TRL>5, from research to production development

TRL<=3, only basic research data available

References for the factsheet

[1] Thomas,J.,Kuruvilla, K.M., Hrideek,T.K. (2012). White Mustard. In: K.V. Peter (ed.),Woodhead Publishing Series in Food Science, Technology and Nutrition, Handbook of Herbs and Spices (Second Edition),Woodhead Publishing, Pages 388-398, ISBN 9780857090393, https://doi.org/10.1533/9780857095671.388. (https://www.sciencedirect.com/science/article/pii/B9780857090393500219)

[2] https://pfaf.org/user/plant.aspx?LatinName=Sinapis+alba

[3] Dorsainvil, F., Dürr, C, Justes, E., Carrera, A. (2005). Characterisation and modelling of white mustard (Sinapis alba L.) emergence under several sowing conditions, European Journal of Agronomy, Volume 23, Issue 2, Pages 146-158, ISSN 1161-0301, https://doi.org/10.1016/j.eja.2004.11.002.

[4] Kaya, M. D., Ergin, N., Seçal, G., & Gümüşçü, A. (2025). Performance of White Mustard (Sinapis alba) Genotypes under Salinity Stress during Germination and Seedling Growth Stages. *Black Sea Journal of Engineering and Science*, *8*(6), 1883-1889. https://doi.org/10.34248/bsengineering.1748127

[5] Özcan, M. M. et al., 2024. White mustard (Sinapis alba L.) seeds: the role of oven and microwave roasting on their bioactive components, antioxidant potential, fatty acids and mineral contents. European Food Research and Technology, Volume 250.

[6] Sáez-Bastante,J., Fernández-García, P., Saavedra, M., López-Bellido, L., Dorado, M.P., Pinzi, S (2016). Evaluation of Sinapis alba as feedstock for biodiesel production in Mediterranean climate, Fuel, Volume 184, 2016, Pages 656-664, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2016.07.022.

[7] Brown, J., Davis, J.B., Esser, A (2005). Pacific Northwest Condiment Yellow Mustard (Sinapis alba L.) Grower Guide. Subcontract Report NREL/SR-510-36307 July 2005. https://docs.nrel.gov/docs/fy05osti/36307.pdf

[8] Mitrović, P. M. et al., 2020. White Mustard (Sinapis alba L.) Oil in Biodiesel Production: A Review. Front. Plant Sci., p. 11.

[9] Dutta, T.K.,Khan, M.R., Phani,V. (2019). Plant-parasitic nematode management via biofumigation using brassica and non-brassica plants: Current status and future prospects, Current Plant Biology, Volume 17, Pages 17-32, ISSN 2214-6628, https://doi.org/10.1016/j.cpb.2019.02.001.

[10] Muhammad et al. (2022). Allometric dynamics of Sinapis alba under different ecological conditions. Journal of King Saud University – Science. https://doi.org/10.1016/j.jksus.2022.102403

References for yield data used in figure A.19 – Yields

Brčić M., Pospišil M., Pospišil A., Kraljić K., Obranović M., Škevin D. (2024). Influence of seeding density on seed and oil yield, and fatty acid composition of white mustard (Sinapis alba L.) [Vpliv gostote setve na pridelek semena in olja ter sestavo maščobnih kislin pri beli gorjušici (Sinapis alba L.)] (2024) Acta Agriculturae Slovenica, 120 (1), Cited 1 times. DOI: 10.14720/aas.2024.120.1.13662
Gazoulis, I., Kanatas, P., Antonopoulos, N., Tataridas, A., & Travlos, I. (2022). Narrow Row Spacing and Cover Crops to Suppress Weeds and Improve Sulla (Hedysarum coronarium L.) Biomass Production. Energies, 15(19), 7425. https://doi.org/10.3390/en15197425
Gesch R.W., Allen B.L., Archer D.W., Jabro J.D., Isbell T.A., Long D.S. (2024). Water use and water use efficiency of three Brassicaceae oilseeds under high- and low-yielding environments (2024) Crop Science, 64 (4), pp. 2382 - 2392, Cited 0 times. DOI: 10.1002/csc2.21273
Kayacetin F. (2023). Influence of Sowing Dates and Genotypes on Phenology, Morphology, Yield and Fatty Acid Compounds of Sinapis alba L. for the Energy Industry (2023) Gesunde Pflanzen, 75 (3), pp. 613 - 623, Cited 6 times. DOI: 10.1007/s10343-022-00726-y
Kayacetin F., Aydin O. (2024). Growth and Yield of Local and Exotic White, Brown, and Black Mustard Lines Sown in the Spring Season in Turkey (2024) Communications in Soil Science and Plant Analysis, 55 (22), pp. 3447 - 3456. DOI: 0.1080/00103624.2024.2397551
Kinay A, Kayacetin F. (2023). Phenology, morphology, yield and quality characteristics of mustard species (brassica spp.) suitable for energy sector. Gesunde Pflanzen. 2023;75(5):1953-1962. doi: https://doi.org/10.1007/s10343-022-00817-w.

Ethiopean mustard/carinata (Brassica carinata A. Braun, family Brassicacea)

Figure A.21 Brassica carinata.

Description of the crop: Ethiopian mustard is closely related to rapeseed (*Brassica napus* L.). The plant can be up to 120 cm height. It has a deep root system. It is a tall, leafy plant (Figure A.21), well adapted in the Mediterranean climate. It can be grown either as winter or spring annual crop. The stems are reddish-green, often profusely branched with lateral buds. Leaves are alternate, non-heading with long petioles. Flowers are usually light yellow about 1.5 cm across, on short pedicels on an extended raceme. Flowers are regular with four free sepals in one series and two sets of stamens. The fruit is a silique up to 5 cm long. The seeds are small but bigger compared to Brassica napus (Figure A.22). The weight of 1000 seeds is approximately 3.5 grams.

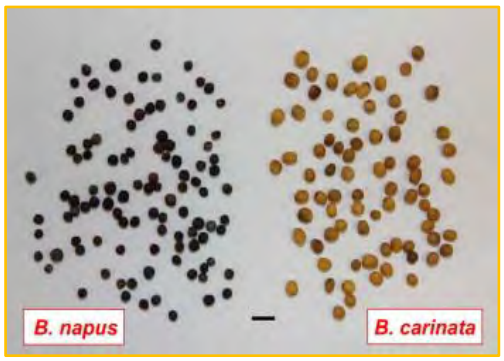


Figure A.22 Comparison between the seeds of B. napus and B. carinata [1].

Origin and research in Europe: It is originated from Ethiopia, where it is grown as oilseed. In south Africa it is grown as leafy vegetable. *Brassica carinata* is an amphidiploid with one genome from *Brassica nigra* (L.) Koch and the other from *Brassica oleracea* L. Several studies have pointed out its high seed yields, its ability to adapt in arid and semi-arid conditions, its tolerance to abiotic and biotic stress and thus have been proposed it as an alternative oilseed crop to *Brassica napus* for the Mediterranean region [2].

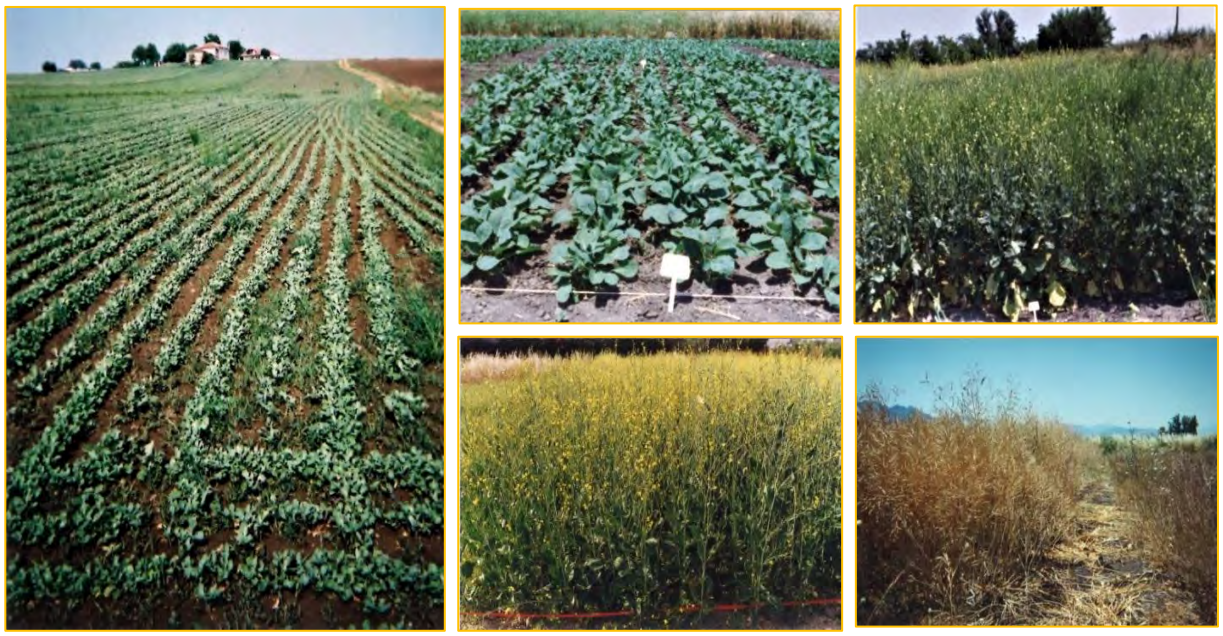


Figure A.23 View of Ethiopian mustard from emergence to the harvesting time (source: CRES; Greece).

Ethiopian mustard has been included in a few EU research projects starting with FAIR CT 96 1946 entitled “Brassica carinata: The outset of a new crop for biomass

and industrial non-food applications", b) ICON project (https://cordis.europa.eu/project/rcn/37448_en.html), c) 4FCROPS (EU project entitled "4FCROPS - Future Crops for Food, Feed, Fiber and Fuel", www.cres.gr/4fcrops) and d) Crops2Industry (EU project entitled "Crops2Industry: Non-food Crops-to-Industry schemes in EU27", www.cres.gr/crops2), e) MAGIC project (https://magic-h2020.eu/), where carinata had been selected as promising industrial crops for marginal lands, f) BIKE project (www.bike-biofuels.eu) where it has been selected as low ILUC feedstock for advanced biofuels project. Among the above-mentioned projects, the cultivation protocol (sowing dates, sowing densities, fertilization rates, harvesting dates and methods) was studied for the Mediterranean region for a high number of *Brassica carinata* lines (1997-2000) on both experimental and demo trials.

Currently, carinata is being studied by the following projects: a) CARINA project (www.carina-project.eu, 2022-26) as an oilseed crop to boost the sustainable diversification in EU farming systems, b) MIDAS project (www.midas-bioeconomy.eu, 2022-26) as an non-edible oilseeds to be grown on marginal lands facing natural constrains and c) IASIS project (www.iasis-soil.eu) for curing contaminated and saline soils and for producing feedstock for biobased applications.
In Figure A.24, the crop from seeds emergence to harvesting time is presented.

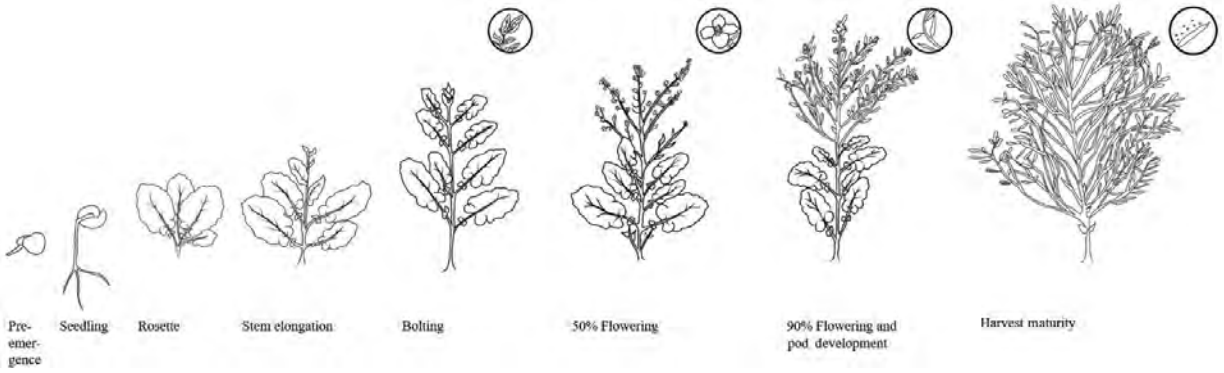


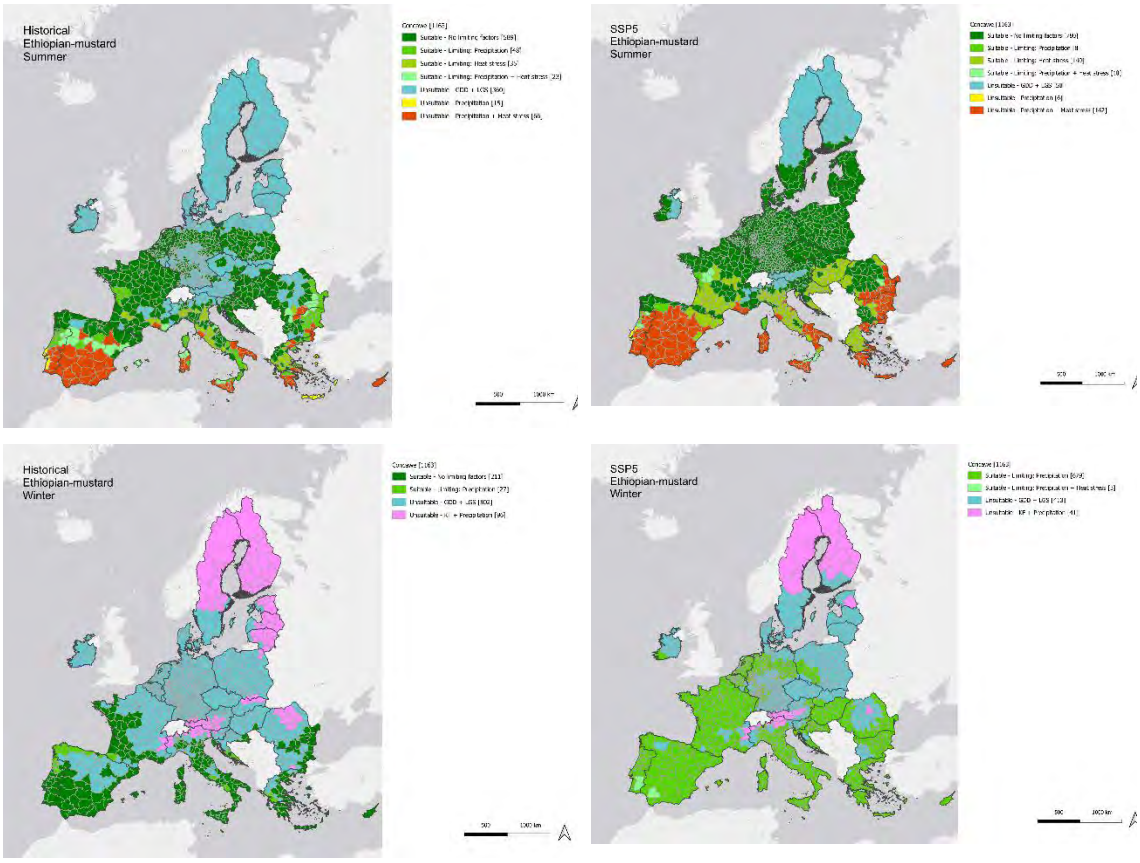
Figure A.24 Phenology of carinata showing different growth stages of its life cycle [3].

Climate preferences: Ethiopian mustard it is well adapted to the temperate climatic zones of Europe. The crop is characterized by high tolerance to heat and drought (thus it is considered as alternative to Brassica napus). It does not tolerate frost however. In the Mediterranean region the crop can be grown both as winter and spring crop, while in central and north Europe should be grown as spring crop.

Table A.7 Overview of climate suitability factors determining suitability for Ethiopian mustard grown as winter and summer crop.

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 ºC in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	140	2000	4 °C	<= 0 °C	YES	>=100 mm	1000 mm
Winter crop	180	2200	4 °C	<= 0 °C	YES	>=100 mm	1000 mm

Figure A.25 Climate suitability for Ethiopian mustard grown as a summer crop (left maps) and as a winter (cover) crop (right maps). Top maps refer to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).



Soil preferences: Ethiopian seeds may not germinate in soils with an above average salinity level. It is not tolerant to waterlogging.

Ethiopian mustard has moderate tolerance to saline conditions [5] and it can be used for phytoremediation purposes due to high tolerance to heavy metals (it is accumulator of Pb, Ni, Zn and has low tolerance to Cd, Pb, Ni, Zn) [2].

Soil preparation and sowing: The soil preparation and sowing is quite similar to *Brassica napus*. For a good establishment a plant rate of 200 seeds per m^2 is recommended (8 kg seeds per ha) [3]. The sowing depth should be 1-2 cm and the distances between the rows should be 30 cm. Sowing date has been found to have a much larger effect on yield than seed rates and, where environments allow, an early autumn sowing is likely to achieve best results [3]. In the ongoing projects the sowing time was either at the end of autumn or at the end of winter.

Carinata, apart from a valuable cover crop, it is considered as a valuable crop for intercropping with cereals and/or legumes and detailed research on this is being carried out by CARINA project with very good results.

Figure A.26 Intercropping of carinata with wheat (2024-25, source: CARINA project by CRES in central Greece).

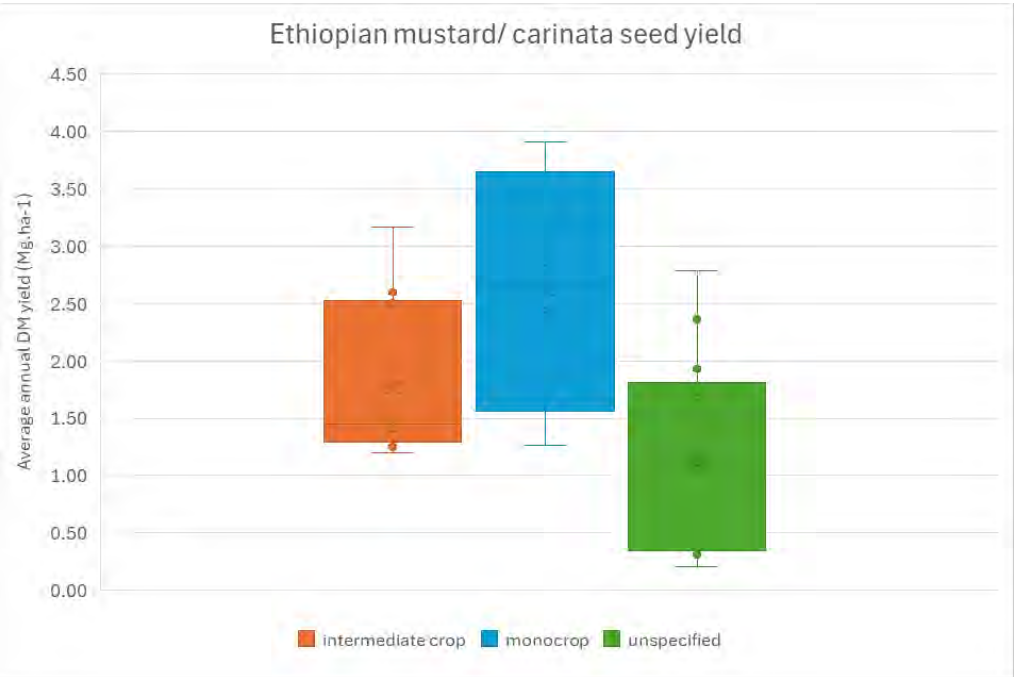
Water and fertilization needs: Ethiopian mustard responds well to organic manure of up to 20 t/ha. Most farmers find it easier to incorporate chemical fertilizers in the plant beds at the rate of about 100 kg N and 30 kg P. According to the soil type the fertilization rates could be: N - 80 to 120 kg/ha (in at least two doses; 30 to 40% at the stage of stems elongation), P - 40 to 60 kg (at the sowing), 40-80 kg/ha (at the sowing), S - 20-30 kg/ha (it affects the soil quality and protein synthesis). Higher levels of nitrogen will increase proteins and enhance leaf production, whereas more phosphorous will enhance the seed production potential [4].

Varieties: Although a number of research projects had been carried out worldwide the number of available varieties in the European market is quite limited and currently is mainly dominated by NUSEED company. In the ongoing research projects in Europe the varieties developed by NUSEED are being tested in CARINA project, while in MIDAS and IASIS the tested variety in Carbon.

Seed Yields: The average yields have ranged from 2 t/ha up to 3.5 t/ha in Europe. In the Greek trials carried out (FAIR CT96 1946 project[1]) the seed yields of the compared lines came up to 1.5 t/ha. In the fields of carinata in CARINA project seed yields higher than 2 t/ha have been recorded when was grown as intermediate crop, while when it was grown on marginal lands (dryness and slope) lower yields of 1.7 t/ha had been recorded (Figure A.27). The yields when grown as an intermediate crop reviewed in literature show a range between 1.4 to 2.5 tonnes/ha. Yields when grown as a mono-crop are higher and can reach up to 3.7 tonnes/ha. In general, the oil content is 40%. So the average oil yield per hectare ranges between 0.56 - 1 tonnes oil/ha.

[1] cordis.europa.eu/project/id/FAIR961946

Figure A.27. Published seed yield levels of Ethiopian mustard (Brassica carinata), differentiated to cultivation systems. Based on 12 references (see literature list at the end of the factsheet).



Diseases and insects: It is sensitive to turnip mosaic virus (TuMV) and especially the leaf crop is vulnerable [6]. TuMV is transmitted by a range of aphids, of which the cabbage aphid (*Brevicoryne brassicae*) and the green peach aphid (*Myzus persicae*) are the most important. The crop is susceptible to black rot (*Xanthomonas campestris*), and black spot (*Alternaria brassicicola*), and to damping off and seedling root rot (*Rhizoctonia solani*) [7]. The best disease control is the proper management rather than a spraying regime with agro-chemicals [7].

Harvesting time and options for use as intermediate crop: In order carinata to be used as intermediate crop it is important to achieve the harvesting as soon as possible to allow the establishment of the second crop (like short cycle sunflower or sorghum as feed and/or biomass crop). Usually, carinata is harvested two to three weeks later than camelina. The harvesting time can come earlier either by using improved varieties with shorter growing cycle and/or by spraying the plantation with the biobased herbicide like the ones that are being tested in CARINA project.

Harvesting and storage: Harvest is a critical operation and losses can be heavy due to the small seeds and because the growth habit prevents all seeds in a crop maturing at the same time. Furthermore, early harvesting can reduce seed quality and late harvesting can enhance pod shuttering. The moisture content of *Brassica carinata* at harvest time of the seed must be around 7-9% and it's recommended for safe storage of rapeseed to be dried to less than 9% [8].

Figure A.28 View of carinata fields on slope and dry areas in north Greece (source: CRES from CARINA project).

