BIKE

BIOFUELS PRODUCTION
AT LOW - ILUC RISK
FOR EUROPEAN SUSTAINABLE
BIOECONOMY

D 2.2

Options to grow crops on unused, abandoned and/or severely degraded lands

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Executive summary

This report presents the results from Task 2.2 in the BIKE project. This task evaluates the potential to produce biomass feedstocks in unused, abandoned or severely degraded land. The review strongly builds on recently finished work in the H2020 project MAGIC, PANACEA and BECOOL and the contract study for DG-ENER on the status of land availability in the EU and use for energy and other non-food crops[1]. The review involves the following aspects:

1) An overview of the characteristics of unused, abandoned and degraded lands in terms of biophysical (soil and climate) characteristics and how they influence on crop growth suitability. This will also involves a discussion of how these categories of land differ from the better agricultural lands where most of the cropping for food takes place.

2) An overview of biomass crops and their characteristics which is discussed particularly in relation to their ability to grow under more marginal conditions. Here we will focus on both annual and perennial crops, but particularly those that are non-food.

3) A review of the yielding potential of the selected crops in lands with good agricultural conditions and under natural constraints.

4) A review of economic and wider environmental performance of the selected crops

[1] ANALYSIS OF ACTUAL LAND AVAILABILITY IN THE EU; TRENDS IN UNUSED, ABANDONED AND DEGRADED (NON-) AGRICULTURAL LAND AND USE FOR ENERGY AND OTHER NON-FOOD CROPS (ENER/C2/2018-440)

1. Introduction

1.1 Introduction

This report presents the results from Task 2.2 in the BIKE project. The work in this task evaluates the potential to produce biomass feedstocks in unused, abandoned or severely degraded land. The review strongly builds on recently finished work in the EU projects of the European projects S2Biom, MAGIC, PANACEA, SoilCare, BIO4A and BECOOL and the DG-ENER contract study on the status of land availability in the EU and use for energy and other non-food crops[2]. The review involves the following aspects.

1) An overview of the characteristics of unused, abandoned and degraded lands in terms of biophysical (soil and climate) characteristics and how they influence on crop growth suitability. This will also involve a discussion of how these categories of land differ from the better agricultural lands where most of the existing (food) cropping takes place.

2) An overview of biomass crops and their characteristics is discussed particularly in relation to their ability to grow under more marginal conditions. Here we will focus on both annual and perennial crops, but particularly those that are not used to produce food or fodder.

3) A review of the yielding potential of the selected crops in situations of fewer compared to abundant natural constraints.

4) A review of economic and wider environmental performance of the selected crops

As part of EU's circular and climate objectives there is a need for sustainable biomass supply with no or low indirect land use change (ILUC) impacts for use as feedstock for conventional biofuels, bioliquids, and biomass fuels. The EU's Renewable Energy Directive II (RED II) mandates the phase-out after 2023 of "high ILUC-risk" biofuels which are fuels produced from feedstocks associated with significant levels of agricultural expansion into land with high carbon stock (EC, 2018; EC, 2019ab). Because of this the REDII also introduces the option to certify ' low ILUC risk' biofuels which are bioliquids and biomass fuels which are based on feedstocks that avoid displacement of food production. The rationale of the low-ILUC concept is rooted in the principle of 'additionality' which implies that feedstock can only be low-ILUC only if there is evidence that it would not have been produced without the advanced biofuel sector. This implies that using the materials for biofuels that will drive up total demand and hence incentivise unintended agricultural expansion is to be avoided. There are 3 ways in which low-ILUC-biomass can be derived/produced:

1) Through the use of residual biomass streams
2) Through dedicated cropping going together with yield increases from improved agronomic practices leading to above baseline yield increases within the same area of land
3) Through cultivation of areas of unused, abandoned or degraded land.

In this report we focus on low ILUC biomass production falling under the third option. The second option is further discussed in BIKE Deliverable 2.1.

[2] ANALYSIS OF ACTUAL LAND AVAILABILITY IN THE EU; TRENDS IN UNUSED, ABANDONED AND DEGRADED (NON-) AGRICULTURAL LAND AND USE FOR ENERGY AND OTHER NON-FOOD CROPS (ENER/C2/2018-440)

The reason to focus in BIKE on the opportunities to source low ILUC-biomass from dedicated cropping is related to the growing consensus in the EU that sustainable biomass supply from residues alone will not be sufficient to match the increasing demand for biomass worldwide (Goh et al., 2020; (e.g. Valin et al., 2015; Plevin et al. 2015; Pelkmans et al., 2016; OECD, 2018). This gap can be expected to widen as RED II targets become more ambitious, RED II caps become more stringent, and as competition for residual biomass streams (e.g. waste oils, straw) increases. Low ILUC-risk biomass from dedicated cropping can therefore be seen as an opportunity to fill this expected supply gap.

When reviewing the option for Low-ILUC biomass production there are many issues that need to be taken into account which are also influenced by different policy instruments. It concerns land availability and productivity, agronomic practices and sustainability, particularly in relation to GHG emissions and carbon sinks, sustainable soils, biodiversity, water quality and quantity, rural and socioeconomic development. All these aspects are influenced by existing and new regulations expected from the EU Green Deal, 'Fit-for 55' and the 'Farm to fork' EU policy packages.