Uses: Ethiopian mustard is usually cultivated for its oil that is rich in erucic and linoleic acids and well-indicated for biofuels. Most of the literature on the energy uses of Ethiopian mustard focuses on the production of biofuels (Seepaul, et al., 2021). The oil profile of zero erucic-acid Ethiopian mustard consists of 33% oleic, 37% linoleic and 21% linolenic acid compared to 61% oleic, 21% linoleic and 11% linolenic acid in *Brassica napus*. The oil finds wide application in the production of water repellents, waxes, polyesters and lubricants. Seed cake that remaining after oil extraction can be used as fertilizer or feed stuff. It is also used as a green fodder crop, green manure and as a cover crop. Interest in this species for industrial uses has been increasing thanks to the particular acid composition of its extracted oil. Outside Africa, especially in western and southern Asia, it is occasionally grown as an oilseed crop or for mustard. The seeds are crushed and the oil is used for cooking and in the mustard industry. The oil has limitations for cooking because of high contents of glucosinolates and erucic acid. In Ethiopia it is used for oiling the baking plates of earthenware 'injera' stoves. It is also used for illumination. The seed is used in folk medicine to treat stomach-ache. People in Ethiopia use the sharp-tasting seeds as a spice to flavour raw meat.

Environmental impacts:

Environmental aspects	Color score	Explanation
1a) Soil structure		Carinata intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting. However, establishment of crop can be done with no-till sowing.
1b) Soil organic carbon		Carinata serves as a cover crop which protects the soil against erosion.
1c) Soil biodiversity		Low requirements in terms of herbicides but in terms of pesticides (due to its similarities with rapeseed) some applications are needed [6], [7].
2a) Risk for leaching to ground and surface water		Carinata as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. The application of nitrogen (80 kg N/ha) is 20% lower than wheat (100 kg N/ha) and 20-30% than rapeseed (120 kg/ha) [2].
2b) Risk for loss from spraying		Pesticide and Herbicide application is not usually required, while pesticides could be required deepening on the site and the prevailing climatic conditions per cultivation site [6], [7].

Environmental aspects	Color score	Explanation
pesticides, herbicides		
3) Water quantity		Compared to other oilseed crops, like rapeseed (>450 mm), carinata shows better performance in semi-arid regions due to its high drought tolerance (~150 mm) [2], [3].
4a) Habitat quality		Nutrient input requirements are less than rapeseed (20-30%) and wheat (20%) [2].
4b) Species viability contribution		Carinata provides food to pollinators in periods in early spring when it flowers. When used as an intermediate crop it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Carinata is not invasive. It is native to Ethiopia [1].

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: As it is presented in the table below carinata is very well fitted for the cropping systems of the south Europe as alternative to rapeseed due to its increased resistance to drought and heat and not ideal for central and northern Europe unless is being growing as spring crops (it is studied in CARINA project). The breeding programme of carinata is being dominated by NUSEED (the only available seeds with high yields).

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

 = TRL >7, industrial production already available at commercial scale,

 = 5<=TRL=>7, production available at demo scale

 = 3<TRL>5, from research to production development

 = TRL<=3, only basic research data available

References for the factsheet

[1] Marillia, E.-F.et al., 2014. Palliser's promise: Brassica carinata, An emerging western Canadian crop for delivery of new bio-industrial oil feedstocks. Biocatalysis and Agricultural Biotechnology, 3(1).

[2] Hagos, R. et al., 2020. Ethiopian Mustard (Brassica carinata A. Braun) as an Alternative Energy Source and Sustainable Crop. Sustainability.

[3] Seepaul, R. et al., 2021. Brassica carinata: Biology and agronomy as a biofuel crop. GCB Bioenergy.

[4] Bonansea, S., Ernst, O. R. & Mazzilli, S. R., 2023. Baseline for Brassica carinata Components of Nitrogen-Use Efficiency in Southern South America. Agronomy .

[5] Mondal, S., Chakraborty, K. (2020). Brassicaceae Plants Response and Tolerance to Salinity. In: Hasanuzzaman, M. (eds) The Plant Family Brassicaceae. Springer, Singapore. https://doi.org/10.1007/978-981-15-6345-4_6

[6] Babu, B, Dankers, H., George, S., Wright, D., Marois, J. and Paret, M. (2013). First Report of Turnip mosaic virus Infecting Brassica carinata (Ethiopian Mustard) in the United States. New Science, Emerging diseases and more. https://apsjournals.apsnet.org/doi/10.1094/PDIS-05-13-0500-PDN

[7] Tonguç, M. & Griffiths, P. D. (2004). Evaluation of Brassica carinata Accessions for Resistance to Black Rot (Xanthomonas campestris pv. campestris). *HortScience*, *39*(5), 952-954. https://doi.org/10.21273/HORTSCI.39.5.952

[8] https://sparc-cap.org/wp-content/uploads/2018/03/Carinata-best-management-practices.pdf

References for seed yield levels (Figure A.27)

Abias M., Gomes L.A., Costa J., Fernando A.L.(2025). Increasing the Sustainable Production of Biofuels – Prospects of Cultivating Oilseed Crops in Soils Contaminated with Heavy Metals. (2025) Lecture Notes on Multidisciplinary Industrial Engineering, Part F4026, pp. 231 - 237. DOI: 10.1007/978-3-031-80330-7_25
Bashyal, M., Mulvaney, M.J., Lee, D., Wilson, C., Iboyi, J.E., Leon, R.G., Landry, G.M. and Boote, K.J. (2021), Brassica carinata biomass, yield, and seed chemical composition response to nitrogen rates and timing on southern Coastal Plain soils in the United States. GCB Bioenergy, 13: 1275-1289. https://doi.org/10.1111/gcbb.12846
Bhattarai D, Kumar S, Nleya T. Nitrogen and sulfur fertilizers effects on growth and yield of Brassica carinata in South Dakota. Agronomy Journal. 2021; 113: 1945-1960. https://doi.org/10.1002/agj2.20501
Bonansea, S., Ernst, O. R., & Mazzilli, S. R. (2023). Baseline for Brassica carinata Components of Nitrogen-Use Efficiency in Southern South America. Agronomy, 13(2), 412. https://doi.org/10.3390/agronomy13020412
Campbell B.T., Seepaul R., Iboyi J.E., Anderson W.F., Baldwin B.S., Bennett R., Crozier C.R., George S., Hagan A.K., Lee D., Macoon B., Mailhot D., Morrison J.I., Mulvaney M.J., Post A., Small I.M., Wright D.L. (2023). Agronomic performance and the effect of genotype-by-environment interaction for Brassica carinata in the southeastern US (2023). Industrial Crops and Products, 203, art. no. 117196 DOI: 10.1016/j.indcrop.2023.117196

Iboyi J.E., Mulvaney M.J., Balkcom K.S., Seepaul R., Bashyal M., Perondi D., Leon R.G., Devkota P., Small I.M., George S., Wright D.L. (2021). Tillage system and seeding rate effects on the performance of Brassica carinata. (2021) GCB Bioenergy, 13 (4), pp. 600 - 617. DOI: 10.1111/gcbb.12809
Iboyi, Joseph E., Mulvaney, Michael J., Leon, Ramon G., Balkcom, Kipling S., Bashyal, Mahesh, Devkota, Pratap & Small, Ian M.. (2023) Double-cropping effects of Brassica carinata and summer crops: I. Effects of summer cropping history on carinata production. Industrial Crops and Products, 194. https://doi.org/10.1016/j.indcrop.2023.116364
Kumar S., Seepaul R., Mulvaney M.J., Colvin B., George S., Marois J.J., Bennett R., Leon R., Wright D.L., Small I.M. (2020). Brassica carinata genotypes demonstrate potential as a winter biofuel crop in South East United States. (2020) Industrial Crops and Products, 150, art. no. 112353. DOI: 10.1016/j.indcrop.2020.112353
Licata M., Farruggia D., Sgroi F., Salamone F., Leto C., Di Miceli G. (2024). A comparative study to assess the production of two oilseed crops (Brassica carinata A. Braun and Carthamus tinctorius L.) and the energy potential of their agricultural biomass residues (2024) Heliyon, 10 (22), art. no. e38654. DOI: 10.1016/j.heliyon.2024.e38654
Seepaul R., Kumar S., Boote K.J., Small I.M., George S., Wright D.L. (2021). Physiological analysis of growth and development of winter carinata (Brassica carinata A. Braun) (2021) GCB Bioenergy, 13 (7), pp. 1112 - 1133. DOI: 10.1111/gcbb.12831
Seepaul, R., Mulvaney, Michael J., Small, Ian M., George, Sheeja & Wright, David L.. (2020). Carinata growth, yield, and chemical composition responses to nitrogen fertilizer management. Agronomy Journal, 112 (6): 5249-5263. https://doi.org/10.1002/agj2.20416
Stiles, S., J. G. Lundgren, C. B. Fenster, and H. Nottebrock. (2021). Maximizing ecosystem services to the oil crop Brassica carinata through landscape heterogeneity and arthropod diversity. Ecosphere 12(7):e03624. 10.1002/ecs2.3624
Tiwari, R., Reinhardt Piskáčková, T.A., Devkota, P., Mulvaney, M.J., Ferrell, J.A. and Leon, R.G. (2021). Growing winter Brassica carinata as part of a diversified crop rotation for integrated weed management. GCB Bioenergy, 13: 425-435. https://doi.org/10.1111/gcbb.12799

Safflower (Carthamus tinctorius L., family Asteraceae)

Description of the crop: Safflower, member of the family Compositae or Asteraceae, is a branching thistle-like herbaceous annual (spring or winter) annual plant, with numerous spines on leaves and bracts. It reaches a plant height of 150 cm. The crop, after germination, has a slow-growing rosette stage in which is being produced: a) numerous leaves near ground level (Figure A.29) and b) strong taproots develop that penetrate deep into the soil. After the stem elongation 3 to 5 branches are being developed; when the crop is being grown at high densities. Each branch ends to a globular flower capitulum, enclosed by clasping bracts, which are typically spiny. The flowering starts with the main branch and continues with the rest. Flowering initiates (Figure A.29) when the day length is long; end of July for Europe. The total bloom stage may last for 4 weeks or more, greatly influenced by growing environment. Each head contains 15 to 20 seeds [1]. The growing period is 110 to 150 days. The weight of 1000 g is 40 to 50 g [1].

Figure A.29 View of safflower from emergence to the harvesting time (source: CRES).

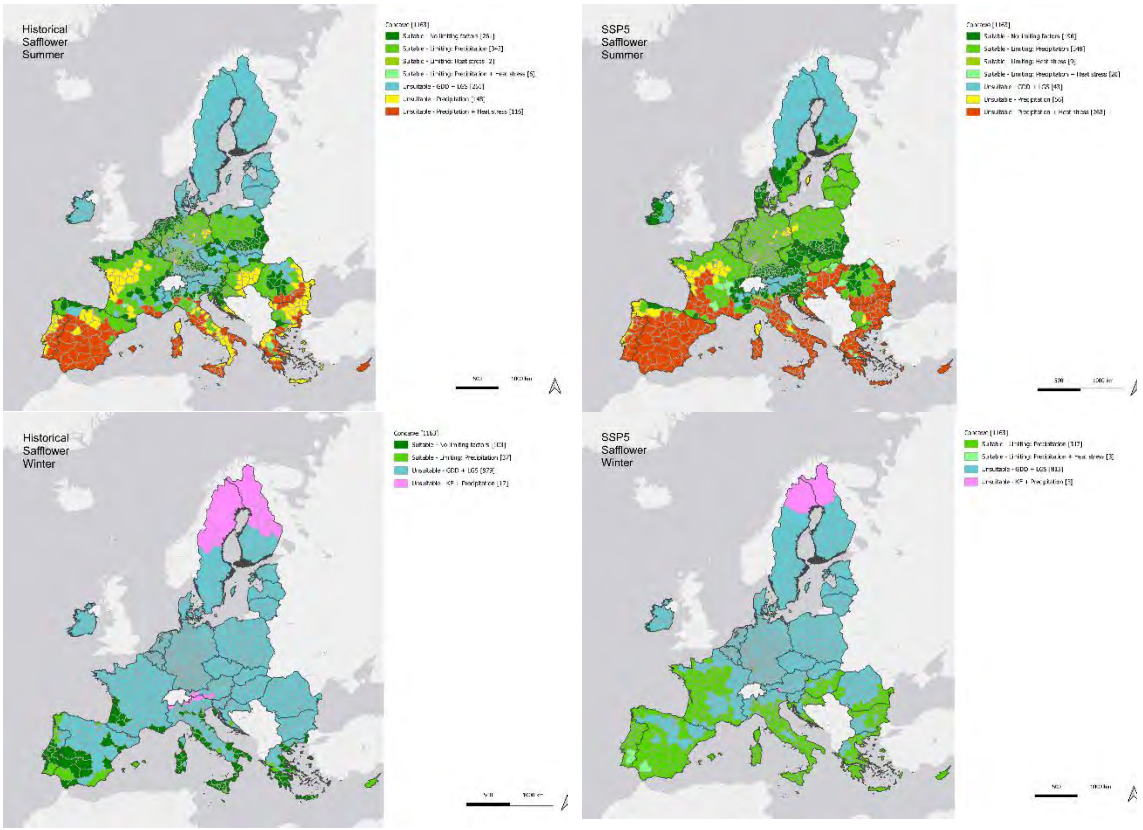
Origin and area of its cultivation: Safflower is native to the Old World, and the genus occurs naturally in the Mediterranean region, North-eastern Africa, and Southwestern Asia to India. It can be cultivated at latitudes between 20ºS and 40ºN which means that it can be cultivated in the entire Europe [2]. Nowadays, it is cultivated for local use as oilseed or as food colorant (substitute of saffron). Although half of the safflower production is from India only small quantities are exported. Safflower is being also cultivated in the USA, Canada [2]. The majority of the crop production is in Australia, Argentina and Mexico and is exported to Japan and Europe. In China, it is mainly produced for its flowers. In Europe, safflower has been included in several research projects such as IENICA, Crops2Industry, Eurobioref and MAGIC project. In Eurobioref, safflower it had been compared with other oilseed crops namely cuphea, lunaria, lesquerella, sunflower, rapeseed and castor. Currently, safflower is being studied as a promising industrial crop for marginal lands [MIDAS (www.midas-bioeconomy.eu)] and contaminated and saline ones [IASIS project (www.iasis-soil.eu)].

Climate preferences: This crop does best in areas with warm temperatures (6-28 ºC) and sunny, dry conditions during the flowering and seed-filling periods. The crop has a deep taproot that can penetrate to soil depths of 2-3 m; thus, it can draw moisture and nutrients from a considerable depth and the crop can be grown on areas with low available moisture on the top soil. Still the crop needs a bit more precipitation then Camelina or Ethiopian Mustard. During the rosette stage, the young plants can survive low temperatures (-7 ºC) but during elongation period the plant is sensitive to cold [3]. Like for all other plants, heat stress can lead to a significant reduction in yield when it occurs in the last growth phase when the seeds are ripening [4].

Table A.8 Overview of climate suitability factors determining suitability for Safflower grown as summer crop.

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 ºC in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Spring crop	120	1750	5 °C	< -10 °C	YES	>200 mm	>1000 mm

Figure A.30 Climate suitability for Safflower grown as a summer crop (left maps) and as a winter (cover) crop (right maps). Top maps refer to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).



Soil preference: The crop is well adapted to semiarid regions. It grows best in deep, fertile, well-drained soils that have a high water-holding capacity. It can be grown successfully on coarse-textured soils with low water-holding capacity when adequate rainfall or moisture distribution is available. Soils that crust easily can prevent good stand establishment. It cannot survive on soils with standing water even for few hours when the air temperature is above 20 ºC. Safflower has almost the same moderate salt tolerance with barley up to ~11.2 dS/m [5]. It accumulates heavy metals: Cd, Pb, Ni, Zn and has low tolerance to Zn. During the emergence and the early stages of growth the crop has less salt tolerance. High levels of soil salinity can decrease the frequency of seed germination and lower seed yield and oil content [6].

Soil preparation and sowing: Seeding rates for optimum production vary from around 10-15 kg/ha in very drought-prone regions or those where branching is to be encouraged, up to 40-45 kg/ha or higher for irrigated environments, and in regions with varieties showing minimal branching. Germination of safflower seed occurs at temperatures as low as 2-5 ºC. At the early stages of growth, the crop is not a good weeds competitor [7].

Figure A.31 View of safflower (29/5/25)-75 days from sowing in south west Greece for MIDAS project (source: CRES).

Water and fertilization needs: In general, if moisture is limiting, one well-timed irrigation prior to bloom can substantially increases the yield [7]. Safflower is a long-season crop with a deep taproot that can draw moisture from deep in the subsoil. Thus, it can access and utilize nutrients from below the root zone of cereal crops. Nevertheless, fertilizers tend to increase yields and oil levels, especially in irrigated or higher rainfall areas. Furthermore, in areas affected by dryland salinity, safflower uses surplus water from recharge areas, drawing down the moisture with the salts dissolved in it, preventing expansion of saline seeps.

The following fertilization plan is recommended: N - 40 to 80 kg/ha (in two doses; 50% at sowing and 50% at stems elongation), P - 30 to 60 kg/ha (at sowing), N - 30 to 50 kg/ha (only when needed, there are soils that having high levels of K), S - 1 to 2 kg/ha.

Varieties: Safflower varieties are classified into two types; those having high percentage in oleic acid (74-80%) and those with high percentage in linoleic acid (70 to 80%) [8]. The high oleic varieties are used as a source of heat-stable cooking oil to fry food, chips and other snack items and are also used in cosmetics, food coatings, and infant food formulations. The high linoleic varieties are used primarily for edible oil products such as salad oils and soft margarines, but are even used for painting in the place of linseed oil, particularly with white, as it does not have the yellow tint which linseed oil possesses. Currently, there is a growing interest for high-oleic varieties for biobased applications and biofuels.

Seed Yields: The seed yields varied from 1.7 to 2.7 t/ha in experiments conducted in Italy. The oil content of the seeds is between 34% and 36%. This would imply an oil yield ranging from 0.6 to 1.0 tonnes oil/ha. A literature review in which 8

references were identified reporting seed yields in field trials showed yields ranging between 0.34-3.7 tonnes seeds/ha (Figure A.33).

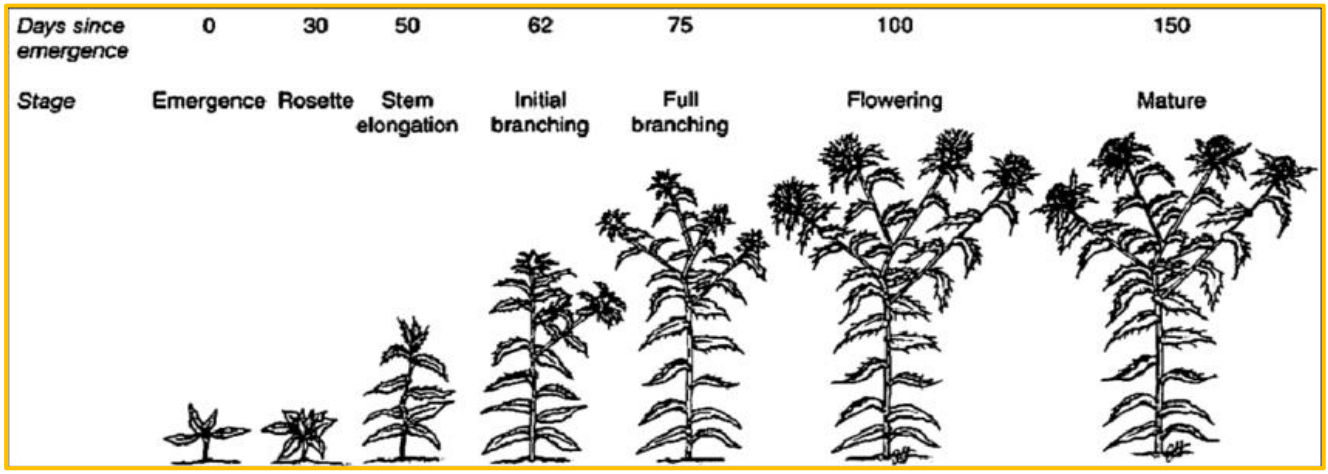
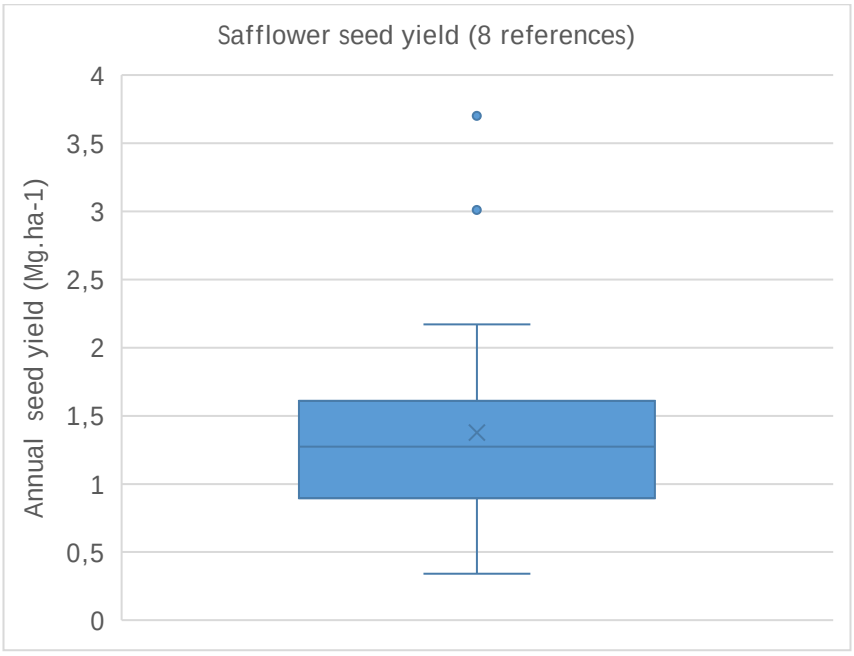


Figure A.32 Growing stages of safflower (OECD,2020).

Figure A.33 Published seed yield levels in safflower, based on 8 references (see literature list at the end of this factsheet).



Safflower seeds contain 92-93% unsaturated fatty acids, making the oil a high-quality edible oil source. The protein content of the seed meal is approximately 24%, with a relatively high fibre fraction. When grown on marginal lands, reported seed yields can reach 1.8 t/ha, as observed in northern Italy [9].

Diseases and insects: When the rainfalls are above the normal and in prolonged period with high humidity, serious diseases have been recorded such as Alternaria (Alternaria carthanti) leaf spot and bacterial blight (Pseudomonas syringae) [10]. Alternaria leaf spot has symptoms of large, brown irregular spots on leaves and

flower bracts. Varieties vary in the degree of resistance they have to leaf spot, and severe losses may occur [10]. Bacterial blight has symptoms similar to those of Alternaria leaf spot that usually appear during periods of heavy rainfall. Diseases' problems could be reduced when following a four-year crop rotation in order to separate safflower with other oilseed crops (safflower, sunflower, canola, mustard, dry bean, soybean) with similar diseases [10].

Harvesting time and options for use as intermediate crop: In south Europe, the crop can grow as spring crop. The final harvest should be done in summer (from early to mid-July to mid-August), thus its use is not viable contrary to camelina and crambe that can really be used as intermediate crops because they can be established as soon as the main crop is harvested. Because of this Safflower is not easily included in existing rotation schemes but it is a great choice for marginal lands.

Harvesting and storage: Safflower is ready for harvest when most leaves turn brown and only a small amount of green remains on the bracts of the latest flowering heads. Stems should be dry but not brittle, and seeds should be white and easily threshed by hand [11]. The crop should be harvested as soon as it reaches maturity to avoid seed discoloration or sprouting in the head, which can occur with late-season rains [11]. Safflower is an excellent crop for direct combining since it stands well and does not shatter easily. Direct combining may require artificial drying or waiting until green weeds are killed by frosts. The crop can be windrowed to dry green weeds when moisture content of seed is as high as 25%. The time for harvesting safflower in Europe can vary from early to late September due to the environmental conditions during the growing season [12]. Quality safflower seed should have a white seed coat, and no sprouting. Safflower seed has recently been purchased on a clean basis with a desired oil content of 34 to 36% and the moisture content should not be higher than 8% for safe long-term storage [11].

Figure A.34 Safflower harvesting in California.

Uses: Traditionally, safflower has been cultivated for its seeds and used to flavour foods and colour textiles [11]. Red and yellow dyes were prepared from safflower. Extracts of the plant were also used to make medicines. More recently, in the last 50 years, safflower seed vegetable oil has been extracted on a commercial basis from the harvested seeds of the plant. The safflower seed oil is colourless and flavourless and similar in nutritional composition to the sunflower oil. It is used for cooking, salad dressing, margarine preparation, as well as in cosmetics. Two main varieties of safflower exist and they produce different kinds of oil. One variety produces oil that is high in monounsaturated fatty acid (oleic acid). This oil is primarily used in cooking. The other variety of safflower is high in polyunsaturated fatty acid (linoleic acid) and is mainly used in paintings. Another lesser-known use of the plant is the use of safflower seeds in cooking as a less expensive substitute for saffron. The orange-red pigment Carthamin extracted from dried safflower flowers is used as a source of natural dye to colour textiles.

As industrial oil, it is considered drying or semidrying oil that is used in manufacturing paints and other surface coatings [13]. The oil is light in colour and will not yellow with ageing; hence it is used in white and light-colour paints. This

oil can also be used as a diesel fuel substitute. The meal that remains after oil extraction is used as a protein supplement for livestock. The meal usually contains about 24% protein and much fiber. Decorticated meal (most of hulls removed) has about 40% protein with a reduced fiber content. Foots are used to manufacture soap. The birdseed industry buys a small portion of the produced seeds. Sheep and cattle can graze succulent safflower and stubble fields after harvest.

Environmental impacts:

Environmental aspects	Color score	Explanation
1a) Soil structure		Safflower intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting.
1b) Soil organic carbon		Safflower serves as a cover crop which protects the soil against erosion. It has large and deep roots and a good soil coverage [1], [2].
1c) Soil biodiversity		Pesticide and herbicide application is required because safflower is sensitive to certain pests for which pesticides and herbicides are needed [10].
2a) Risk for leaching to ground and surface water		Safflower as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. Nitrogen and other nutrient requirements are very low compared to other oil crops [5], [7].
2b) Risk for loss from spraying pesticides, herbicides		Safflower usually when is grown at the right plant density can avoid the herbicides applications and in the majority of the cases the problems with diseases is small and thus pesticides application can be avoided [10].
3) Water quantity		Compared to other oilseed crops, like rapeseed, safflower shows better performance in semi-arid regions due to its drought tolerance (it can be grown in areas with rainfalls 200 mm) [5] [9].
4a) Habitat quality		Nutrient input requirements are very low in safflower as compared to a conventional crop like wheat. But applying some pesticides is needed because it is disease sensitive. As a cover crop safflower also prevents leaching of nutrients in winter [5] [7].
4b) Species viability contribution		High provision of food to pollinators in periods in spring when it flowers [1]. When used as an intermediate crop, it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Safflower is not invasive. Safflower is native to the Old World, and the genus occurs naturally in the Mediterranean region.

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: Safflower is best grown in south Europe and up to 400N. In central Europe, it can be grown as spring/winter crop. The availability remains a problem for the further deployment of the crop. The industry is looking for high-oleic varieties that are quite limited.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

 = TRL >7, industrial production already available at commercial scale

 = 5<=TRL=>7, production available at demo scale

 = 3<TRL>5, from research to production development

 = TRL<=3, only basic research data available

References for the factsheet

[1] Bergman, J, Kandel, H. (2019). Safflower production. NDSU extension. https://www.ndsu.edu/agriculture/sites/default/files/2021-05/a870.pdf

[2] Sehgal, D., Raina, S.N. (2011). Carthamus. In: Kole, C. (eds) Wild Crop Relatives: Genomic and Breeding Resources. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-14871-2_4

[3] Emongor, V. 2010. Safflower (*Carthamus tinctorius* L.) the Underutilized and Neglected Crop: A Review. *Asian Journal of Plant Sciences, 9: 299-306.* DOI: 10.3923/ajps.2010.299.306
URL: https://scialert.net/abstract/?doi=ajps.2010.299.306

[4] Rahnama, A., Salehi, F., Meskarbashee, M. et al. High temperature perturbs physicochemical parameters and fatty acids composition of safflower (Carthamus tinctorius L.). BMC Plant Biol 24, 1080 (2024). https://doi.org/10.1186/s12870-024-05781-3,

[5] Hussain, M.I., Lyra, DA., Farooq, M. et al. Salt and drought stresses in safflower: a review. Agron. Sustain. Dev. 36, 4 (2016). https://doi.org/10.1007/s13593-015-0344-8.

Up to ~11.2 mmhos/cm (≈ dS/m) (Francois, Yermanos & Bernstein (California Agriculture, 1964).

[6] Hadjadj, S., Mahdjoubi, S., Hidoub,Y., Bahaz,T., Ghedamsi, Z., Regagda,S., Arfa, Y., Ould El Hadj-Khelil, A (2023). Comparative effects of NaCl and Na2SO4 on germination and early seedling stages of the halophyte Carthamus tinctorius L.,

Journal of Applied Research on Medicinal and Aromatic Plants, Volume 35, 100463, ISSN 2214-7861, https://doi.org/10.1016/j.jarmap.2023.100463.

[7] GRDC (2017). Growthnotes. Safflower. Section 3 Planting. Northern 2017. https://grdc.com.au/__data/assets/pdf_file/0031/370579/GrowNote-Safflower-North-03-Planting.pdf

[8] Hamdan, Y.A.S., Pérez-Vich, B., Velasco, L. et al. (2009) Inheritance of high oleic acid content in safflower. Euphytica 168, 61-69. https://doi.org/10.1007/s10681-008-9879-y

[9] Zanetti, F. et al., 2022. Safflower (Carthamus tinctorius L.) a winter multipurpose oilseed crop for the Mediterranean region: Lesson learnt from on-farm trials. Industrial Crops and Products, Volume 184.

[10] Nyvall, R.F. (1989). Diseases of Safflower. In: Field Crop Diseases Handbook. Springer, Boston, MA. https://doi.org/10.1007/978-1-4757-5221-2_16

[11] E. A. Oelke, E. S. Oplinger, T. M. Teynor, D. H. Putnam, J. D. Doll, and K. A. Kelling, B. R. Durgan, and D. M. Noetzel (2026). Safflower. Corn Agronomy. https://corn.agronomy.wisc.edu/Crops/Safflower.aspx

[12] Abou Chehade, L., Angelini, L. G., & Tavarini, S. (2022). Genotype and Seasonal Variation Affect Yield and Oil Quality of Safflower (*Carthamus tinctorius* L.) under Mediterranean Conditions. *Agronomy*, *12*(1), 122. https://doi.org/10.3390/agronomy12010122

[13] Rheineck, A.E., Cummings, L.O. Safflower oil utilization in surface coatings. J Am Oil Chem Soc 43, 409-412 (1966). https://doi.org/10.1007/BF02646801

References yield data Figure A.32

Budak, İ., Serim, A. T., & Asav, Ü. (2020). Determination of The Efficacy of Some Herbicides on the Weeds in Safflower. Plant Protection Bulletin, 60(3), 81-87. https://doi.org/10.16955/bitkorb.708869

da Silva, R.A.D., da Silva Filho, E.M., Costa, M., Gracindo, Â.P.A.C., de Aquino Pessoa, P.M., Gondim, A.D., Rafael Medeiros, L. and Lichston, J.E. (2021), Oil Quality and Yield of Different Carthamus tinctorius Cultivars: Promising Oilseeds for Biodiesel in Semi-Arid Regions. J Am Oil Chem Soc, 98: 241-251. https://doi.org/10.1002/aocs.12471

Hajghani, M., Ghalavand, A. and Modarres Sanavy, S. A. M. (2017). Evaluation of Yield, Yield Components and Growth Indices of Safflower (Carthamus tinctorius L.) in Conventional and Organic Farming Systems. Journal Of Agroecology, 9(1), 15-30. doi: 10.22067/jag.v9i1.31520

Koç H. (2025). The effects of seasonal climate change on the safflower genotypes productivity under Central Anatolian conditions. J Am Oil Chem Soc. 2025; 102(2): 295-304. https://doi.org/10.1002/aocs.12886

Licata M., Farruggia D., Sgroi F., Salamone F., Leto C., Di Miceli G. (2024). A comparative study to assess the production of two oilseed crops (Brassica carinata A. Braun and Carthamus tinctorius L.) and the energy potential of their agricultural biomass residues (2024) Heliyon, 10 (22), art. no. e38654. DOI: 10.1016/j.heliyon.2024.e38654

Mosupiemang, M. ., Emongor, V. E., Malambane, G., & Mapitse, R. (2023). Growth, development and yield of safflower genotypes in response to environmental variations. Journal of Phytology, 15, 145-154. https://doi.org/10.25081/jp.2023.v15.8255

Rosseto R.E., Santos R.F., Gurgacz F., Johann J.A., Kaiser F., Bassegio D., Chang P., Maziero C., da Cruz Balena F.L., Lewandoski C.F., de Lima Bueno P. (2023). Sowing depth and loads on press wheels in emergence, growth, and yield of safflower (2023) Australian Journal of Crop Science, 17 (8), pp. 608 - 613, Cited 0 times. DOI: 10.21475/ajcs.23.17.08.p2830.

Shyurova N.A., Dubrovin V.V., Narushev V.B., Kozhevnikov A.A., Milovanov I.V. (2020). Biofuel as an alternative energy source for the automobile industry: The experience of the lower Volga region (Russia). (2020) Journal of Ecological Engineering, 21 (6), pp. 29 - 35. DOI: 10.12911/22998993/123164

CASTOR (Ricinus communis L., family Euphorbiaceae)

Description of the crop: Castor is a valuable oilseed crop that can be either annual or perennial (small tree). The crop varies greatly in its growth (80 cm to 3 m high) and appearance (shape, colour). It can be found in many sites worldwide as native species. The annual growing cycle depends on the cultivation site and can be up to 180 days when it is grown in India and between 120 and 150 days in the Mediterranean region. It has glossy leaves 15-45 cm long, usually palmate, with five to twelve deep lobes with coarsely toothed segments. The colour of the leaves and of the whole plant can vary from red to green. The panicles are racemes, which erect up to 40 cm long, have male flowers towards the base, and female ones towards the top [1]. It is a cross-pollinated crop that under natural conditions can exceed 80% of the cross-pollination, but the actual level of cross pollination depends on genotypes and environmental conditions [2]. The flowers have 3-5 sepals and no petals. Each raceme has many capsules (80-120 per raceme), each one containing three seeds. The weight of 1000 seeds vary from 100 to 150 g. The crop from emergence to seed maturity is presented in Figure A.35.

Origin and research in Europe: Ethiopia is considered to be the most possible site of origin due to the presence of high diversity of castor [3]. Castor is indigenous to the south-eastern Mediterranean Basin, Eastern Africa, and India, but is widespread throughout tropical and subtropical regions as ornamental crop [3]. Castor is being reported as a crop with tolerance to insects and diseases, nematodes, drought and heat, high and low pH, poor soil and slope [4]. It is commercially grown in India, China, and Brazil. Currently, more than 3 million hectares of land are planted with castor around the world [5]. In 2015, the global castor oil seed production was 1.8 million tonnes and the main producer was India with 1.55 million tonnes. Although the crop can be cultivated in the Mediterranean region, it is found only on experimental and demonstrative fields. It should be pointed out that Europe is one of the main importers of castor oil. It has been studied in a few EU research projects, the most recent being EUROBIOREF, where it had been compared with other oilseed crops (cuphea, lesquerella, lunaria, safflower, sunflower and rapeseed). Currently, castor bean is being studied as a promising industrial crop for

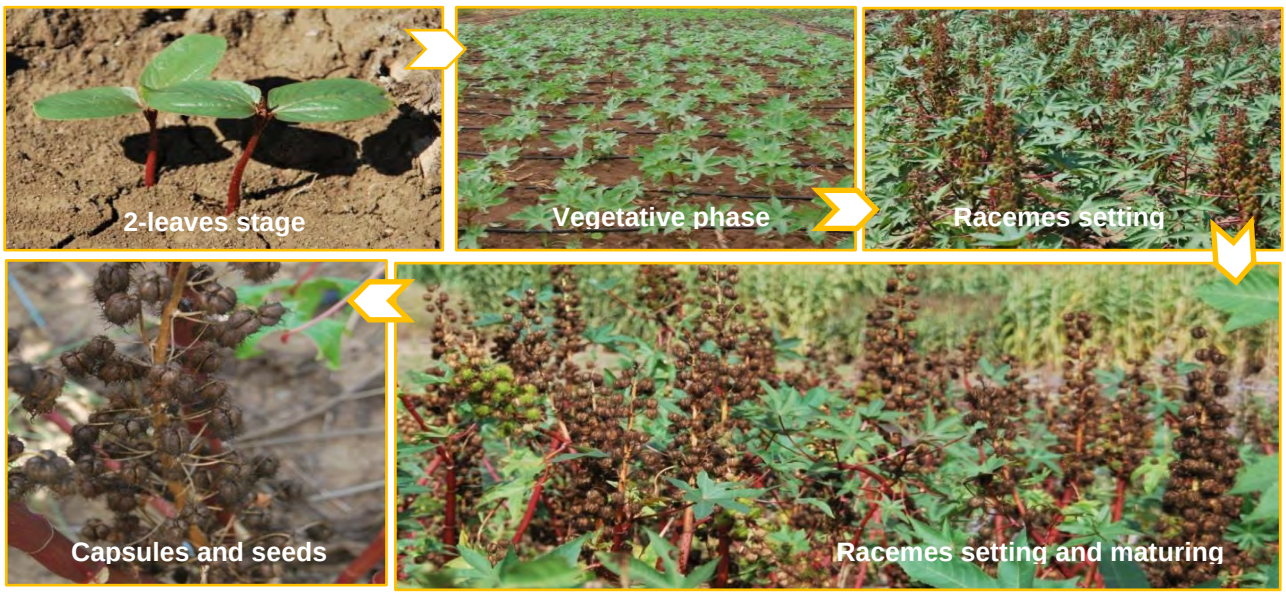


Figure A.35 View of castor at several stages of growth (source: CRES; Greece).

marginal lands [MIDAS (www.midas-bioeconomy.eu)], where the whole production chain is being studied.

Climate preferences: The crop can be grown under low rainfall and fertility conditions and it is considered appropriate for dry-land farming [6]. In India, the crop is being grown without irrigation. Castor is a hardy crop and can be grown in a wide range of climates of warm regions with a rainfall of 250-750 mm [6], [7]. It performs best in moderate temperature (20-26 ºC) with low relative humidity and clear sunny days throughout the crop season. Areas with temperature higher than 40 ºC or lower than 15 ºC are not conducive for castor cultivation [6]. A frost-free climate is mandatory for the crop. It is a drought resistant crop due to its tap root and due to light reflecting characteristics of its stems and leaves that reduce heat load and improve survival under moisture stress [7]. At flowering and capsule formation stages, high rainfalls have negative effects since they help the appearance of botrytis disease.

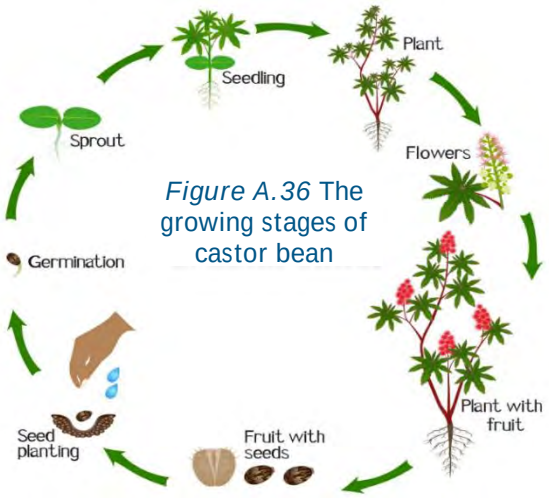
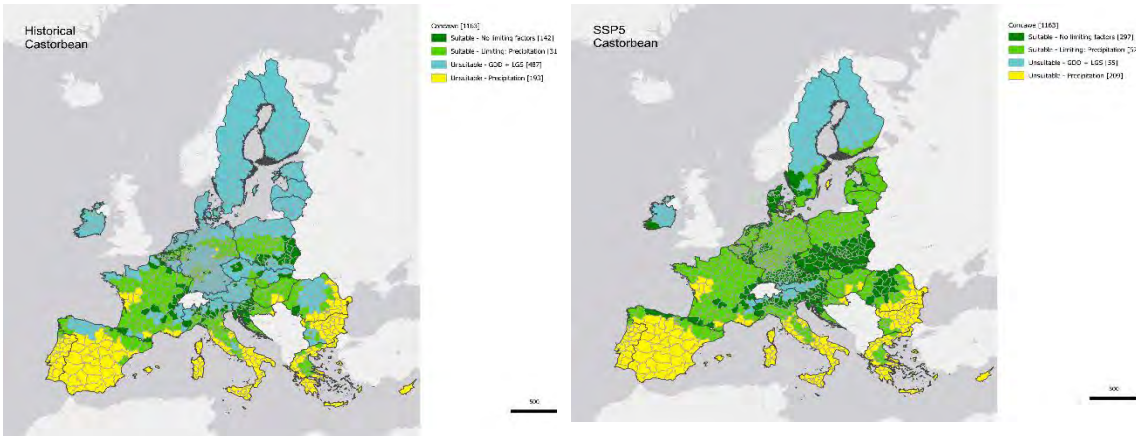


Figure A.36 The growing stages of castor bean

Table A.9 Overview of climate suitability factors determining suitability for Castor grown as summer crop.

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32*C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	130	1200	8 °C	< 0 °C	NO	>=250 mm	-

Figure A.37. Climate suitability for Castor. Left map refers to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario (elaborated in this study, see chapter 4).



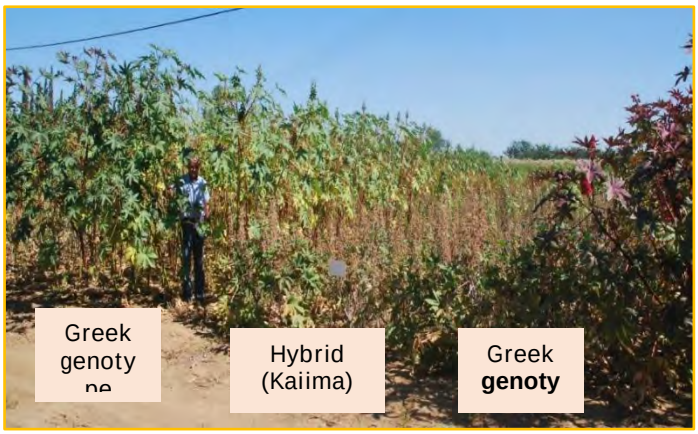


Figure A.38 Comparison between two local Greek genotypes (one green and one red) and a short high yielding hybrid (Source: CRES).

Soil preference: The crop can be grown successfully on most of the soils apart from heavy clay and poorly drained soils [8]. Moreover, soils with low water holding capacity like the sandy soils are also not appropriate for castor cultivation. Soils with pH > 9.0 or < 4.0 should be avoided [8], [9]. Moderately fertile soils are preferred as high fertility induces excess vegetative growth, prolonged flowering and delay the maturity, leading finally to poor yields.

Soil preparation and sowing: A deep ploughing is necessary, for weed control and conserving moisture followed by harrowing. The appropriate plant density strongly depends on the cultivated genotype (high, short) growth habit and plant architecture [8]. It has been recommended to sow in rows with 1 m distance between the rows and 25 cm within the rows; 15 kg seeds/ha for sowing. In general, the distances between the rows should be large varying from 60 to 100 cm, while within the rows should be between 15 and 60 cm (12-15 kg seeds per ha) [8]. Castor has an initial slow growth rate that increases after a month from sowing. The soil depth at sowing varies according to the soil type from 6 to 10 cm. Shallow soil depth at sowing (6 to 8 cm) is recommended in heavy soils. The soil temperature at sowing should be higher than 12 ^{0}C [8].

Water and fertilization needs: Although castor tolerates moisture stress, it responds positively when it is grown under irrigation [9]. The crop performance is poor when the crop experiences moisture stress from seedling to flowering stages and during this critical period 2-3 irrigations are needed. When the water is limited, it should be irrigated once in the beginning of the flowering phase. During the maturity phase irrigation should be avoided since it prolongs the vegetative phase and results in delayed maturity of the seeds. In the Mediterranean region, the water needed (included rainfalls) during the growing period is around to 400 mm.

Castor exhausts the soil quickly. It has been estimated that for the production of 2000 kg seeds/ha and the following are removed from the soil: 80 kg/ha N, 18 kg/ha P_2O_5, 32 kg/ha of K_2O, 13 kg/ha CaO, and 10 kg/ha of MgO [10]. In India, it is rotated with ragi, groundnuts, cotton, dryland chili pepper, tobacco or horse gram [11].

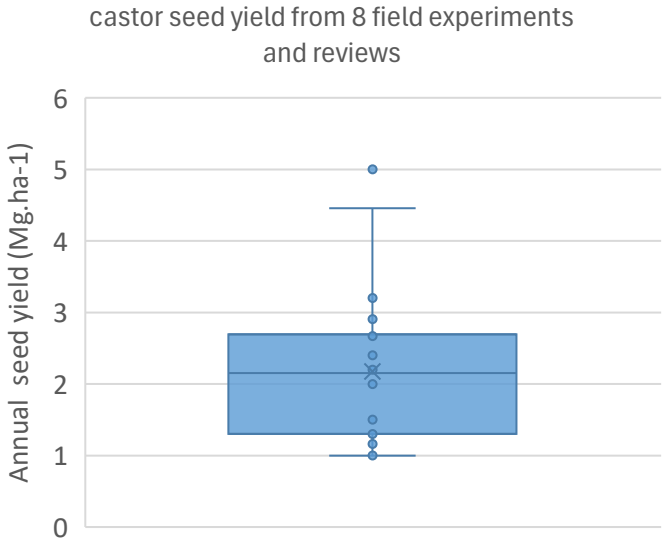
With the field trial experiences derived in projects like MAGIC and MIDAS, the general requirements for fertilization are as follows: P - 60 to 120 kg/ha (in two to three doses, 50% at the sowing), P & N 30 to 60 kg/ha. N should be applied in two doses with the 1st to be at the sowing (50%) and the second around 30 days from emergence.

Varieties: Several varieties and hybrids are available worldwide that differ greatly in terms of plant architecture and growth habit. Nowadays, the research has been focused on developing short annual varieties and/or hybrids with increased seed yields, uniform seed maturity, increased tolerance to pests and diseases and increased performance to mechanical harvest. The last years, a number of hybrids have been tested in the Mediterranean region (developed in Israel by KAIIMA company) with very good seed yields that in some cases reached around 5 t seeds

per ha. In this research work, the local genotypes (Figure A.38) although developed higher plants, their seed yields were lower and the seeds had uniform maturity.

Seed Yields: Seed yields vary according to the cultivated variety/hybrid and the cultivation site. Generally, seed yields 2-5 t/ha are being reported (see Figure A.39). The oil content of the seeds is quite high (50% or even higher). In MAGIC project, a large number of castor bean hybrids had been tested on marginal lands and yields of 2 t_{seeds}/ha were confirmed [12].

Figure A.39 Published seed yield levels in castor, based on 8 references (see literature list at the end of the factsheet).