Research activities in the field of low input biomass resources have intensified during the last decade. Key research themes included the feasibility of restoring land with natural constraints, the biophysical capacity of crops to grow under different agro-climatic conditions, and their economic profitability both in farming land and in land with natural constraints.

The most recent developments in relation to the war in Ukraine are influencing the world food market situation leading to higher prices for cereals and oil crops. In our assessment of future low ILUC biomass supply availability for dedicated biomass crops it is difficult to already predict the effect of this war but it is likely that land abandonment processes may be partly reversed. Where possible we will discuss what the influence of this potential 'game changer' may be on low ILUC crop production options.

What is currently being discussed is already the 'REPowerEU' which is about rapidly reducing Europe's dependence on Russian fossil fuels by fast forwarding the clean transition and joining forces to achieve a more resilient energy system and a true Energy Union. In that respect, the Commission is proposing to increase the target in the Renewable Energy Directive to 45% of renewable energy sources in the overall energy mix by 2030, up from 40% in last year's proposal. This would bring the total renewable energy generation capacities to 1236 GW by 2030, in comparison to 1067 GW by 2030 envisaged under Fit for 55 for 2030.

Finally it should be mentioned that part of the contents of this deliverable is overlapping with the information recently published in a review paper:

Panoutsou, C., Giarola, S., Ibrahim, D., Verzandvoort, S., Elbersen, B., Sandford, C., Malins, C., Politi, M., Vourliotakis, G., Zita, V. E., Vásáry, V., Alexopoulou, E., Salimbeni, A. & Chiaramonti, D. (2022), Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe. 1 May 2022, In: Applied Sciences (Switzerland). 12, 9, 4623.

This review paper is based on the content presented in D2.1 and D2.2 (this report) and these were written simultaneously with the review paper.

1.2 Approach

In this report a review is presented of the biophysical and economic opportunities for low ILUC risk dedicated cropped biomass produced on lands with natural constraints which are often applicable to unused, abandoned and degraded lands. This review is based on current results from seven relevant European Union funded projects: S2Biom, MAGIC, PANACEA, SoilCare, and BIO4A, BECOOL and DG-ENER contract study on the status of land availability in the EU and use for energy and other non-food crops[3]. The focus of the analysis is on inedible oil and lignocellulosic biomass crops that could be produced without competing with food and feed markets, are adapted to European agro-ecological zones (AEZ) (Metzger et al, 2018) suitable to be grown in both good agricultural lands and in lands with natural constraints that are often occurring in unused, abandoned and severely degraded lands.

The following approach was taken to compile all information presented in this report.

Firstly, a review was made of the latest EU policy developments regarding low ILUC biomass production. This review is based on a consultation of most recent publicly available policy documents and recent publications.

Secondly, an overview of the characteristics of unused, abandoned and degraded lands is made in terms of biophysical (soil and climate) characteristics, their potential extend and location and how they influence crop growth suitability. The presented information is mostly based on the information generated on this topic in the MAGIC project and in the DG-Ener contract study.

Thirdly, an overview of biomass crops and their characteristics is discussed particularly in relation to their ability to grow under natural constraints. Here we will focus on both annual and perennial crops, but particularly those that are not suitable to produce- food or fodder from. For selecting crops we build on the knowledge generated mostly in the MAGIC and Panacea projects. The selection of crops to be used for the production of low-ILUC biofuels is determined by:

1) the technological readiness level (TRL) for 2030 while being adapted to European agroecological climatic zones,
2) suitability as feedstock for advanced biofuels and,
3) good adaptability when cultivated in land with natural constraints.

The PANACEA project used the TRL (Panacea, 2019) as a method to evaluate the readiness of twenty-nine near-to-practice non-food crops that are suitable to grow in different European regions as feedstocks for biofuel and bioenergy. The ranking (Table 1) was performed for the crop productivity and ability to be grown and harvested using existing machinery. In this paper we narrowed down the selection to include only oil and lignocellulosic crops.

Table 1.1 Technology readiness level (TRL) for the criteria used in assessing strengths for non-food biomass crops.

TRL	Selection	Scale of Technological Readiness Level
TRL > 7	+++	(a) industrial production at commercial scale (b) used at commercial scale for multiple end-uses (c) high
TRL5–7	++	(a) production available at demo scale (b) recognized for its multiple end-uses (c) medium

[3] ANALYSIS OF ACTUAL LAND AVAILABILITY IN THE EU; TRENDS IN UNUSED, ABANDONED AND DEGRADED (NON-) AGRICULTURAL LAND AND USE FOR ENERGY AND OTHER NON-FOOD CROPS (ENER/C2/2018-440)

TRL	Selection	Scale of Technological Readiness Level
TRL3–5	+	(a) research to production development (b) recognized end-use but still at the research level (c) low
TRL < 3	-	(a) basic research data available (b) no recognized end-use (c) very low