Diseases and insects: Castor is affected by several diseases; however, only a few are regarded to be of economic importance and thus it is considered as a crop with tolerance to most diseases. The three major diseases affecting castor are: gray mold (*Botryotinia ricini* G.H. Godfrey or *Amphobotrys ricini* N.F. Buchw. in its anamorphic), vascular wilt (*Fusarium oxysporum f.*sp. *ricini* Nanda and Prasad), and charcoal rot (*Macrophomina phaseolina* [Tassi] Goid.) [8]. Gray mold is one of the most serious castor diseases worldwide and can be found in racemes when the moisture content is increased (rainfalls) at the flowering phase [8]. The castor seedlings are susceptible to vascular wilt when cultivated in wet soils [12].

Harvesting time and options for use as intermediate crop: Castor bean should be grown as summer crop. As summer crop the irrigation is mandatory for the Med region. It can grow after a winter crop that should be harvested by the end of May. The growing cycle is from May till the beginning to end of September.

Figure A.40 Castor harvesting.

Harvesting and storage: In South Europe, a period of 120 -150 days is needed for the crop to reach maturity (first half of September). The harvesting should be done when the capsules turn to yellow-brown. The seeds do not mature at the same time (Figure A.40) and in most of the cases the plantations should be sprayed in order the growth to be stopped and the harvesting to be scheduled.

Castor seeds are very susceptible to cracking and splitting at the maturity stage. Thus, adjustment to the combine cylinder speed and cylinder-concave clearance is very important. Usually, a low cylinder speed and wide cylinder concave clearance are recommended. Combine operators should frequently inspect harvested beans for breakage. At the harvest seed losses up to 30% have been recorded.

Uses: The oil content of castor seeds is around 48%. The importance of castor oil arises from its richness (85%) in ricinolic acid (12-hydroxy 9-octadecenoic acid). Castor oil has numerous chemical and medicinal applications and in the international market finds application in more than 700 uses. Castor oil is mainly used for lubricants, but also for polymers such as polyurethanes. It has a history of more than 50 years in the production of Polyamide-11, also known as Rilsan-11. More recently, castor oil gained interest for the production of sebacic acid (a 10 carbon atoms linear diacid), which can be used as a monomer or to produce solvents. Europe is the main world user of castor oil, presently the only commercial source of hydroxy fatty acids (HFA), consuming almost a quarter (150,000 tonnes per year) of the entire world production. The castor meal has high protein content of 34-36% [13], which could be high protein source for animal feeding. Castor meal has not yet used as protein supplement because it contains several toxic compounds.

Environmental impacts:

Environmental aspects	Color score	Explanation
1a) Soil structure		Castor intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting [8], [9].
1b) Soil organic carbon		Castor provides some soil cover which may give some protection against erosion. However, plant density is relatively low.
1c) Soil biodiversity		Some pesticides and herbicides are needed [9], [12].
2a) Risk for leaching to ground and surface water		Castor is not providing a very dense coverage against soil erosion. Furthermore, nutrient inputs are very high which will go together with losses [10], [11].

2b) Risk for loss from spraying pesticides, herbicides		See 1c
3) Water quantity		Compared to other spring crops grown in Med region (cotton, corn), castor bean requires less water, but irrigation cannot be avoided in critical growth phases. It requires 400 mm (including rainfalls) [6], [7].
4a) Habitat quality		Requires relatively high nutrient inputs and moderate pesticides and herbicides inputs.
4b) Species viability contribution		Castor is not providing very attractive flowers to insects and does not provide attractive shelter options [14]; while insects (including bees) may visit castor blooms, wind remains the main pollination mechanism and the plant is not highly attractive to bees in the way true bee-forage crops are [14]. When used as an intermediate crop it may contribute to crop diversity and structural landscape diversity.
4c) Invasive species		Castor bean is invasive. Castor bean genotypes can be found in all med countries as shrubs, especially in riparian areas where it displaces native vegetation. It is therefore included in the IUCN/ISSG global Invasive Species Database [15] and the CABI Invasive Species Compendium [16].

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: Castor bean is grown well in south Europe, where the crop can be found with local genotypes, and in certain areas in central Europe (depending on the temperatures during the summer). There are improved hybrids developed by Kaiima company with short cycle and high yields. The mechanical harvesting of the crop is not yet well organised and this affects the whole production chain of castor bean. There is a growing interesting of castor bean as low ILUC feedstock.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		

= TRL >7, industrial production already available at commercial scale

= 5<=TRL=>7, production available at demo scale

= 3<TRL>5, from research to production development

= TRL<=3, only basic research data available

References for the factsheet

[1] Sims, J., and R.J. Frey. 2005. Castor oil. In J. Longe, The Gale Encyclopedia of Alternative Medicine. Farmington Hills, Mich: Thomson/Gale. ISBN 0787693960.

[2] Filho, A.S. 2005. Melhoramento da mamona. In: A. Borém, editor, Melhoramento de especies cultivadas (In Portuguese.) Universidade Federal de Viçosa, Viçosa. p. 385-407

[3] Anjani, K. 2012. Castor genetic resources: A primary gene pool for exploitation. Ind. Crops Prod. 35:1-14.10.1016/j.indcrop.2011.06.011. doi:10.1016/j.indcrop.2011.06.011

[4] Duke, J.A. 1978. The quest for tolerant germplasm. p. 1-61. In: ASA Special Symposium 32, Crop tolerance to suboptimal land conditions. Am. Soc. Agron. Madison, WI.

[5] World Oil World, www.castoroilworld.com Accessed on 2/9/2021.

[6] Duke, J.A. 1978. The quest for tolerant germplasm. p. 1-61. In: ASA Special Symposium 32, Crop tolerance to suboptimal land conditions. Am. Soc. Agron. Madison, WI.

[7] Lima, J.R.S., Antonino, A.C.D., Lira, C.A.B.O., Souza, E.S., Silva, I.F., 2011. Energy balance and evapotranspiration cowpea under rainfed conditions. Revista Ciência, Agronômica 42, 65-74

[8] Severino, L.S., Auld, D. L., Baldanzi, M., Cândido, M. J. D., Chen, G., Crosby, W., Tan D., He X., Lakshmamma, P., Lavanya, C., Machado, O. L. T., Mielke, T., Milani, M., Miller, T.D., Morris, J. B., Morse, S. A., Navas, A. A., Soares, D.J., Sofiatti, V., Wang, M. L., Zanotto, M. D., Zieler, H. 2012. A Review on the Challenges for Increased Production of Castor. Agronomy Journal, Vol. 104, Issue 4, 853-880.

[9] Duke 1993, Handbook on energy crops, https://www.hort.purdue.edu/newcrop/duke_energy/Ricinus_communis.html

[10] Koutroubas, S.D., Papakosta, D.K., Doitsinis, A., 2000. Water requirements for castor oil crop (Ricinus communis L.) in a Mediterranean climate. Journal of Agronomy and Crop Science 184, 33-41.

[11] Filho, V.C., and E.S. Freire. 1958. Adubação da mamoneira: Experiências preliminares. Bragantia 17:243-259. doi:10.1590/S0006-87051958000100019

[12] Alexopoulou E., Papatheohari Y, Zanetti F., Tsiotas K., Papamichael I., Christou M., Namatov E., Monti A. Comparative studies on several castor (Ricinus communis L.) hybrids: Growth, yields, seed oil and biomass characterization. Industrial Crops and Products 75 (2015) 8-13. http://dx.doi.org/10.1016/j.indcrop.2015.07.015

[13] Dubois, J. L., Piccirilli, A., Magne, J. b, He, X. 2013. Detoxification of castor meal through reactive seed crushing. Industrial Crops and Products 43, 194-199.

[14] Rizzardo, R. A. G., Milfont, M. O., Silva, E. M. S. d. & Freitas, B. M., 2012. Apis mellifera pollination improves agronomic productivity of anemophilous castor bean (Ricinus communis). An Acad Bras Cienc.

[15] Bakewell-stone, P. (2024). Ricinus communis (castor bean). Data set https://doi.org/10.1079/cabicompendium.4761

[16] https://www.iucngisd.org/gisd/speciesname/Ricinus+communis

References for yield data in Figure A.39

Amjid M., Sajid M., Ibtahaj I., Riaz F., Mudassar M.A., Chughatta A.R., Ibrahim M.U. (2025). Assessment of seed, biodiesel and oil yield of castor bean (Ricinus communis l.) under differential phosphorus doses. Pakistan Journal of Botany, 57 (1), pp. 217 - 224. DOI: 10.30848/PJB2025-1(17)
Aslam, K., Mushtaq, A., Nadeem, F., Ghnia, J. B., Rafique, M., & Sillanpää, M. (2020). Economic feasibility of non-edible oils as biodiesel feedstock: A brief review. International Journal of Chemical and Biochemical Sciences, 18, 145-150.
Cafaro V., Piccitto A.S., Calcagno S., Copani V., Patanè C., Testa G., Cosentino S.L. BREEDING AND SELECTION OF A CASTOR GENOTYPE TO EXPLOIT IN THE MEDITERRANEAN AREA (2024) European Biomass Conference and Exhibition Proceedings, pp. 87 - 91.
Landoni M., Bertagnon G., Ghidoli M., Cassani E., Adani F., Pilu R. (2023). Opportunities and Challenges of Castor Bean (Ricinus communis L.) Genetic Improvement (2023) Agronomy, 13 (8), art. no. 2076. DOI: 10.3390/agronomy13082076.
Monti et al., 2022. D4.5. - Report on "Comparative studies on selected industrial crops grown on large scale fields on marginal land". D4.5 of the EU-MAGIC project.
Rahbari A., Sinaki J.M., Damavandi A., Rezvan S. (2021). Castor bean (Ricinus communis L.) responses to drought stress and foliar application of Zn-nano fertilizer and humic acid: grain yield, oilcontent, antioxidant activity, and photosynthetic pigments (2021). Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 49 (4), art. no. 12003. DOI: 10.15835/nbha49412003 https://www.notulaebotanicae.ro/index.php/nbha/article/view/12003/9263
Rosales-Serna, R., Arellano-Arciniega, Sergio; Nava-Berumen, Cynthia Adriana; Jimenez-Ocampo, Rafael; Santana-Espinoza, Saul; Borja-Bravo, Mercedes; Ortiz-Sanchez, Ixchel Abby; Martinez-Reyes, Ernesto (2023). Productivity and quality of the grain of castor bean cultivated in the Central-North Mexico. [Spanish]. Ecosistemas y Recursos Agropecuarios. 2023. 10(2). 29 ref. https://www.scielo.org.mx/pdf/era/v10n2/2007-901X-era-10-02-e3223.pdf
Scordia, D. (2022). D4.4 - Identification of low-input practices for the cultivation of the selected industrial crops on marginal land facing natural constraints (First). D4.4 of the EU-MAGIC project. Zenodo. https://doi.org/10.5281/zenodo.7576224

Sorghum (Sorghum bicolor L., Poaceae)

Description of the crop: Sorghum is an annual herbaceous spring C4 crop with erect stems that can reach 5 m height. The stems are large with a diameter up to 5 cm and consist of alternating nodes and internodes with each node supporting one leaf. Each stem can produce up to 30 leaves (30-35 cm long and 1.3-15 cm wide). At the flowering, one panicle is being developed on the top of each stem. The panicles can greatly vary in terms of colour, size (short, compact, lose or open) and seed production. Sorghum has an extensive and deep root system with three types of roots: the primary, the secondary and the brace or buttress roots. The primary roots develop from the radicle and after their senescence, the adventitious roots are being developed from the underground nodes and can extend up to 2 m depth. Adventitious roots are small and uniform and supply nutrients to the plant. The brace roots develop from the root primordia of the basal nodes above the ground level (Figure A.41). These roots provide anchorage to the plant. The weight of 1000 seeds is 13-14 g.

Figure A.41 View of sorghum at several stages of growth (source: CRES and BECOOL project).

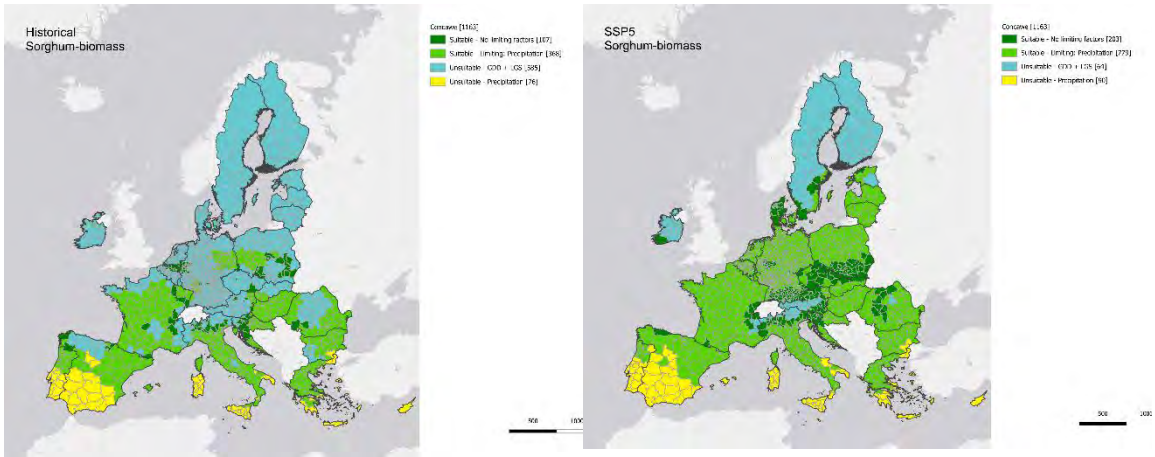
Origin and area of its cultivation: It is originated from Africa. It was first domesticated in Sudan, Chad and Ethiopia and then it was spread first to India and China. Since the late 1980s, sorghum (sweet and fiber) had been included in several EU research projects. The most recently completed projects are: SWEETFUEL project (https://cordis.europa.eu/project/id/227422/reporting) in which countries outside EU participated (India, South Africa and Brazil), BECOOL project (www.becoolproject.eu) where sorghum has been included in the lignocellulosic crops that could be used for second generation biofuels and MAGIC (www.magic-h2020.eu) as a promising industrial crop for marginal lands facing natural constraints. Currently, sorghum is being studied in projects; MAGIC, IASIS, WaterMellon.

Climate preferences: Sorghum genotypes (sweet and fibre sorghum) attracted the researchers' interest due to its remarkable yield potential even when grown on marginal lands [1]. Sorghum can be grown at altitudes from sea level up to 1000 m and at latitudes between 40 ºN and 40 ºS [1] [2]. It is primarily a plant for hot climates and thus thrives best on semi-arid tropical environments with an annual rainfall of 400-600 mm [3]. It is a drought resistant crop and thus can be grown in areas that are considered too dry for maize cultivation. The waxy layer on the sheaths and the stem contribute to reducing evaporation and increase the drought resistance. Sorghum is adapted to a wide range of temperatures and soil moisture conditions. It does not grow well in shade. Sorghum is a short-day plant, although temperatures below 20 ºC can delay head differentiation. In the EU, biomass sorghum can be grown best in the central Atlantic, Continental and Mediterranean zones. Towards the North of Europe, the length of growing season/GDD becomes too short (Figure A.43). In future climate conditions, the area suitable for biomass sorghum will increase towards the north and central Europe. In the Mediterranean areas, the temperature range is very suitable for Sorghum but low water availability will negatively impact on the yield levels. Irrigation, even at low levels, will significantly improve the yields.

Table A.10 Overview of climate suitability factors determining suitability for Biomass Sorghum grown as spring/summer crop. (source: see Appendix 4).

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32*C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	120	1400	8 °C	< 0 °C	NO	>=200 mm	-

Figure A.43 Climate suitability for Biomass sorghum grown as a summer crop. Left map refers to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario.



Soil preferences: Sorghum is adapted to a wide range of soils, temperatures and soil moisture conditions. It tolerates a soil pH from 5 to 8.5 and it can survive temporary waterlogging. Sorghum plants produce sufficient juice, and rich in sugars

biomass in fields with soil salinity up to 3.2 dS/m, even when the plants receive 50-75% of the water regimes typically applied to sorghum [4]. Therefore, sorghum may be viable as an alternative crop system under increased salinity and reduced irrigation conditions, especially in semi-saline and semi-arid fields where the irrigation water is limited during crop development.

Soil preparation and sowing: The soil preparation is the same with the one followed for other spring crops (corn, cotton, etc.). The sowing for the climatic conditions of Europe should be done in spring (from the beginning to the end of April) when the soil temperature is above 12 ºC [5]. Due to its small seed dimension, it needs an adequate preparation of the seedbed. The sowing depth should be 2-3 cm on heavy soils and 3-5 cm on sandy ones [5]. The plant's density is depending on variety, environmental conditions, earliness and varies from 110,000 to 400,000 plants/ha [5]. The most recommended sowing distances are: 45 to 70 cm between the rows and 10-20 cm within the rows. The seedling rate is varied between 10 and 15 kg/h [6].

Water and fertilization needs: Sorghum used to be called as camel because it can survive with water supply less than 300 mm for a period of 100 days. It has a high water use efficiency (WUE = 193 mm of water/kg of dry matter produced or 5.2 g of dry matter/kg of water consumed) [7]. Typically, sorghum needs between 550 to 800 mm of water (rain and/or irrigation) to achieve good yields, i.e. 50-100 t/ha total above ground biomass (fresh weight) [7]. Although sorghum is a dry land crop, sufficient moisture availability for plant growth is critically important for high yields. The major advantage of sorghum is that it can become dormant especially in vegetative phase under adverse conditions and can resume growth after relatively severe droughts. Sorghum is considered very efficient in utilising nutrients from the soil because of a large fibrous root system. However, like other crops, sorghum needs adequate nutrients to produce good yields. Good responses to fertilisation can be expected on many soils. In places where soil fertility ranges from low to moderate, the fertilisation needs are about: 100-150 kg N, 60-100 kg P_2O_5 and 60-100 kg K_2O per hectare. Nitrogen application is recommended to be done in two times: before sowing and 20-30 days after the emergence.

Varieties: The commercial sorghum varieties are divided into six groups: grain sorghum, forage or fodder sorghum, fiber sorghum, broom sorghum, sweet sorghum and biomass sorghum [8]. Grain sorghums cultivars are cultivated for food and feed consumption. Fibre sorghums cultivars have a high content of fibre and potentially can be used as fibre or energy crop. The broom sorghums cultivars have long and elastic branches and are mainly used for brooms. The sweet sorghums cultivars have juicy stems with high juice sugar content and used as an energy and/or food crop. Finally, the biomass sorghum cultivars have high lingo-cellulosic biomass yield and are used as energy crop.

Yields: The grain yields can be up to 0.3 - 2 t/ha when it is grown under rainfed conditions (India and Africa) and 4.5 to 6.5 t/ha under irrigation (USA and Australia). The yields of sorghum (fiber and sweet) can be up to 140 t/ha (on fresh basis) and 20 to 25 t/ha (oven dried) (see Figure A.44).

Diseases, insects and weed control: Sorghum has similar pests to corn. In order to minimize the diseases and pest problems, it is suggested to cultivate improved varieties/hybrids and to follow a proper rotation system [9], rather using pesticides. The most common disease known to attack sorghum and cause economic losses is Anthracnose [10]. A wide variety of insect pests can affect sorghum throughout its life cycle. Insect pressure depends on location, weather and growth stage of the crop. Since the first stages of the crop, namely from sowing to canopy closure, sorghum is very sensitive to weed competition and many weeds can infest sorghum.

Mechanical or manual weeding is needed in the first growth stage. One disease that can cause an important damage in some regions in the world, is the root parasite Striga spp., commonly known as Witch weed, which mainly occurs under low input farming conditions [11]. Most of the damage is done before the parasite emerges from the soil. Rotation with cotton, groundnut, and pea will reduce the incidence of Striga.

Harvesting time and options for use as intermediate crop: In BeCool project, a number of innovative rotation schemes have been tested for a period of four years (2017-22) in three Mediterranean countries (Greece, Italy and Spain) where sorghum have been included (among other alternatives) to produce feedstock for advanced biofuels. In the view of this project, two complete cycles of the proposed schemes were completed.

The conventional rotation was: Year 1: Maize (April to October), Year 2: fallow till October when wheat was sown, Year 3: Wheat (by June) and then fallow till April next year and the innovative rotation where sorghum was added was as follows: Year 1: Maize (spring), Year 2: Sorghum (spring) + Wheat (winter), Year 3: continuation of Wheat (winter)+ Sunn hemp (summer) (Figure A.42).

As it is presented, the yields of the two food crops (wheat and maize) did not reduce when the innovative rotation replaced the conventional one and at the same time low ILUC feedstock was produced by two intermediate crops; Sorghum and Sunn hemp.

Figure A.44 Published levels of above-ground biomass yield in (biomass) sorghum, based on 13 references (see literature list at the end of the factsheet).

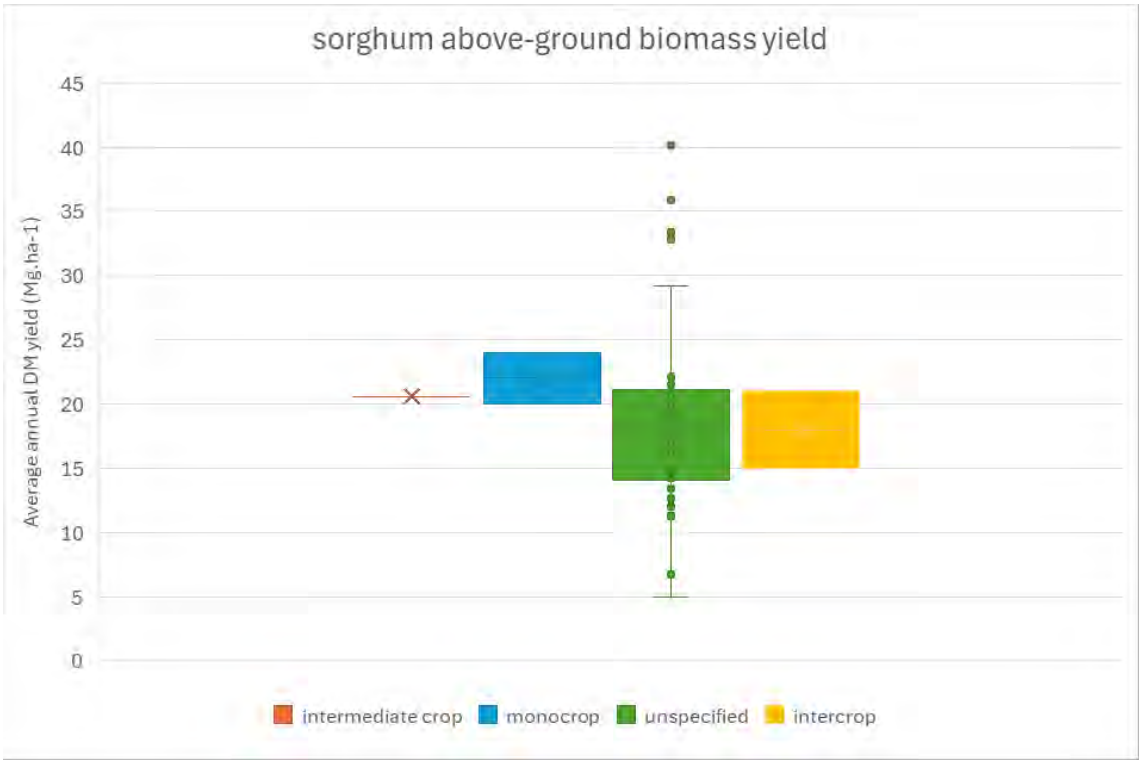


Figure A.45 Studied rotation scheme for sorghum and comparison with the conventional one (BECOOL project).

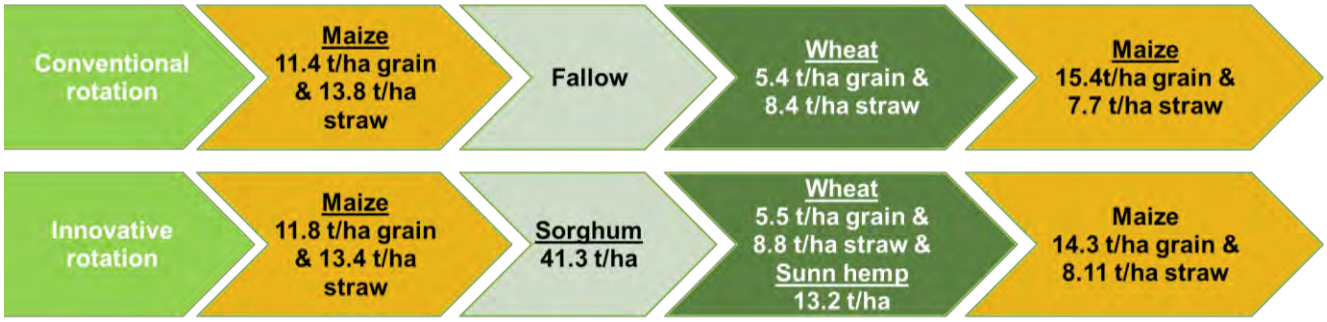


Figure A.46 View of sorghum harvesting process.

Harvesting and storage: Harvesting and logistics of sorghum differ according to the end-use. For example, for bioethanol production, the crop should be harvested when the sugars in the stalk juice are measured to be between 15.5 to 16.5 Brix [12]. A harvester for sugar cane it is used and the cut height of the stems should be 20 cm aboveground. In this type of harvesting, it is very important the juice of the stems to be stabilized in order the decrease of the sugar juice quality and quantity to be avoided and thus the total processing period to be prolonged. The harvesting for grain sorghum is quite similar to harvesting applied to other small grains like wheat. The mechanical harvesting of the crop for both grain and stems is not yet fully organized. In general, the upper part should be removed (with the panicles) and at the same time the stems should be harvested (6). In India, where sorghum is being cultivated for both grain and stems, the harvesting is done manually. A forage harvester is being used when the cultivation aims to bioethanol production [13]. In this case, the harvesting time depends on the variety, on specific climatic conditions and on biomass demand and it could be done from late September to late October. The two most common methods for harvesting sorghum for biomass are swathing followed by baling or chopping of windrows, and direct forage chopping of the standing crop.

Uses: Sorghum is the fifth most important cereal in the world and an important staple food in the semi-arid tropical areas of Africa and Asia. Being a multipurpose crop, it can be cultivated not only for its grain, but also for: sugar juice from its stalk for making syrup or ethanol, bagasse and green foliage which can be used as an excellent fodder for animals, for biofuels production, as organic fertiliser, for paper manufacturing or for bioenergy generation [14] [15] [16]. In developing countries, sorghum provides opportunities for the simultaneous production of food and bioenergy, thereby contributing to improved food security as well as increased

access to affordable and renewable energy sources. In Europe, sorghum is seen as a promising feedstock for advanced biofuels.

Environmental impacts: The performance of sorghum in terms of the main environmental aspects is presented in the table below.

Environmental aspects	Color score	Explanation
1a) Soil structure		Sorghum is an intermediate crop that requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting.
1b) Soil organic carbon		Sorghum serves as a cover crop which protects the soil against erosion [5] [17].
1c) Soil biodiversity		Pesticides are usually not required because sorghum has different varieties that pest and disease resistant [7] [10]. For planting, it is important to use the right density (to avoid herbicides) and apply manual weed control because at early stages of growth competes poorly with weeds.
2a) Risk for leaching to ground and surface water		Sorghum as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. Sorghum has lower N demand (typically 60-120 kg/ha vs. corn's 150-250 kg/ha in high-yield systems). Sorghum is more nitrogen-use efficient. Sorghum's deep, fibrous roots scavenge nutrients better, making it suitable for low-fertilizer conditions [3] [6] [7].
2b) Risk for loss from spraying pesticides, herbicides		The proper cultivation management can play a key role to reduce and even avoid the herbicides application. Pesticides applications are not commonly needed [10].
3) Water quantity		Compared to other spring crops, like corn and cotton, sorghum shows better performance in semi-arid regions due to its drought tolerance and high WUE [7] [18]. Sorghum physiology and drought tolerance).
4a) Habitat quality		The need for herbicides and pesticides applications can be well avoided provided the right varieties and management practices are applied.
4b) Species viability contribution		Sorghum is a wind-pollinated grass, so it doesn't produce nectar like flowers of many insect-pollinated crops. However, sorghum does produce pollen, and various studies show bees (especially wild bees) collect sorghum pollen, particularly when other floral resources are scarce in late summer (e.g., August). It is a secondary resource for pollinators, valuable in lean periods [19]. Insect pollination of crops.
4c) Invasive species		Sorghum is not invasive. It is originated from North America and came to Europe in the 16th century [20].

The scoring options are as follows:

Color	Scoring
	Very positive effect
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: The crop is fully mechanized in Europe.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

TRL >7, industrial production already available at commercial scale
5<=TRL=>7, production available at demo scale
3<TRL>5, from research to production development
TRL<=3, only basic research data available

References

[1] Mariani, G., Belocchi, A., Calabrò, G., Nisi, D., 1989. Sorghum for cellulose production. Cellulosa Carta 2, 14-22.

[2] Gherbin, P., Quaglietta Chirandà, F., 1994. Effetti del regime idrico su sorgo da fibra nel Metapontino. Inform. Agric. 21, 43-45.

[3] Xin, Z., Aiken, R. Sorghum, a promising multiple-use crop for dry and hot climates. Planta 255, 83 (2022). https://doi.org/10.1007/s00425-022-03866-7

[4] Vasilakoglou, I., Dhima, N., Karagiannidis, N. & Gatsis, T., 2011. Sweet sorghum productivity for biofuels under increased soil salinity and reduced irrigation. Field Crops Research, 120(1).

[5] https://groundcover.grdc.com.au/agronomy/soil-and-nutrition/patience-a-virtue-for-sorghum-start

[6] https://globalsorghumandmillet.com/wp-content/uploads/2025/05/Small-Holder-Production-Guidelines-Tirfessa.pdf

[7] P. Steduto, N. Katerji, H. Puertos-Molina, M. U¨nlu¨, M. Mastrorilli, G. Rana,1997). Water-use efficiency of sweet sorghum under water stress conditions Gas-exchange investigations at leaf and canopy scales,Field Crops Research, Volume 54, Issues 2-3, Pages 221-234, ISSN 0378-4290, https://doi.org/10.1016/S0378-4290(97)00050-6.

[8] Okoye, T., Uzor, P., Onyeto, C. & Okereke, E. (2014). Safe African Medicinal Plants for Clinical Studies. In: Kuete (ed) (2014). Toxicological Survey of African Medicinal Plants. Elsevier. DOI: 10.1016/C2013-0-15406-2

[9] Olabimpe O Okosun, Kerry C Allen, James P Glover, Gadi V P Reddy, Biology, Ecology, and Management of Key Sorghum Insect Pests, *Journal of Integrated Pest Management*, Volume 12, Issue 1, 2021, 4, https://doi.org/10.1093/jipm/pmaa027

[10] Stutts, L. and Vermerris, W (2020). Elucidating Anthracnose Resistance Mechanisms in Sorghum—A Review. Phytopathology vol. 110, no.12, Dec 2020, https://apsjournals.apsnet.org/doi/10.1094/PHYTO-04-20-0132-RVW

[11] Begna, T. (2021). Effect of Striga Species on Sorghum (Sorghum Bicolor L Moench) Production and its Integrated Management. Approaches International Journal of Research Studies in Agricultural Sciences (IJRSAS). Volume 7, Issue 7, 2021, PP 10-22 ISSN No. (Online) 2454-6224, DOI: http://dx.doi.org/10.20431/2454-6224.0707002

[12] Oktem, A., Gulgun Oktem, A. (2024). Bioethanol obtained from soluble sugars in sweet sorghum, influencing properties and their interrelationships, Industrial Crops and Products, Volume 221, 2024, 119351, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2024.119351.

[13] Chauhan, J., Solanki, S., Singh, A., Singh, M. (2025). Forage Sorghum: Potential Feedstock for Bioenergy. In: Singhal, R.K., Indu, El Sabagh, A., Dwivedi, K.K. (eds) Forage Crops in the Bioenergy Revolution. Springer, Singapore. https://doi.org/10.1007/978-981-96-2536-9_9

[14] Andreuccetti, P., Bacchiet, P., Barbucci, P., Belletti, A., Frati, G., 1991. Energy crops: farming tests in two different Italian sites, and preliminary assessment of technologies to use them for electricity production. In Grassi, G., Bertini, I. (Eds.), First European Forum on Electricity Production from Biomass and Solid Wastes by Advanced Technologies, Firenze, 27-29 November, pp. 223-228.

[15] Grassi, G., Moncada, P., Zibetta, H., 1992. Promising industrial energy crop sweet sorghum. Commission of the European Communities.

[16] Recchia, L., Desiderio, E., Bilancini, L., Brizzi, M., Belocchi, A., Quaranta, F., 1998. Influenza del genotipo e della tecnica agronomica sulle caratteristiche qualitative di sorgo da fibra. Agric. Ric. 178, 79-93.

[17] SARE, 2012. Managing Cover Crops Profitably. 3rd ed. s.l.:United Book Press,Inc.

[18] Blum, A., 2005. Drought Resistance, Water-Use Efficiency, and Yield Potential— Are They Compatible, Dissonant, or Mutually Exclusive?. Australian Journal of Agricultural Research, Volume 56.

[19] Free, J., 1993. Insect Pollination of Crops. 2nd ed. s.l.:Academic Press, London.

[20] Doggett, H., 1988. Sorghum. 2nd ed. s.l.: Longman Scientific and Technical.

References for yield data in Figure A.44

Chattha M.U., Hassan M.U., Khan I., Chattha M.B., Aamer M., Nawaz M., Anjum S.A., Ashraf U., Kharal M. (2020). Impact of planting methods on biomass production, chemical composition and methane yield of sorghum cultivars. Pakistan Journal of Agricultural Sciences, 57 (1), pp. 43 - 51. DOI: 10.21162/PAKJAS/20.7112

Choi N., Kim G., Park W., Jeong Y., Kim Y.-H., Na C.-I. (2022). Additional N application and ecotype affect yield and quality of ratoon harvested sorghum x sudangrass hybrid for temperate regions. Biomass and Bioenergy, 160, art. no. 106423. DOI: 10.1016/j.biombioe.2022.106423

Dalton J.C., Huntington T., Pidatala V., Lei M., Hill C., Angeles J., Putnam D., Dahlberg J., Gladden J., Simmons B.A., Hutmacher R., Scown C.D., Scheller H.V. (2024). Impact of Drought

Stress on Sorghum bicolor Yield, Deconstruction, and Microbial Conversion Determined in a Feedstocks-to-Fuels Pipeline. ACS Sustainable Chemistry and Engineering, 12 (42), pp. 15613 - 15622. DOI: 10.1021/acssuschemeng.4c05826

Patel B., Patel A., Syed B.A., Gami B., Patel P. (2021). Assessing economic feasibility of bio-energy feedstock cultivation on marginal lands. Biomass and Bioenergy, 154, art. no. 106273. DOI: 10.1016/j.biombioe.2021.106273

Pravdyva L., Prysiazhniuk O., Khakhula V., Fedoruk Y., Shushkivska N. (2023). Seed Yield and the Possibility of Biofuel Production from Sorghum (Sorghum bicolor L.) in Ukraine (2023) Ecological Engineering and Environmental Technology, 24 (5), pp. 94 - 99. DOI: 10.12912/27197050/163715

Reinhardt, J., Hilgert, P. & Von Cossel, M. (2021). A review of industrial crop yield performances on unfavorable soil types. Agronomy, 11(12). https://doi.org/10.3390/AGRONOMY11122382

Reinhardt, J., Hilgert, P. & Von Cossel, M. (2022). Yield performance of dedicated industrial crops on low-temperature characterized marginal agricultural land in Europe – a review. Biofuels, Bioprod. Bioref., 16: 609-622. https://doi.org/10.1002/bbb.2314

Schetter A., Lin C.-H., Zumpf C., Jang C., Hoffmann L., Jr, Rooney W., Lee D.K. (2022). Genotype-Environment-Management Interactions in Biomass Yield and Feedstock Composition of Photoperiod-Sensitive Energy Sorghum. Bioenergy Research, 15 (2), pp. 1017 - 1032. DOI: 10.1007/s12155-021-10272-6

Scordia, D. (2022). D4.4 – Identification of low-input practices for the cultivation of the selected industrial crops on marginal land facing natural constraints (First). D4.4 of the EU-MAGIC project. Zenodo. https://doi.org/10.5281/zenodo.7576224

Von Cossel, M. et al. (2022). D4.6 – Long-term performance of perennial industrial crops grown on marginal land. D4.6 of the EU-MAGIC project.

Von Haden A.C., Burnham M.B., Yang W.H., DeLucia E.H. (2021). Comparative establishment and yield of bioenergy sorghum and maize following pre-emergence waterlogging. Agronomy Journal, 113 (6), pp. 5602 - 5611. DOI: 10.1002/agj2.20832

Zegada-Lizarazu W., Parenti A., Monti A. (2021). Intercropping grasses and legumes can contribute to the development of advanced biofuels. Biomass and Bioenergy, 149, art. no. 106086, Cited 15 times. DOI: 10.1016/j.biombioe.2021.106086

Industrial hemp (Cannabis sativa L., family Cannabinaceae)

Description of the crop: Hemp is an annual spring crop that traditional used to be cultivated for its fiber stems. It is a rapid growing crop that can reach a height of 4 m in 100 days [1]. Traditionally, hemp is a dioecious species. The male plants form loose, strongly branched panicle with very low number of leaves, while the female ones produce compact panicles with lots of small leaves. In both cases the inflorescence is a panicle. Three main sections can be distinguished in the stems; the bark where the fibres bundles can be found, the woody core body and a hollow space in the middle of the stem. The leaves have a palmate shape with 5 to 11 sections depending on their location on the stems (lower on the top of the stem). The leaves fade gradually and fall off the plant as the plant matures. It has a strong tap root system, reaching 1.5-2 m deep into the soil. The main root mass is located 20-40 cm soil depth. Hemp seeds have a spherical-oval shape slightly flattened from both sides, gray-green with a characteristic, marble-like pattern on the shell.

Figure A.47 Male plants on the left and female on the right.

Origin and area of its cultivation in Europe: It is originated from middle Asia from where it migrated to Eastern and Southern Asia [2]. It was first grown in China (5000

Figure A.48 View of hemp (Futura 75) at several stages of growth (source: CRES); a week from sowing, four weeks from sowing, vegetative phase, flowering phase and top of the stems.

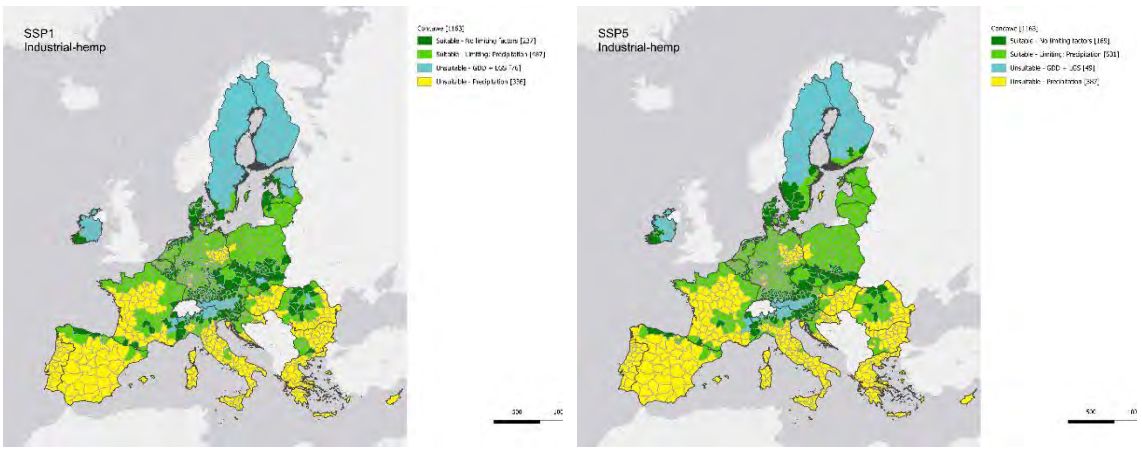
years ago) and from there it was spread to the whole world. Hemp is considered as an old-new crop [2]. The last years an increasing interest for industrial hemp has been recorded worldwide [3]. In particular in Europe, the area of its cultivation from 14,000 ha in 2012 increased to 42,500 ha in 2017. Although, the main producer in Europe is still France, an increasing growing area has been recorded in Italy, Italy, Netherlands, Lithuania, Estonia, Ukraine, Romania and Germany [3]. Research on industrial hemp has been carried out in several EU research projects namely HEMPSYS, 4FCROPS (www.cres.gr/4crops), Crops2Industry (www.crops2industry.eu), MULTIHEMP (www.multihemp.eu), FIBRA (www.fibrafp7.net), GRACE (www.grace-bbi.eu) and MAGIC (www.magic-h2020.eu) projects. Currently, industrial hemp it was studied by GOLD (www.gold-h2020.eu), MIDAS, IASIS as industrial crops on marginal and/or contaminated lands.

Climate preferences: Hemp requires a mild, temperate climate and an annual rainfall or irrigation of at least 500 to 700 mm [4]. The hemp plant is sensitive to short day length which induces early flowering. Flowering time is a very important factor in hemp yield determination, both in terms of quantity and quality. It requires long days (14-16 hours) during its vegetative phase [4].

Table A.11 Overview of climate suitability factors determining suitability for Industrial hemp grown as summer crop.

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32*C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	90	1800	10 °C	< -10 °C	NO	>=200 mm	-

Figure A.49 Climate suitability for Industrial Hemp grown as a summer crop. Left map refers to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario.



Soil preference: Hemp grows best on fertile soils with pH = 7.1-7.6. It should not be grown on acid soils where pH is below 6.0. Hemp has no special requirements in terms of the preceding crop [3] [4]. It grows well after root crops grown on manure and legume crops. It can even grow on the same field for a few years. It improves

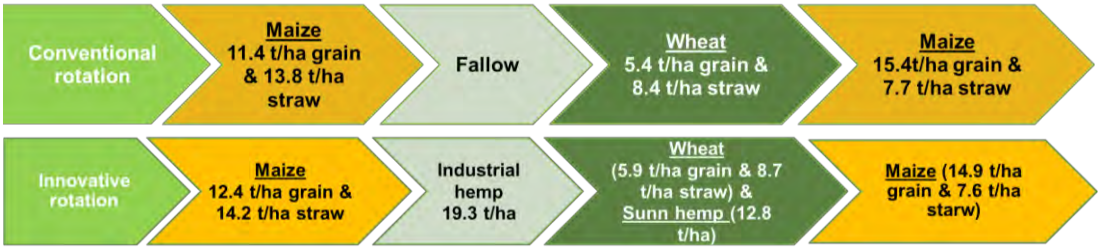
the structure of the soil due to its tap roots. Hemp absorbs heavy metals such as Cd, Pb, Zn, Cu, and thus contributes to the cultivation of contaminated soils [5].

Soil preparation and sowing: It can be sown once the average air temperature stabilizes at 8-10 ^{o}C. The sowing density is strongly dependent on the crop's end-use [6]. For example, for fibre production, 60-70 kg seeds/ha should be applied, while for seeds production this is much smaller (10-15 kg seeds/ha). The rows spacing should be 12.5-25 cm or 50-70 cm, respectively. The seeds should be sown 3-4 cm deep. When it is grown for seeds, weed control is important, with *Elymus repens (L.) Gould* being of primary concern [6]. In contrast, when hemp is grown at high densities for fibre production, the crop canopy rapidly closes and effectively suppresses weeds, removing the need for additional weed control [10]. Soil bed preparation should follow practices similar to those used for spring cereals.

Rotation schemes: In BeCool project, a number of innovative rotation schemes have been tested for a period of four years (2017-22) in three Mediterranean countries (Greece, Italy and Spain) where sorghum have been included (among other alternatives) to get feedstock for advanced biofuels. In the view of this project two completely cycles of the proposed schemes had been completed.

The conventional rotation was: Year 1: Maize (April to October), Year 2: fallow till October when wheat was sown, Year 3: Wheat (by June) and then fallow till April next year and the innovative rotation where sorghum was added was as follows: Year 1: Maize, Year 2: Industrial hemp + Wheat, Year 3: continuation of Wheat + Sunn hemp (see the graph below).

The results of the trials in BeCool showed that the yields of the two food crops (wheat and maize) did not reduce when the innovative rotation replaced the conventional one and at the same time low ILUC feedstock was produced by two intermediate crops; industrial and sunn hemp.



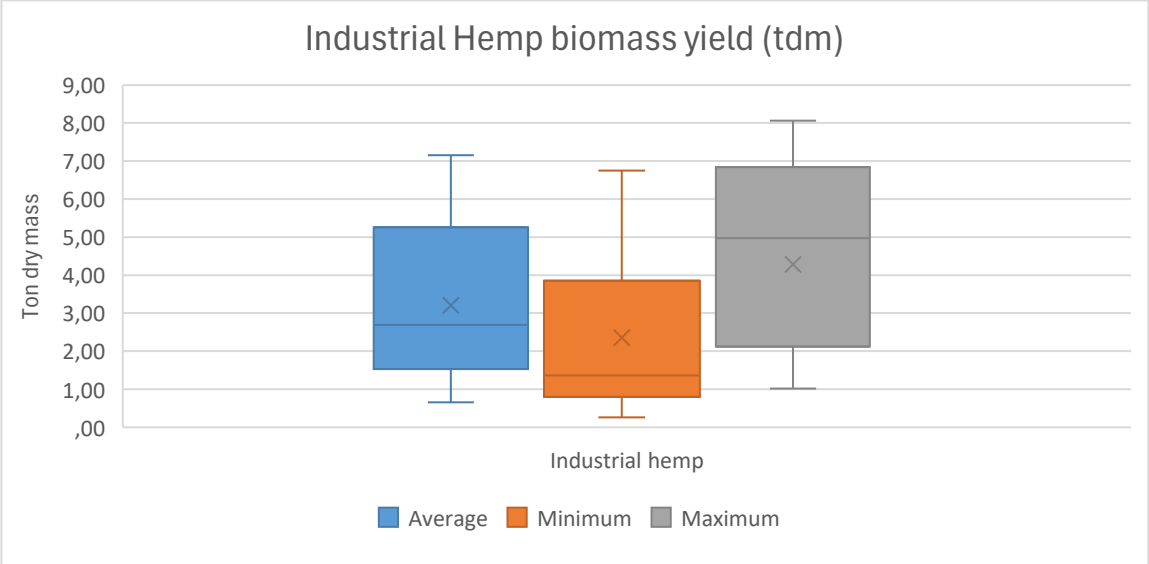
Fertilization and irrigation needs: The optimum fertilizers doses are: N: 90-120 kg/ha, P_2O_5: 70-100 kg/ha, K_2O: 150-180 kg/ha [8]. When the crop is grown for fibre potassium and calcium balance are important (for plant cell formation), while when grown for seeds the phosphorus availability is very critical for seeds formation. For fibre production, the NPK ratio should be 1:0.7:1.5, while for seed production should be 1:0.8:1. When hemp follows legumes, less nitrogen fertilization is needed. High nitrogen fertilization can prolong the vegetative phase and the risk for lodging is increased. It grows best when supplied with moisture throughout its growing season and especially during the first six weeks of growth. For optimum yields, 250 to 300 mm of moisture during the vegetative growing stage is required [8]. Droughts at germination and flowering phases can seriously damage the growth and yields of the crop.

Varieties: Hemp is naturally a dioecious crop with male and female plants. The male plants are shorter with higher fiber content that mature earlier than the taller female plants that have a higher productivity in terms of seeds. Currently, a number

of monoecious varieties have been selected in order to reduce the agronomic problems related to the sexual vegetative dimorphism present in dioecious varieties [8]. The monoecious varieties produce uniform plantations and the plants have similar maturity, height, fiber content and seed productivity and ultimately efficient mechanical harvest. Currently, a total number of 116 varieties are being registered in the European catalogue and cultivated either for fibers, for seeds or for both [9].

Yields: It is dual purpose crop. There are many varieties that produce both lignocellulosic biomass and seeds. In Europe, a typical yield is 7.5 t/ha for dry stems and 2.5 t/ha for fibres. The seeds contain 32.5% oil, with 70% of it corresponding to polyunsaturated fatty acids.

Figure A.50 Above-ground biomass yield based on Eurostat data (2016-2024).



Diseases: Hemp can suffer from fungi, specifically from diseases like Fusarium wilt, septoriosis and gray mildew, especially during the winter months. Sometimes, especially if hemp is grown several times on the same stand, it may suffer from a parasitic plant - branched broomrape (Orobranche ramosa L.) [11]. Also, virus diseases may sometimes attack hemp.

Harvesting time and options for use as intermediate crop: In BeCool, project a number of innovative rotation schemes have been tested for a period of four years (2017-22) in three Mediterranean countries (Greece, Italy and Spain) where industrial hemp was included (among other alternatives) to produce feedstock for advanced biofuels. In the view of this project two completely cycles of the proposed schemes had been completed.

Harvesting and storage: The time of harvesting depends on the purpose of cultivation of hemp. When it is grown for fibres, the harvesting should be done in the beginning of flowering. At that time the fibres are delicate and quite strong and appropriate to textile production. When the harvesting is being delayed, the fiber yields are increasing but because the lignification is also increased, the fibres are not appropriate for textiles but can be used for pulp production. When it is grown for seeds and/or fibres, the crop should be harvested at its full maturity phase, when seeds in the middle part of panicle are mature. At that time, the fibres can be used for non-textile applications (insulation mats, etc.). In Figure A.51, the harvesting of hemp for both seeds and fibres in Romania is presented.

Figure A.51 View of harvesting in Romania (source: CREA).

Uses: Although industrial hemp is considered as fiber crop, high-value bio-products can be produced from all plant parts (stems, leaves, seeds and flowers) and thus it is considered a natural biorefinery. Figure A.52 presents the current main uses of the crop per plant part. The fibres of its stem are being used for paper and pulp, insulation mats, bio-composites and textiles. The shivs (the woody part of its stem) are being used as construction material, for animal bedding, garden mulch, etc. The seeds can be consumed as food and/or feed, the seeds oil can be used either for food and feed consumption or for cosmetics and heath care products. The flowers have numerous pharmaceutical uses from THC, CBD and other cannabinoids. Finally, from its leaves are being produced pharmaceutical products, tea bags, etc.

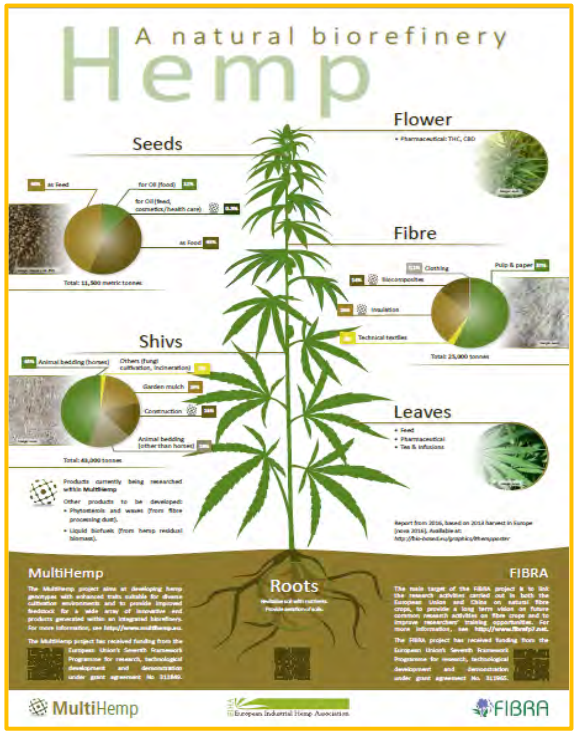


Figure A.52 Industrial hemp: a natural biorefinery (poster developed by EU projects Multihemp & FIBRA).

Hemp has a very long history of medicinal use. It has been traditionally used by different cultures in treatment of various types of ailments: asthma, cystitis, diarrhoea, dysentery, gonorrhoea, gout, epilepsy, malaria, fevers etc. The whole plant is considered to be anodyne, anti-inflammatory, antispasmodic, cholagogue, diuretic, emollient, hypnotic, hypotensive, laxative, narcotic, ophthalmic and sedative. Today, hemp is used for relieving side effects of cancer treatments, such as nausea and vomiting. Since it increases the desire for

food, it is also used in treatment of anorexia nervosa. It can be used as food component and for production of technical products such as: detergents, varnishes, paints, lamp fuel or an emulsifying medium in pharmacy. Hempseed oil is described as desired raw material for production of so-called greasy soap (grey soap). This soap is called also green soap in many counties from the colour given to it by chlorophyll contained in the soap. It is worth mentioning that hemp essential oil, a different substance extracted from hemp is used for a medium repelling parasite found e. g. on horse skin. It also displays properties similar to many other essential oils - bacteriostatic, repellent to pests.

Environmental impacts:

Environmental aspects	Color score	Explanation
1a) Soil structure		Industrial intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting.
1b) Soil organic carbon		Industrial hemp serves as a spring cover crop which protects the soil against erosion [1].
1c) Soil biodiversity		Low requirements in terms of herbicides when proper management is followed and due to allelopathy [1].
2a) Risk for leaching to ground and surface water		Industrial hemp has deep root and can absorb heavy metals from the soils as well as nutrients [12].
2b) Risk for loss from spraying pesticides, herbicides		See 1c, hemp may be affected by some diseases and insect problems but use of pesticides can generally be limited but not always avoided [3][6]. A weed control should be applied at sowing in order to avoid weed problems at the early stages of growth. Thereafter the crop can compete the weeds.
3) Water quantity		Industrial hemp needs less water compared to corn. It needs at least 300 mm and in order to minimise the irrigation demand it should be established quite early in the spring. Industrial hemp generally needs less water (300-500 mm) than corn (500-800 mm) [1]. Early sowing in spring allows hemp to use rainfall more effectively, reducing irrigation requirements.
4a) Habitat quality		The application of some pesticides and possibly herbicides is needed [3] [6].
4b) Species viability contribution		Industrial hemp provides food to pollinators at the end of summer when it flowers [1]. When used as an intermediate crop, it contributes to increasing the crop diversity and structural landscape diversity.
4c) Invasive species		Industrial hemp is not invasive. Its origin is from China.

TRL:

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

 = TRL >7, industrial production already available at commercial scale,

 = 5<=TRL=>7, production available at demo scale

 = 3<TRL>5, from research to production development

 = TRL<=3, only basic research data available

References

[1] Amaducci, S. et al., 2015. Key cultivation techniques for hemp in Europe and China. Industrial Crops and Products, Volume 68.

[2] McPartland, J.M., Hegman, W. & Long, T. Cannabis in Asia: its center of origin and early cultivation, based on a synthesis of subfossil pollen and archaeobotanical studies. Veget Hist Archaeobot 28, 691–702 (2019). https://doi.org/10.1007/s00334-019-00731-8

[3] https://eiha.org/media/2017/12/17-03_European_Hemp_Industry.pdf

[4] https://www.arc.agric.za/arc-iic/Pages/Hemp.aspx

[5] Sward, S.; Brye, K.R.; Miller, D.M.; Thurston, D.V. Use of Biochar and Industrial Hemp for Remediation of Heavy-Metal-Contaminated Soil: Root Uptake and Translocations for Cd, Pb, and Zn. Soil Syst. 2025, 9, 29. https://doi.org/10.3390/soilsystems9020029

[6] https://extension.oregonstate.edu/sites/extd8/files/documents/em9239.pdf

[7] Podder, S.; Shafian, S.; Thomason, W.E.; Wilson, T.B.; Fike, J.H. Hemp Seed Yield Responses to Nitrogen Fertility Rates. Crops 2024, 4, 145-155. https://doi.org/10.3390/crops4020011

[8] Pavlovic Radmila , Panseri Sara , Giupponi Luca , Leoni Valeria , Citti Cinzia , Cattaneo Chiara , Cavaletto Maria , Giorgi Annamaria (2019). Phytochemical and Ecological Analysis of Two Varieties of Hemp (Cannabis sativa L.) Grown in a Mountain Environment of Italian Alps. Frontiers in Plant Science. Volume 10 - 2019URL=https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2019.01265, DOI=10.3389/fpls.2019.01265

[9] https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/hemp_en

[10] Kaur, N., Kumar, A., Malik, T. et al. Herbicide use and weed management strategies in hemp cultivation. J Cannabis Res 7, 27 (2025). https://doi.org/10.1186/s42238-025-00280-0

[11] https://pnwhandbooks.org/plantdisease/host-disease/hemp-cannabis-sativa-fusarium-wilt

[12] Sandra Citterio, A. S., Pietro Fumagalli, N. P., Ranalli, P. & Sgorbati, S., 2003. Heavy metal tolerance and accumulation of Cd, Cr and Ni by Cannabis sativa L. Plant and Soil

Sunn hemp (Crotalaria juncea L., family Fabaceae)

Description of the crop: Sunn hemp is an annual herbaceous short-day plant with erect fibrous ridged stems. It is the fastest growing species of the genus Crotalaria. It is considered multipurpose crop and can be used for green manure, fiber and animal fodder crop [1]. The leaves are simple, up to 12 cm long and up to 3.5 cm wide, oblong lance-like in shape, covered with short, downy hairs, and arranged spirally along the stem. The plant has a strong taproot with well-developed lateral roots. Its stems develop branches when it is grown at low plant densities. Flowering starts eight weeks from sowing. Deep yellow flowers develop acropetally on the inflorescence, which is a terminal open raceme.

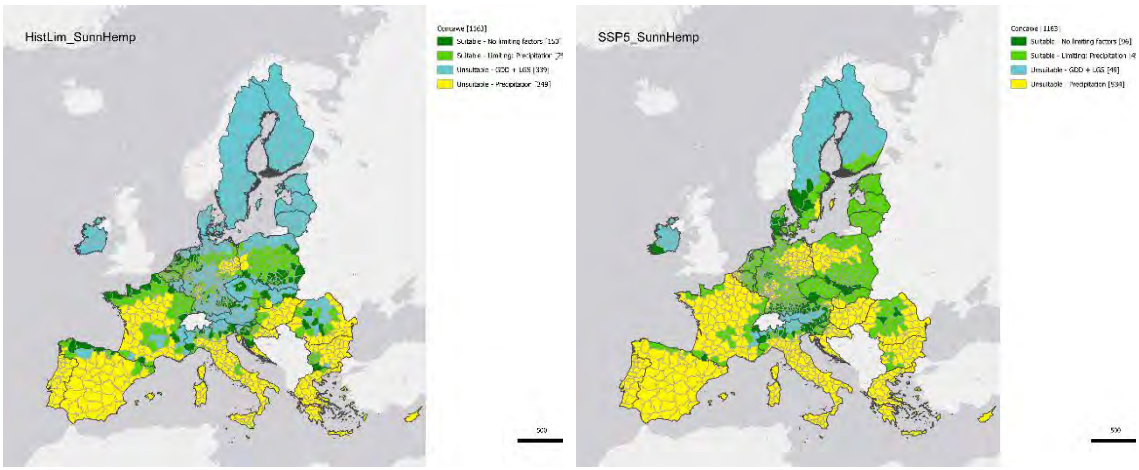
Origin and area of its cultivation: Sunn hemp is native to India and Pakistan. In Europe, sunn hemp can be found as alien crop, so plant species cultivated outside its native geographic range. In Southeast Asia, sunn hemp has been grown as a green manure crop for centuries and now is cultivated in many tropical and sub-tropical regions worldwide. The main seed producers are: India, Hawaii, Colombia, and South Africa. In 2017, the area of cultivation for sunn hemp was 31,500 ha. In the USA, Sunn hemp has been grown as a summer cover crop, however, seed production is generally not possible because the crop is short-day, with flowering initiation delayed until early September. Sunn hemp has been selected as a potential biofeedstock in the framework of BeCool project and research trials have been run in Italy, Greece and Spain [2].

Climate preferences: Sunn hemp grows well under mean annual air temperatures from 20 to more than 38 ^{0}C [3]. High temperature with moderate humidity is preferable for sunn hemp growth and development. Growth may be slowed by cold weather, and the plant is susceptible to freezing injuries when the temperature is less than -2 ^{0}C [3]. Sunn hemp is drought tolerant and, generally, no irrigation is necessary during the summer, unless precipitation does not meet the minimal threshold of 200-300 mm during the growth season [3]. In the Mediterranean area, this is a challenge (see Figure A.53), as the crop there can grow well but needs additional irrigation.

Table A.12 Overview of climate suitability factors determining suitability for Sunn hemp grown as a summer crop

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 °C in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	60	1300	8 °C	< -2 °C	NO	>=300 mm	-

Figure A.53 Climate suitability for Sunn hemp grown as a summer crop. Left map refers to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario.



Soil preferences: Although sunn hemp tolerates poor fertility soils and no fertilizer is necessary, its productivity is enhanced on fertile soils. Sunn hemp can grow well in soils with pH ranging from 5.0 to 8.4 [3]. This plant is also adapted to well-drained calcareous soils and acidic sandy soils, but not to water-logged or saline/sodic soils [3].

Soil preparation and sowing: The soil must be prepared in such a manner that favours an adequate settlement of cultures, by using appropriate equipment in the right period, taking into consideration that land preparation is one of the most important aspects for germination. The seedbed should be loose and well-levelled, allowing for a uniform and adequate sowing depth. In particular, the soil surface should be finely prepared, with approximately 1 cm of well-structured topsoil, as seedling emergence is poor when seeds are placed too deeply. Seeds should be sown in soil temperatures greater than 20°C for successful germination. Seeds usually germinate within 3 days, and seedlings rapidly develop a dense ground cover. To establish as a cover crop, Sunn hemp should be sown at a rate of 10 to 40 kg seeds per ha. Lower seeding rates can promote lateral branching [4]. Seeds can be inoculated with cowpea inoculant to improve nitrogen fixation. The soil depth should be 2-3 cm.

Water and fertilization needs: It is worth mentioning that the Crotalaria juncea is one of the legume families; therefore, it has an intrinsic capacity for the fixation of nitrogen in the soil, an action that is carried out by receiving CO_2 from the atmosphere and transforming into nitrogen through its fixation in its roots [4] [5]. The fixation of nitrogen, as well as the creation of organic material and the reduction of the nematode population in the soil are their main characteristics, which make the Crotalaria juncea a widely used green fertilizer. When sunn hemp is grown for fodder, agronomic management should aim to maximise yield while maintaining its soil-improving functions. The applied fertilizers should be not rich in nitrogen and with high phosphor and potash levels [5].

Varieties: Sunn hemp is a self-incompatible plant. Most of sunn hemp cultivars have originated from selection of improved types suited to specific localities, rather than by breeding procedures [6]. These selections generally focused on early maturity, improved fiber yield, and resistance to pests [6]. More recently, genetic research and breeding procedures have been conducted on sunn hemp in Brazil and India. In

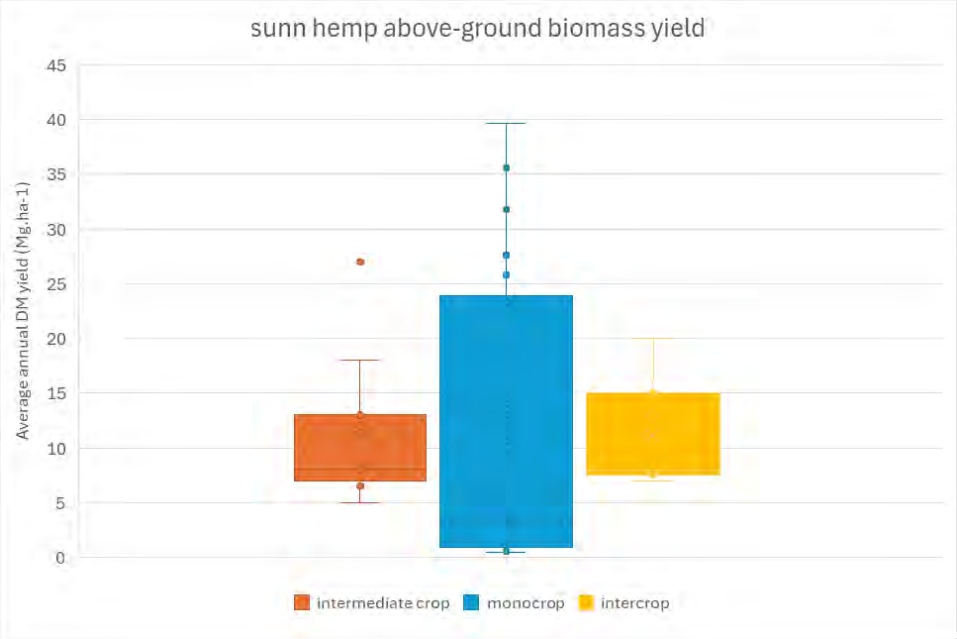
these breeding programmes, it had been found that the final plant height and basal stem diameter are positively correlated with total stalk dry matter, indicating selections for these traits could result in higher yielding cultivars. Some sunn hemp varieties that have been recently developed in India are: Shailesh (SH-4), Swastik

Figure A.54 View of sunn hemp (source: CRES).

(SUIN-053), Ankur (SUIN-037) & Prankur (JRJ-610).

Yields: Field tests indicate that sunn hemp can produce 800 to 2,200 kg seeds per ha when seeded in narrow rows with a grain drill. In terms of dry matter, yields equal to 10-16 t/ha have been measured during the BeCool project. Sowing it in wide rows has been found to produce lower seed yields.

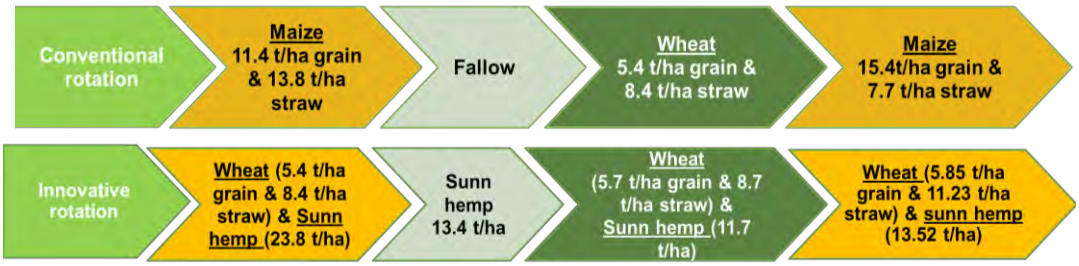
Figure A.55 Yield levels of above-ground biomass of sunn hemp, based on 7 public references (see literature list at the end of this factsheet).



Diseases, insects and weed control: Although several insect species attack sunn hemp, most of do not cause substantial economic losses and thus no chemicals are applied [2] [3]. In wet soils, significant yield losses can be recorded by Pythium spp. and Fusarium spp. Sunn hemp is resistant to soil root-knot and soybean cyst nematodes and thus by adding sunn hemp to rotations with nematode-susceptible crops the nematode pressure can be reduced [2]. Due to its rapid growth, it can effectively control weeds during the summer months.

Harvesting time and options for use as intermediate crop: In BeCool project, a number of innovative rotation schemes were tested for a period of four years (2017-22) in three Mediterranean countries (Greece, Italy and Spain) where sorghum has been included (among other alternatives) to produce feedstock for advanced biofuels. In the view of this project, two completely cycles of the proposed schemes had been completed.

The conventional rotation was: Year 1: Maize (April to October), Year 2: fallow till October when wheat was sown, Year 3: Wheat (by June) and then fallow till April next year and the innovative rotation where sunn hemp was added was as follows: Year 1: Maize, Year 2: Wheat + Sunn hemp, Year 3: continuation of Wheat + Sunn hemp (see the graph below).



As it was presented, the yields of the two food crops (wheat and maize) did not reduce when the innovative rotation replaced the conventional one and at the same

time a low ILUC feedstock was produced by two intermediate crops including sunn hemp.

Harvesting and storage: The harvesting time depends on the end use. When it is grown for its fibre, the harvesting should be done at the flowering stage (mid-September for Europe). When the crop is cultivated for green manure, the harvesting should be done two months from emergence when the plants begin to flower as it decomposes more rapidly and it will have a positive nitrogen balance at this stage. As a forage crop, sunn hemp should be harvested up to four times under favourable growing conditions during its growing cycle; the first 6 to 8 weeks from sowing, and thereafter every four weeks.

Figure A.56 Mechanical harvest of sunn hemp for fibres (source: www.cetabol.bo) on the left and for green manure (source: Yuncong C. Li / University of Florida) on the right.

It has been recommended to sun-dry sunn hemp foliage prior to feeding animals as they do not eat fresh sunn hemp. When sunn hemp has been harvested for fibre, the top portion of the stem is used for fodder or hay after mixing with paddy straw.

Harvesting can be done by hand or with a mechanical harvester. The top portion of the plants is chopped off soon after harvesting for use as cattle fodder. The main portion of the stem is left to dry on the ground for 1 to 6 days, so that it sheds its leaves and becomes ready for retting. In some areas, stems are left up to 15 days on the ground and retting occurs naturally thanks to morning dew.

Seeds can be easily harvested with a combine when most of the pods (about 70-80%) are mature. Seed maturity can be recognized by the rattling sound of the seeds within the pods. When seeds are mature, they fall to the lowest end of the pod, thus shaking the plant will produce a rattling sound. If needed, defoliation of the plants can be accomplished by spraying with a mixture of gramoxone and sodium chlorate or with a 50% solution of liquid nitrogen. Plants can be harvested with a combine with a standard header (grain platform) that needs to be raised to reduce the amount of straw going in. Concave clearance and cylinder speed need to be adjusted depending on the crop conditions.

Uses: The main uses of industrial hemp are green manure, animal feeding, fibre and seed production. In India, clothing, twine, and rope are made from the fiber of older, densely grown plants [7]. In some areas, seeds are fed to pigs and horses

without adverse effects. However, since some sunn hemp varieties contain moderately toxic levels of pyrrolizidine alkaloids, sunn hemp fodder and seeds are usually provided at no more than 45% of the feed ration for ruminants, swine, and horses [8].

Environmental impacts:

Environmental aspects	Color score	Explanation
1a) Soil structure		Sunn hemp intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting.
1b) Soil organic carbon		Sunn hemp serves as a spring/summer cover crop which protects the soil against erosion [2] [4] [5].
1c) Soil biodiversity		Pesticides application is not required, while in terms of herbicides, it depends on the cultivation protocol [3] [4].
2a) Risk for leaching to ground and surface water		Sunn hemp as a cover crop prevents loss of nutrients through soil erosion and leaching in the soil. Nitrogen and other nutrient requirements are lower compared to other conventional crops (it is a Fabaceae and can contribute to nitrogen fixation in the soil) [6][7].
2b) Risk for loss from spraying pesticides, herbicides		See 1c
3) Water quantity		As a spring/summer crop, irrigation is needed but is lower compared to other conventional crops like corn. It is considered as drought resistant, with water requirements estimated at least 300 mm.
4a) Habitat quality		Sunn hemp is a legume and thus fixes its own nitrogen through symbiosis with Rhizobium. It requires little or no nitrogen fertiliser if well-inoculated or grown in soils with existing compatible bacteria [6] [7] [9].
4b) Species viability contribution		It blooms in September and can provide food to pollinators. Sunn hemp is indeed considered pollinator-friendly and supports bee and insect populations when in bloom.
4c) Invasive species		Sunn hemp is not invasive. Sunn hemp is native to India and has spread globally as a valuable leguminous cover and fiber crop.

The scoring options are as follows:

Colour	Scoring
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL:

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		
					

 = TRL >7, industrial production already available at commercial scale

 = 5<=TRL=>7, production available at demo scale

 = 3<TRL>5, from research to production development

 = TRL<=3, only basic research data available

References

[1] https://www.echocommunity.org/resources/808239c5-009a-49f3-8f3a-8a9790836070

[2] Parenti, A., Cappelli,G., Zegada-Lizarazu, W., Martín Sastre, C., Christou, M., Monti, A., Ginaldi, F. (2021). SunnGro: A new crop model for the simulation of sunn hemp (Crotalaria juncea L.) grown under alternative management practices, Biomass and Bioenergy, Volume 146, 2021, 105975, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2021.105975.

[3] Wang, Q, Li, Y. C., Klassen, W., Hanlon, E (2015). Sunn Hemp—A Promising Cover Crop in Florida: Historical Fact Sheets, Vol. 2015 No. 7, SL 306/TR003, rev. 9/2015. https://doi.org/10.32473/edis-tr003-2015. https://journals.flvc.org/edis/article/view/124497

[4] https://www.nrcs.usda.gov/plantmaterials/njpmcpg11706.pdf

[5] https://www.nrcs.usda.gov/plantmaterials/flpmctn12687.pdf

[6] Rangappa Thimmaiah, M., Choudhary, S.B., Sharma, H.K. et al. Late-acting self-incompatibility: a barrier to self-fertilization in sunnhemp (Crotalaria juncea L.). Euphytica 214, 19 (2018). https://doi.org/10.1007/s10681-017-2096-9

[7] Purseglove JW(1981) Leguminosae. In: Purseglove JW(ed) Tropical crops: dicotyledons. Longman, Essex, UK, pp 250-254

[8] White GA, Haun JR (1965) Growing Crotalaria juncea, a multi-purpose legume, for paper pulp. Econ Bot 19:175-183

[9] https://www.feedipedia.org/node/313?utm

[10] https://www.ars.usda.gov/arsuserfiles/11809/2019_Meagher_etal_EnvironEntomol.pdf

References for crop yield data in Figure A.55

Parenti A., Zegada-Lizarazu W., Monti A. (2024). Relay-cropping enhances the availability of low iLUC risk lignocellulosic feedstock for advanced biofuels. Industrial Crops and Products, 219, art. no. 118998. DOI: 10.1016/j.indcrop.2024.118998
Zegada-Lizarazu W., Carvalho J.L.N., Parenti A., Tenelli S., Martín Sastre C., Ciria P., Christou M., Efthymia A., Bonomi A., Monti A. (2022). The effects of integrated food and bioenergy cropping systems on crop yields, soil health, and biomass quality: The EU and Brazilian experience. GCB Bioenergy, 14 (5), pp. 522 - 538. DOI: 10.1111/gcbb.12924
Zegada-Lizarazu W., Parenti A., Monti A. (2021). Intercropping grasses and legumes can contribute to the development of advanced biofuels. Biomass and Bioenergy, 149, art. no. 106086. DOI: 10.1016/j.biombioe.2021.106086
Xu Y., Porter N., Foster J.L., Muir J.P., Schwab P., Burson B.L., Jessup R.W. (2020). Silica production across candidate lignocellulosic biorefinery feedstocks. Agronomy, 10 (1), art. no. 82. DOI: 10.3390/agronomy10010082
Sarkar, S. K., Hazra, S. K., Sen, H. S., Karmakar, P. G., Tripathi, M. K. (2015). Sunnhemp in India. ICAR-Central Research Institute for Jute and Allied Fibres (ICAR), Barrackpore, West Bengal. https://www.researchgate.net/publication/304570874_sunnhemp_in_India. Cited in: Heuzé V., Thiollet H., Tran G., Lebas F. (2018). Sunn hemp (Crotalaria juncea). Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO. https://feedipedia.org/node/313 Last updated on November 27, 2018, 11:46
Kasirajan, S., Veeramani, P. and Zhou, W.J. (2021). Does heat accumulation alter crop phenology, fibre yield and fibre properties of sunnhemp (Crotalaria juncea L.) genotypes with changing seasons? Journal of Integrative Agriculture, Volume 20, Issue 9, Pages 2395-2409, ISSN 2095-3119, https://doi.org/10.1016/S2095-3119(20)63357-3.
Chaudhary B., Tripathi M.K., Bhandari H.R., Pandey S.K., Meena D.R., Prajapati S.P. (2015). Evaluation of sunnhemp (Crotalaria juncea) genotypes for high fibre yield. Indian Journal of Agricultural Sciences, 85 (6), pp. 850 - 853

Kenaf (Hibiscus cannabinus L., family Malvaceae)

Description of the crop: Kenaf is an annual summer crop that is cultivated for its fibrous stem. Kenaf stems are generally round with thorns that ranging from quite tiny to large, similar to those found on a black berry bush. Stem colour varies from pure green to deep burgundy. Kenaf stems have a thin bark over a woody core, surrounded by a leaf tuft [1]. Kenaf stems contain two major fiber types, the one contains long fibers situated in the cortical layer, and the other one contains short fibers located in the ligneous zone. The flowers are large (7.5 to 10 cm) with five petals. The flower colour ranges from light cream to dark purple. The seed develops in five-lobular capsule. The capsules of cultivated varieties are generally indehiscent and remain intact for several weeks after reaching maturity [2]. The seed is small (1.5-3.3 gr/100 seeds), black in colour and subreniform in shape (Figure A.57).

Origin and area of its cultivation in Europe: The existence of semi-wild kenaf in Africa (Kenya and Tanzania) might be an indication of the origin of the cultivated kenaf from this continent. In Europe, it has been investigated in a number of EU research projects namely BIOKENAF, 4FCROPS, Crops2Industry, FIBRA. The BIOKENAF project offered an integrated approach for kenaf covering the whole production chain (production, harvesting and storage) testing the suitability of the crop for industrial products (high added value) and energy. This integrated approach was carried out taking into consideration the environmental and the economic aspects of the crop and a market feasibility study was also conducted, Currently, kenaf is being investigated in the BeCool project. In Figure A.58, the crop at several stages of growth in field trials contacted in Greece is presented.

Figure A.57 View of the plant's parts (stems, flowers, roots, leaves and seeds).

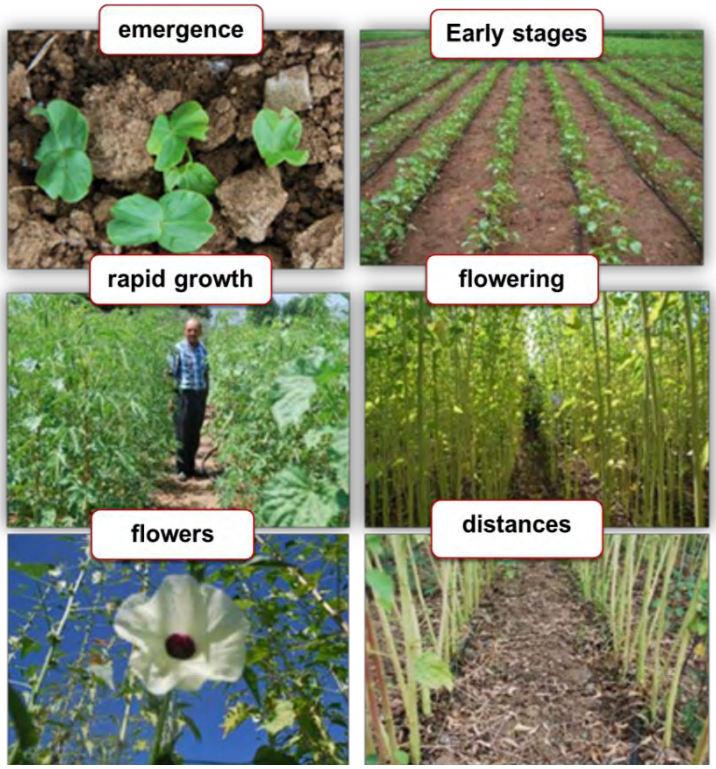


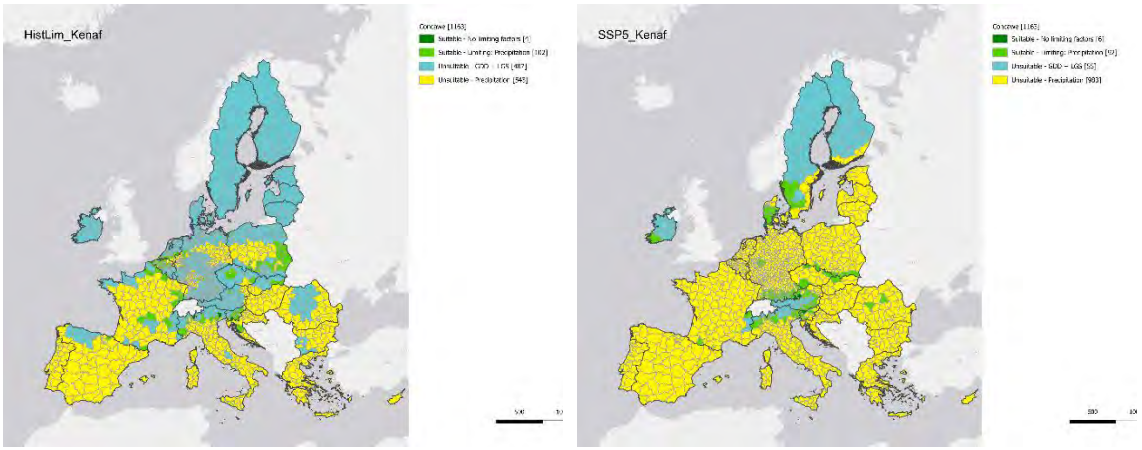
Figure A.58 View of kenaf plantation at several stages of growth (source: CRES).

Climate preferences: It can be grown in a wide range of climates and soils. In general, it can be grown up to 45 ^{0}N (South Europe). Its yields are higher in areas with high temperatures, long growing seasons and abundant soil moisture [3]. It is quite sensitive to low temperatures and grows slowly when temperature is below 10°C. In the current climate, the minimal length of the growth season/GDD, because of the high base temperature, is only met in the Mediterranean region and in some central regions in the EU. In the future, the area where the minimum length of growth season/GDD is met will increase. The limiting factor however in the Mediterranean region is the medium water demand. Additional irrigation cannot be avoided. Still the WUE of the crop is between 2.47-3.68 kg/ m^{-3} (dry matter biomass) under different irrigation levels (field trials, 2019-2020) [4].

Table A.13 Overview of climate suitability factors determining suitability for Kenaf grown as a summer crop.

Season	Minimum length of growth season (GS)	Minimum of growth degree days (thermal time)	Base temperature (°C)	Killing frost (°C)	Heat stress >32 ºC in final growth cycle	Minimum precipitation in GS	Max precipitation in GS
Summer Crop	90	1200	9 °C	< 0 °C	NO	>=400 mm	-

Figure A.59 Climate suitability for Kenaf grown as a summer crop. Left map refers to current climate and bottom maps refer to climate by 2050 in SSP5-8.5 scenario.



Soil preferences: Although it is adapted to a wide range of soil types, it performs best on the heavier, well drained, fertile soils. Areas with drainage problems should be avoided [5].

Soil preparation and sowing: Kenaf seeds are relatively small and require good seed-soil contact for germination. Therefore, a fine, firm, well-prepared seedbed is necessary. The ground temperature should be at least 15 ºC and warmer temperatures result in an increase in growth rate. Under favourable soil conditions, kenaf seeds emerge after two to four days. In south Mediterranean countries, kenaf can be planted in the spring once the soil has been warmed to 13°C and there is no threat of frost (April to May). The sowing depth should be up to 2.5 cm. Kenaf is a self-thinning crop and reduces its population during the growing season. When kenaf is cultivated at high plant populations, ranging from 300,000 to 500,000 plants/ha, a total quantity of 10-15 kg seed/ha is required, while when it is cultivated to achieve final plant populations of 185,000 to 370,000 plants/ha a quantity of about 8 to 12 kg/ha seed is needed [2]. In warm climates, kenaf emerges and grows so rapidly that it competes with weeds effectively. In cooler climates and with earlier planting dates, cultivar and/or chemical weed control measures are more important. One weed species, which is especially competitive with kenaf, is velvetleaf, a relative of kenaf. At the seedling stage, velvetleaf and kenaf are very similar in appearance and rate of growth. Fields with high populations of this weed are not recommended for kenaf production.

Figure A.60 Roots that have been affected by nematodes.

Fertilization and irrigation needs: Kenaf, unlike traditional agricultural crops that are grown for their seedσ, is grown mainly for its fiber stems and recently it is grown for both (stems and seeds). When the crop is harvested after the first killing frost the stems are defoliated. It has been estimated that the leaves (after they drop) return significant quantities of nitrogen (as high as 4.0% by weight), calcium, magnesium, phosphate and potassium back to the soil where the stalks that remain prevent them from blooming away. 500-625 mm of rainfall over a period of 5-6 months is essential for the successful production of kenaf fibres. A well-distributed rainfall of about 125 mm for each month during the growing season leads to optimal yields [6].

Varieties: Kenaf varieties, according to their reaction to flowering, can be grouped to early and late ones [7]. The flowering in the late varieties is closely related to the day length (the flowering starts when the day length is lower than 12½ hours). More than 240 varieties have been produced in τηε USA but onlyx a few are commercially grown (Tainung 1, Tainung 2, Everglades 41, Everglades 71, Dowling, Gregg, SF 459, and Whitten). Recently, a number of high yielding varieties have been developed in China (H328, H368, etc.). These varieties have been tested in the Mediterranean region and their productivity was higher compared to the imported varieties from USA.

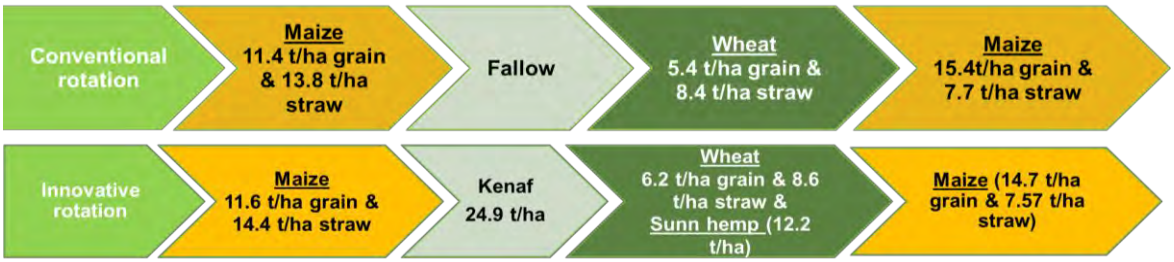
Biomass yields: In the view of the EUROKENAF project, demonstrative field trials were carried out in all the Mediterranean countries. The achieved yields were affected by the sowing date, the site of the trial, the water availability and the soil fertility. Dry stem yields of 8 to 18 t/ha were recorded in Greece, 12 to 17 t/ha in Italy, and 13 to 24 t/ha in Spain.

Diseases: Kenaf has high susceptibility to root knot nematodes caused by Meloidogyne incognita, Meloidogyne javanica and Meloidogyne arenaria. Nematodes are multicellular, microscopic, worm-like animals that feed mainly on plant root systems [8]. Leaves on plants infested with nematodes become yellow and fall down. The infested plants are stunted and in case of a heavy infestation, the plant may eventually die. The problem is particularly severe in light, sandy soils (Figure 3). The problem of nematodes could be managed by a combination of crop rotation and chemical control. Another approach is the development of nematode resistant varieties. The variety SF 459 is reported as nematode resistant [8]. It is also reported that the rotation kenaf/soybean was successful in terms of yields but did not reduce stunt nematode populations.

Harvesting time and options for use as intermediate crop: In BeCool project, a number of innovative rotation schemes have been tested for a period of four years (2017-22) in three Mediterranean countries (Greece, Italy and Spain) where sorghum have been included (among other alternatives) to get feedstock for advanced biofuels. In the view of this project, two completely cycles of the proposed schemes were completed.

The conventional rotation was: Year 1: Maize (April to October), Year 2: fallow till October when wheat was sown, Year 3: Wheat (by June) and then fallow till April next year and the innovative rotation where kenaf was added was as follows: Year 1: Maize, Year 2: Kenaf + Wheat, Year 3: continuation of Wheat + kenaf (see the graph below).

As it is presented, the yields of the two food crops (wheat and maize) did not reduce when the innovative rotation replaced the conventional one and at the same time low ILUC feedstock was produced by two intermediate crops; kenaf and sunn hemp.



Harvesting and storage: According to the end use of the crop, kenaf can be harvested as green or dry material. The green material is harvested during flowering (for high fiber quality), while the dry material during winter, when the plants are senesced and are still upright in the field, free of leaves, and with stems degraded by atmospheric and biological processes. The harvesters that can be used are: a) sugarcane type, b) jute/reed type, c) forage type combined with baling equipment and d) combined harvesting when stems and seeds should be harvested at the same time.

In the BIOKENAF project [9], harvesting trials were carried out in winter when the harvesting material had the lowest possible moisture content (Figure A.62) and a maize harvester (JAGUAR 870 - CLAAS) was used. The moisture content of the chopping material was 23%. The chopped material had been delivered to KEFITALIA Company, where it was separated to bark and core. The bark material it was used for insulation mats production (Figure A.63).

Figure A.62 Harvesting trials in northern Italy (source: CETA; BIOKENAF project).

Uses: Kenaf is a traditional third world crop that is poised to be introduced as a new annually renewable source of industrial fiber in the so-called developed economies. Kenaf like all the other important fiber crops (jute, roselle, hemp, flax, ramie, etc.) can be pulped to make a range of paper and pulps comparable in quality to those produced from wood [10]. With forests dwindling, the virgin wood becoming more expensive and the increasing demand for paper products, non-wood fiber crops such as kenaf could be important. Kenaf in a period of six months reaches a plant height of 3 to 4 m and its productivity is two to three times higher (per ha and per year) than the southern pine forests.

Figure A.63 Insulation mats produced by KEFITALIA (BIOKENAF project).

Although the importance of the crop is mainly for paper pulp production, kenaf is being characterized as a multi-purpose crop because it has a number of additional industrial applications. Thus, kenaf fibers (either derived from the bark or the core of the plant stem) can be an excellent source for several other uses such as fabrics, building materials (particleboards, low-density panels, wall paper backing, furniture underlays etc.), bedding material, poultry and/or cat litter, oil absorbent, etc [11]. Additionally, the whole plant has a high protein content and good digestibility and may be pelletized. Its seeds contain 20-25% oil which is rich in polyunsaturated fatty acids. Preliminary studies showed that kenaf oilseed can cure many health disorders such as blood pressure, cholesterol balance and some types of cancer. The crude protein in kenaf seed meal is 44.5 %.

Environmental impacts:

Environmental aspects	Color score	Explanation
1a) Soil structure		Kenaf as intermediate crop requires some additional mechanical disturbances of the soil for field preparation, plant treatment & harvesting.
1b) Soil organic carbon		Kenaf serves as a cover spring/summer crop which protects the soil against erosion.
1c) Soil biodiversity		Some herbicides are needed at the early stages of growth and kenaf can have problems in nematodes is sandy soils [8]. This may lead to some chemical inputs used.
2a) Risk for leaching to ground and surface water		Kenaf has a deep tap root and can absorb remaining nutrients from the soil and at the same time can accumulate heavy metals from the contaminated soil [2].
2b) Risk for loss from spraying pesticides, herbicides		See 1c
3) Water quantity		It requires 450 to 500 mm of water. It requires more water compared to sunn hemp and biomass sorghum [3] [4].
4a) Habitat quality		In the light of need for some pesticide use and medium levels of water needs it may have adverse effect on habitats quality.

4b) Species viability contribution		It flowers in September and the flowering phase can be limited and terminated earlier when low temperatures are coming earlier in the autumn [2][5].
4c) Invasive species		Kenaf is not invasive. It is native from Africa (Tanzania).

The scoring options are as follows:

Colour	Scoring
	Positive effect
	No effect
	Low to medium adverse effect
	High adverse effect

TRL: The same harvesting machinery with hemp can be used that in south Europe is not always available. It can produce seeds when it is grown in Europe (especially the varieties that are short day length) and the seeds should be imported either from USA or China.

Production level	Climatic suitability to Europe			Availability of propagation materials	Availability of mechanization systems
	North	Central	South		

= TRL >7, industrial production already available at commercial scale

= 5<=TRL=>7, production available at demo scale

= 3<TRL>5, from research to production development

= TRL<=3, only basic research data available

References

[1] Kaldor A F (1989) Preparation of kenaf bark and core fibres for pulping by the Annkel method. Tappi, J. 72 (9), 137-140.

[2] Alexopoulou, E., Papatheohari, Y., Christou, M., Monti, A. (2013). Origin, Description, Importance, and Cultivation Area of Kenaf. In: Monti, A., Alexopoulou, E. (eds) Kenaf: A Multi-Purpose Crop for Several Industrial Applications. Green Energy and Technology. Springer, London. https://doi.org/10.1007/978-1-4471-5067-1_1

[3] Alexopoulou, E., Li, D., Papatheohari, Y., Siqi, H., Scordia, D., Testa, G. (2015). How kenaf (Hibiscus cannabinus L.) can achieve high yields in Europe and China, Industrial Crops and Products, Volume 68, 2015, Pages 131-140, ISSN 0926-6690, https://doi.org/10.1016/j.indcrop.2014.10.027.

[4] Candoğan, B. N., Yetik, A. K., Sincik, M., Demir, A. O., & Büyükcangaz, H. (2025). Water Productivity and Yield Response of Deficit-Irrigated Kenaf (Hibiscus cannabinus L.) under Subhumid Climate Conditions. Journal of Irrigation and Drainage Engineering, 151(3), 04025006.

[5] https://corn.agronomy.wisc.edu/Crops/Kenaf.aspx

[6] Mambelli, S., & Grandi, S. (1995). Yield and quality of kenaf (Hibiscus cannabinus L.) stem as affected by harvest date and irrigation. Industrial Crops and Products, 4(2), 97-104

[7] https://www.sciencedirect.com/science/chapter/edited-volume/abs/pii/B9780128183984000050?via%3Dihub

[8] Vawdrey, L.L., Stirling, G.R. Reaction of kenaf and roselle grown in the burdekin river irrigation area to root-knot nematodes. Australasian Plant Pathology 21, 8-12 (1992). https://doi.org/10.1071/APP9920008

[9] https://www.cres.gr/biokenaf

[10] Wood, I. M. and S. de Jong. 1997. Plant fibre crops. In "The New Rural Industries". A handbook for Farmers and Investors. Edited by Keith Hype, pp. 453-463.

[11] Kaldor A F, Karlgren C, Yerwest H (1990) Kenaf – a fast growing fiber source for papermak-ing. Tappi – J 73 11, pp. 205-209.

APPENDIX 6. SCENARIOS NARRATIVE

1) Climate change

The table below describes the narrative characterising the two climate change scenarios used in this study (Reference: Riahi, K. & Vuuren, D. P. v., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change,* Volume 42.)

SSP	Narrative
1-2.6	Sustainability - Taking the Green Road (Low challenges to mitigation and adaptation): The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
5-8.5	Fossil-fuelled Development - Taking the Highway (High challenges to mitigation, low challenges to adaptation): This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

2) Land use change scenarios; detailed assumptions in policy narratives

EGD/F2F policy goals	BAU scenario 2050	SA scenario 2050
Organic farming	Not implement. Level 2020=2050	• 25% organic of UAA in 2050 • Yield reduction: -25% in new organic land • Yield reduction compensated by 50% additional production (additional land demand) • Increase animals for organic manure in regions where livestock is absent and water quality and nature quality allows
Pesticides	Not implement. Level 2020=2050	• Use and risk of chemical pesticides -50% & use of more hazardous pesticides -50% • Yield reduction: -10% (in combination with reduced nitrogen gift)
Reduce nutrient losses & fertilizer use	Not implement. Level 2020=2050	• Nutrient losses reduced by at least: -50%, • Through reduction fertilizer use: -20% • Through livestock reduction to reach good water quality and reduction of ammonia emissions below critical loads for nature • Leads to yield reduction: -10% (in combination with reduced pesticides gift)

EGD/F2F policy goals	BAU scenario 2050	SA scenario 2050
Nature restoration Law	Not implement. Level 2020=2050	• Restoration targets reached in all Natura 2000 and (through organic agriculture, reduction inputs) • No over exploitation of water resources • Discontinuation 17% of agricultural peatlands
Soil monitoring and resilience	No specific measures (outside CAP conditionality) Land-take built-up continues	• Soil in good status (reduction in soil loss, soil biodiversity) • Zero land take by 2050
Biobased & circular economy	Markets dictate demands for biobased developments. No active support- except for RED targets 2020	• Stricter GHG mitigation requirements in all sectors • Stricter requirements for defossilisation in all sectors

Climate change adaptation	No specific measures In drought-prone areas: 2% yield reduction	• Adaptation measures: new crop varieties and types adapted to climate change, including non-food crops • Investments in efficient water use
Protein transition	Not implemented diet 2020=2050	• Land released from decline in livestock used for vegetal protein crops and other non-food demands

APPENDIX 7. DETAILED SCENARIO RESULTS

Table A.14 Biomass potentials for summer oil crop intermediates for current, 2030, 2040 and 2050 for HT and LT scenario (ton seeds).

Countries	Current_Oil Summer (ton seeds)	HT_2030_Oil Summer (ton seeds)	LT_2030_Oil Summer (ton seeds)	HT_2040_Oil Summer (ton seeds)	LT_2040_Oil Summer (ton seeds)	HT_2050_Oil Summer (ton seeds)	LT_2050_Oil Summer (ton seeds)
Austria	308,530	343,050	341,230	377,569	373,930	412,089	406,630
Belgium	48,069	51,415	53,687	54,761	59,305	58,106	64,923
Bulgaria	181,723	146,146	139,016	110,569	96,310	74,993	53,604
Cyprus	-	-	-	-	-	-	-
Czechia	588,094	684,078	659,827	780,062	731,559	876,046	803,292
Germany	1,226,232	1,397,032	1,374,351	1,567,832	1,522,471	1,738,632	1,670,591
Denmark	353,307	487,404	473,775	621,501	594,242	755,597	714,709
Estonia	131,666	165,997	166,375	200,329	201,085	234,660	235,794
Greece	32,633	36,385	34,699	40,136	36,764	43,888	38,829
Spain	174,321	194,923	131,044	215,525	87,767	236,127	44,489
Finland	353,092	391,506	378,174	429,920	403,255	468,334	428,336
France	887,125	1,183,475	1,092,657	1,479,826	1,298,189	1,776,177	1,503,721
Croatia	93,257	74,441	67,399	55,625	41,541	36,808	15,683

Countries	Current_Oil Summer (ton seeds)	HT_2030_Oil Summer (ton seeds)	LT_2030_Oil Summer (ton seeds)	HT_2040_Oil Summer (ton seeds)	LT_2040_Oil Summer (ton seeds)	HT_2050_Oil Summer (ton seeds)	LT_2050_Oil Summer (ton seeds)
Hungary	534,471	543,670	534,246	552,870	534,021	562,069	533,797
Ireland	27,516	29,910	30,717	32,304	33,918	34,698	37,119
Italy	160,246	174,683	172,315	189,120	184,383	203,557	196,452
Lithuania	623,962	619,263	683,556	614,564	743,149	609,865	802,743
Luxembourg	4,584	5,633	5,225	6,682	5,866	7,731	6,507
Latvia	316,347	410,327	405,237	504,308	494,127	598,289	583,017
Malta	-	-	-	-	-	-	-
Netherlands	51,320	51,131	53,072	50,941	54,825	50,751	56,577
Poland	2,512,102	2,716,807	2,795,264	2,921,512	3,078,427	3,126,218	3,361,589
Portugal	77	54	58	31	39	8	20
Romania	635,258	580,529	542,491	525,800	449,725	471,071	356,958
Sweden	290,848	379,553	357,043	468,258	423,239	556,963	489,434
Slovenia	478	473	522	468	567	463	612
Slovakia	214,348	241,611	240,252	268,874	266,156	296,137	292,060
EU27	9,749,604	10,909,495	10,732,232	12,069,386	11,714,859	13,229,277	12,697,486

Table A.15 Biomass potential for summer lignocellulosic crop intermediate (biomass sorghum) for current, 2030, 2040 and 2050 for HT and LT scenario (t_{dm}=ton dry mass).

Countries	Current_Ligno Summer (tdm)	HT_2030_Ligno Summer (tdm)	LT_2030_Ligno Summer (tdm)	HT_2040_Ligno Summer (tdm)	LT_2040_Ligno Summer (tdm)	HT_2050_Ligno Summer (tdm)	LT_2050_Ligno Summer (tdm)
Austria	290,801	326,764	385,859	362,727	480,917	398,690	575,976
Belgium	16,882	46,023	86,154	75,163	155,427	104,304	224,699
Bulgaria	1,256,636	1,244,438	1,223,892	1,232,241	1,191,148	1,220,043	1,158,403
Cyprus	-	-	-	-	-	-	-
Czechia	31,868	433,632	700,577	835,397	1,369,287	1,237,161	2,037,996
Germany	445,093	1,431,586	1,787,698	2,418,080	3,130,304	3,404,573	4,472,909
Denmark	-	29,689	97,379	59,379	194,758	89,068	292,136
Estonia	-	-	103,533	-	207,067	-	310,600
Greece	289,755	289,930	290,182	290,106	290,609	290,281	291,036
Spain	156,459	206,575	192,354	256,692	228,250	306,808	264,146
Finland	-	-	-	-	-	-	-
France	1,836,728	2,482,088	2,435,295	3,127,448	3,033,863	3,772,808	3,632,430
Croatia	704,785	541,980	498,859	379,176	292,934	216,372	87,008
Hungary	2,124,411	2,057,809	2,053,796	1,991,207	1,983,181	1,924,605	1,912,567
Ireland	-	-	220	-	440	-	660
Italy	790,302	839,450	867,544	888,598	944,786	937,746	1,022,029
Lithuania	-	169,012	1,521,177	338,024	3,042,354	507,037	4,563,530
Luxembourg	-	2,517	5,245	5,035	10,490	7,552	15,735
Latvia	-	63,866	851,221	127,731	1,702,442	191,597	2,553,663

Countries	Current_Ligno Summer (tdm)	HT_2030_Ligno Summer (tdm)	LT_2030_Ligno Summer (tdm)	HT_2040_Ligno Summer (tdm)	LT_2040_Ligno Summer (tdm)	HT_2050_Ligno Summer (tdm)	LT_2050_Ligno Summer (tdm)
Malta	-	-	-	-	-	-	-
Netherlands	11,867	25,326	41,470	38,786	71,074	52,246	100,677
Poland	1,230,397	3,891,644	4,948,223	6,552,892	8,666,049	9,214,139	12,383,876
Portugal	376	259	260	142	144	26	29
Romania	3,399,291	3,391,724	3,431,332	3,384,158	3,463,374	3,376,592	3,495,415
Sweden	-	10,985	61,330	21,970	122,661	32,955	183,991
Slovenia	842	851	972	859	1,102	868	1,231
Slovakia	176,421	207,006	221,978	237,592	267,536	268,177	313,093
EU27	12,762,911	17,693,157	21,806,552	22,623,402	30,850,193	27,553,648	39,893,834

Table A.16 Biomass potentials for winter oil crop intermediates for current, 2030, 2040 and 2050 for HT and LT scenario (ton seeds).

Countries	Current_Oil Winter (ton seeds)	HT_2030_Oil Winter (ton seeds)	LT_2030_Oil Winter (ton seeds)	HT_2040_Oil Winter (ton seeds)	LT_2040_Oil Winter (ton seeds)	HT_2050_Oil Winter (ton seeds)	LT_2050_Oil Winter (ton seeds)
Austria	3,622	4,420	3,632	5,219	3,643	6,017	3,654
Belgium	5,430	6,339	5,025	7,247	4,619	8,155	4,214
Bulgaria	6,025	5,220	11,027	4,415	16,030	3,610	21,032
Cyprus	1,897	1,424	1,416	952	935	479	454
Czechia	-	2,492	1,072	4,983	2,144	7,475	3,216
Germany	7,066	14,783	9,888	22,500	12,710	30,218	15,532
Denmark	-	1,067	749	2,135	1,497	3,202	2,246
Estonia	-	-	-	-	-	-	-
Greece	68,076	52,684	64,417	37,292	60,758	21,899	57,099
Spain	409,657	359,991	375,599	310,326	341,541	260,660	307,483
Finland	-	-	-	-	-	-	-
France	211,125	240,940	316,791	270,755	422,458	300,570	528,124
Croatia	1,856	1,388	1,259	919	661	450	63
Hungary	10,064	8,560	8,282	7,056	6,500	5,552	4,718

Countries	Current_Oil Winter (ton seeds)	HT_2030_Oil Winter (ton seeds)	LT_2030_Oil Winter (ton seeds)	HT_2040_Oil Winter (ton seeds)	LT_2040_Oil Winter (ton seeds)	HT_2050_Oil Winter (ton seeds)	LT_2050_Oil Winter (ton seeds)
Ireland	71	148	204	226	338	304	472
Italy	175,502	129,192	132,860	82,883	90,218	36,574	47,576
Lithuania	-	213	474	425	948	638	1,422
Luxembourg	-	36	33	73	66	109	99
Latvia	-	-	668	-	1,336	-	2,005
Malta	97	65	65	33	34	1	2
Netherlands	5,270	8,745	4,496	12,219	3,721	15,693	2,947
Poland	1,037	9,062	5,453	17,087	9,869	25,112	14,284
Portugal	56,273	43,712	42,470	31,152	28,667	18,591	14,864
Romania	9,731	8,660	9,420	7,588	9,110	6,516	8,799
Sweden	-	-	262	-	524	-	786
Slovenia	138	176	150	214	163	252	176
Slovakia	1,130	1,159	1,406	1,188	1,683	1,218	1,959
EU27	974,067	900,476	997,119	826,885	1,020,172	753,295	1,043,225

Table A.17 Area (ha) climatically suitable and area (ha) where climate and rotation match with the LGS needs of the intermediate summer crops.

Current scenario summer intermediates											
	Cropland with summer fallow (ha)	CamelinaS climate suitable (ha)	WhiteMust climate suitable (ha)	CrambeS climate suitable (ha)	BiomSorgh climate suitable (ha)	Camelina fits in rotation (ha)	WhiteMust fits in rotation (ha)	Crambe fits in rotation (ha)	BiomSorgh fits in rotation (ha)	Max area Oil (ha)	Max area Ligno (ha)
Alpine	222,653	222,283	137,638	218,449	2,352	104,479	70,219	33,363	112	104,727	112
Atlantic	8,527,884	8,472,126	7,874,471	8,472,109	4,241,216	1,439,255	1,300,793	537,203	123,191	1,448,970	123,191
Continental	19,339,019	17,492,572	18,136,858	17,492,276	10,057,925	5,947,813	6,013,577	2,105,447	759,328	6,132,164	759,328
Mediterranean	6,131,557	1,794,073	2,847,781	1,483,575	4,013,375	268,397	415,006	53,998	129,835	415,075	129,835
North	3,643,279	3,641,375	2,173,172	3,429,660	-	1,903,208	1,067,307	1,078,609	-	1,903,208	-
EU27	37,864,391	31,622,430	31,169,920	31,096,068	18,314,868	9,663,152	8,866,902	3,808,621	1,012,466	10,004,144	1,012,466
High Transition scenario summer intermediates (2050)											
	Cropland with summer fallow (ha)	CamelinaS climate suitable (ha)	WhiteMust climate suitable (ha)	CrambeS climate suitable (ha)	BiomSorgh climate suitable (ha)	Camelina fits in rotation (ha)	WhiteMust fits in rotation (ha)	Crambe fits in rotation (ha)	BiomSorgh fits in rotation (ha)	Max area Oil (ha)	Max area Ligno (ha)
Alpine	161,801	161,792	161,729	149,940	123,801	74,821	74,804	20,681	3,862	74,843	3,862
Atlantic	9,121,426	9,052,254	9,121,336	8,951,120	7,978,835	1,624,874	1,636,820	562,433	276,144	1,636,820	276,144
Continental	16,491,338	13,213,297	13,525,221	14,367,933	16,092,887	4,522,542	4,595,910	1,688,129	1,383,504	4,795,226	1,383,504
Mediterranean	5,752,444	1,144,720	2,360,054	2,832,103	4,323,438	121,318	345,291	125,800	147,392	415,575	147,392

North	3,137,084	3,135,606	3,125,631	1,702,945	1,327,310	1,743,732	1,736,491	454,563	46,094	1,743,732	46,094
EU27	34,664,094	26,707,670	28,293,971	28,004,041	29,846,271	8,087,287	8,389,316	2,851,606	1,856,995	8,666,196	1,856,995

Low Transition scenario summer intermediates (2050)

	Cropland with summer fallow (ha)	CamelinaS climate suitable (ha)	WhiteMust climate suitable (ha)	CrambeS climate suitable (ha)	BiomSorgh climate suitable (ha)	Camelina fits in rotation (ha)	WhiteMust fits in rotation (ha)	Crambe fits in rotation (ha)	BiomSorgh fits in rotation (ha)	Max area Oil (ha)	Max area Ligno (ha)
Alpine	159,903	159,887	159,887	155,310	153,132	76,452	76,452	22,078	18,690	76,452	18,690
Atlantic	8,480,909	8,387,843	8,419,322	8,327,387	8,311,122	1,530,238	1,535,112	536,960	334,534	1,545,635	334,534
Continental	16,794,766	12,587,361	13,084,395	14,021,122	16,694,452	4,446,492	4,594,327	1,700,321	1,779,254	4,840,057	1,779,254
Mediterranean	6,078,200	597,928	1,642,920	2,262,555	3,985,738	76,985	213,336	117,938	149,406	294,677	149,406
North	3,250,989	3,250,064	3,248,261	2,888,415	2,307,600	1,829,151	1,827,699	981,849	550,064	1,829,151	550,064
EU27	34,764,768	24,983,082	26,554,785	27,654,789	31,452,044	7,959,318	8,246,926	3,359,146	2,831,948	8,585,973	2,831,948

Table A.18 Relative area (% of total cropland) per crop climatically suitable and relative area where climate and rotation match with the LGS needs of the intermediate summer crops.

Current scenario summer intermediates											
	Cropland with winter fallow (ha)	CamelinaS climate suitable (ha)	WhiteMust climate suitable (ha)	CrambeS climate suitable (ha)	BiomSorgh climate suitable (ha)	Camelina fits in rotation (ha)	WhiteMust fits in rotation (ha)	Crambe fits in rotation (ha)	BiomSorgh fits in rotation (ha)	Max area Oil (ha)	Max area Ligno Current (ha)
Alpine	100%	100%	62%	98%	1%	47%	32%	15%	0%	47%	0%
Atlantic	100%	99%	92%	99%	50%	17%	15%	6%	1%	17%	1%
Continental	100%	90%	94%	90%	52%	31%	31%	11%	4%	32%	4%
Mediterranean	100%	29%	46%	24%	65%	4%	7%	1%	2%	7%	2%
North	100%	100%	60%	94%	0%	52%	29%	30%	0%	52%	0%
EU27	100%	84%	82%	82%	48%	26%	23%	10%	3%	26%	3%
High Transition scenario summer intermediates (2050)											
	Cropland with winter fallow (ha)	CamelinaS climate suitable (ha)	WhiteMust climate suitable (ha)	CrambeS climate suitable (ha)	BiomSorgh climate suitable (ha)	Camelina fits in rotation (ha)	WhiteMust fits in rotation (ha)	Crambe fits in rotation (ha)	BiomSorgh fits in rotation (ha)	Max area Oil (ha)	Max area Ligno Current
Alpine	100%	100%	100%	93%	77%	46%	46%	13%	2%	46%	2%
Atlantic	100%	99%	100%	98%	87%	18%	18%	6%	3%	18%	3%
Continental	100%	80%	82%	87%	98%	27%	28%	10%	8%	29%	8%
Mediterranean	100%	20%	41%	49%	75%	2%	6%	2%	3%	7%	3%
North	100%	100%	100%	54%	42%	56%	55%	14%	1%	56%	1%
EU27	100%	77%	82%	81%	86%	23%	24%	8%	5%	25%	5%

Low Transition scenario summer intermediates (2050)											
	Cropland with winter fallow (ha)	CamelinaS climate suitable (ha)	WhiteMust climate suitable (ha)	CrambeS climate suitable (ha)	BiomSorgh climate suitable (ha)	Camelina fits in rotation (ha)	WhiteMust fits in rotation (ha)	Crambe fits in rotation (ha)	BiomSorgh fits in rotation (ha)	Max area Oil (ha)	Max area Ligno Current
Alpine	100%	100%	100%	97%	96%	48%	48%	14%	12%	48%	12%
Atlantic	100%	99%	99%	98%	98%	18%	18%	6%	4%	18%	4%
Continental	100%	75%	78%	83%	99%	26%	27%	10%	11%	29%	11%
Mediterranean	100%	10%	27%	37%	66%	1%	4%	2%	2%	5%	2%
North	100%	100%	100%	89%	71%	56%	56%	30%	17%	56%	17%
EU27	100%	72%	76%	80%	90%	23%	24%	10%	8%	25%	8%

Table A.19 Area (ha) climatically suitable and area (ha) where climate and rotation match with the LGS needs of the intermediate winter crops.

Current scenario winter intermediates						
	Cropland with summer fallow (ha)	CamelinaW climate suitable (ha)	CrambeW climate suitable (ha)	Camelina fit in rotation (ha)	Crambe fit in rotation (ha)	Max area Oil (ha)
Alpine	409,092	6,523	80	26	-	26
Atlantic	10,408,327	8,854,186	5,843,759	116,791	39,205	116,791
Continental	17,546,520	8,431,605	5,853,901	19,618	12,024	19,618
Mediterranean	10,124,819	8,922,435	7,522,633	566,810	348,450	566,810
North	1,972,956	-	-	-	-	-
EU27	40,461,713	26,214,749	19,220,374	703,245	399,679	703,245
High Transition scenario winter intermediates (2050)						
	Cropland with summer fallow (ha)	CamelinaW climate suitable (ha)	CrambeW climate suitable (ha)	Camelina fit in rotation (ha)	Crambe fit in rotation (ha)	Max area Oil (ha)
Alpine	421,611	242,093	50,930	6,977	5,931	539
Atlantic	12,157,565	12,074,727	11,174,934	200,266	57,539	199,709
Continental	20,528,531	19,534,894	10,144,971	41,041	24,810	35,863
Mediterranean	9,152,241	9,064,189	8,636,402	276,290	153,596	276,117
North	2,042,330	42,879	-	1,249,667	1,244,511	369
EU27	44,302,279	40,958,782	30,007,237	1,774,241	1,486,388	512,597

Low Transition scenario winter intermediates (2050)						
	Cropland with summer fallow (ha)	CamelinaW climate suitable (ha)	CrambeW climate suitable (ha)	Camelina fit in rotation (ha)	Crambe fit in rotation (ha)	Max area Oil (ha)
Alpine	377,827	347,060	221,412	588	347	588
Atlantic	11,457,250	11,457,250	11,046,307	334,360	63,840	334,360
Continental	19,434,210	19,421,938	18,254,805	34,757	20,454	34,757
Mediterranean	8,511,754	8,448,314	8,441,633	452,482	210,593	452,482
North	1,833,310	654,508	45,079	2,301	78	2,301
EU27	41,614,351	40,329,071	38,009,236	824,489	295,312	824,489

Table A.20 Relative area (% of total cropland) per crop climatically suitable and relative area where climate and rotation match with the LGS needs of the intermediate winter crops.

Current scenario summer intermediates						
	Cropland with summer fallow (ha)	CamelinaW climate suitable (ha)	CrambeW climate suitable (ha)	Camelina fit in rotation (ha)	Crambe fit in rotation (ha)	Max area Oil (ha)
Alpine	100%	2%	0%	0%	0%	0%
Atlantic	100%	85%	56%	1%	0%	1%
Continental	100%	48%	33%	0%	0%	0%
Mediterranean	100%	88%	74%	6%	3%	6%
North	100%	0%	0%	0%	0%	0%
EU27	100%	65%	48%	2%	1%	2%
High Transition scenario summer intermediates (2050)						
	Cropland with summer fallow (ha)	CamelinaW climate suitable (ha)	CrambeW climate suitable (ha)	Camelina fit in rotation (ha)	Crambe fit in rotation (ha)	Max area Oil (ha)
Alpine	100%	57%	12%	2%	1%	0%
Atlantic	100%	99%	92%	2%	0%	2%
Continental	100%	95%	49%	0%	0%	0%
Mediterranean	100%	99%	94%	3%	2%	3%
North	100%	2%	0%	61%	61%	0%
EU27	100%	92%	68%	4%	3%	1%
Low Transition scenario summer intermediates (2050)						
	Cropland with summer fallow (ha)	CamelinaW climate suitable (ha)	CrambeW climate suitable (ha)	Camelina fit in rotation (ha)	Crambe fit in rotation (ha)	Max area Oil (ha)
Alpine	100%	92%	59%	0%	0%	0%
Atlantic	100%	100%	96%	3%	1%	3%

Continental	100%	100%	94%	0%	0%	0%
Mediterranean	100%	99%	99%	5%	2%	5%
North	100%	36%	2%	0%	0%	0%
EU27	100%	97%	91%	2%	1%	2%

Concawe
Av. des Nerviens 85
1040, Brussels | Belgium

Tel: +32-2-566 91 60
e-mail: info@concawe.eu
http://www.concawe.eu

ISBN 978-2-87567-213-1