Chapter 3 presents an overview of the selected crops for this report and how they score on TRL (see Table 1), suitability as feedstock for advanced biofuel generation and suitability to cope with natural constraints. The focus here is on oil and lignocellulosic crops as discussed in chapter 3. For these crops an extensive characterization is presented in this same chapter 3. In chapter 4 the review is presented of the yielding potentials of the selected crops in situations of cropping on good quality agricultural land and in situations of different types of natural constraints. Information on the yield performance of the selected industrial crops was derived from reviews and reports on the yield performance of industrial crops cultivated under favourable and unfavourable conditions with regard to climate and/or soil and terrain. The reviews and reports considered were mostly compiled in the framework of the EU-project MAGIC[4]. The conditions are referred to as respectively 'non-marginal' and where one or more natural constraints apply as 'marginal' . The marginal conditions considered in the compilation are discussed further in chapter 2.

[4] https://magic-h2020.eu/ Horizon 2020 project, grant agreement No. 727698.

2. Unused, abandoned and degraded lands: policies and status

2.1 Introduction

As already explained before one of the options to obtain biomass for biofuels to comply with the low ILUC risk category in the REDII is through cultivation of areas of unused, abandoned or degraded lands. In the following we will first explain in more detail how policy addresses Low ILUC risk biofuels, why and how this is worked out so far in the RED II, and which policy instruments exist or are being developed that stimulate, support and regulate the sustainable production of biomass for biofuels and wider non-food purposes.

In Section 3 a further explanation is then given of how 'Unused, abandoned and degraded lands' are defined in the REDII, what statistical and spatial information is already available in practice and how they can be further characterised and identified. This information is an important starting point for the identification of crops that are most suitable to be grown in these types of lands to provide the biomass for low ILUC risk biofuels.

2.2 Policies of relevance for Low ILUC risk biomass production

There are several policy instruments that have recently been introduced and are being further elaborated as part of the wider EU suit of sectoral policies and visions and strategies that all support reaching the overarching targets of climate change mitigation, overall improved sustainability, including reversing ecosystem service and biodiversity decline. Biomass production for a low carbon economy plays a central role in the European political aspirations for energy and agriculture. The European Green Deal and the Common Agricultural Policy (CAP) are therefore major instruments that aim to improve competitiveness and economic resilience at the farm level, diversifying production pathways (and hence enhancing the viability of farm incomes) across European regions.

In the context of low ILUC risk biomass production, the RED II (and REDIII) and Common Agricultural Policy are most relevant to discuss.

REDII

The Renewable Energy Directive (2009/28/EC) (now often referred to as REDI) that established an over-all policy for the production and promotion of energy from renewable sources in the EU. It required the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets specified in National Renewable Action plans (NREAPs) and to ensure that at least 10% of the transport fuels consumed in every EU country come from renewable sources by 2020. These targets ranged from a low of 10% in Malta to a high of 49% in Sweden. End 2018 an update of the REDI entered into force, the recast Renewable Energy Directive (2018/2001/EU), (now often referred to as REDII) as part of the 'Clean energy for all Europeans' pack-age. It established new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023. The final text of RED II also requires Member States to apply a mandate of 14% of transport fuels from renewable energy sources. The current 10% target which is binding on Member States (as specified in RED, 2009/28/EC) and is replaced by a requirement for Member States to introduce an obligation on fuel suppliers enabling the achievement of a 14% target for renewables including a sub target for advanced biofuels. The REDII also aims to phase out biofuels with a high ILUC risk and to promote biofuels with a low ILUC risk. Banning this ILUC risk is based on the EU wide acknowledgement that the process of ILUC may cause the release of CO2 stored in trees and soil, indirect land use change risks negating the greenhouse gas savings that result from increased biofuels. To address the issue of ILUC in the Clean Energy for All Europeans package, the REDII introduced a new approach. The limit set on the high ILUC fuels affects the amount of these fuels that Member States can count towards their national targets when calculating the overall national share of renewables and the share of renewables in transport. Member states will still be able to use (and import) fuels covered by these limits, but they will not be able to include these volumes when calculating the extent to which they have fulfilled their renewable targets. These limits consist of a freeze at 2019 levels for the period 2021-2023, which will gradually decrease from the end of 2023 to zero by 2030[5].

In the mean time policy developments continue. In the framework of the Fit for 55 Package (in July 2021) the EC also came with a new proposal for RED II amendment in order to be in line with the aspirations of the Green Deal and the 2030 Climate Target Plan. To that direction, there has been a substantial increase in both the overall renewable energy consumption target in transport and of the sub target for advanced biofuels. More specifically, the current EU-level target of ‘at least 32%’ of renewable energy sources in the overall energy mix to at least 40% by 2030, which represents doubling the current renewables share of 19.7% in just a decade. In the transport sector, the proposal introduces a target for reducing the greenhouse gas intensity of transport fuels by 13% by 2030 compared to the new emissions-based benchmark covering all transport modes (equivalent to an energy-based target of 28% using the methodology in the current Directive) with an additional sub-target of 2.2% for advanced biofuels (single counted). This represents a substantial increase of ambition in this key sector compared with the current 14% transport target (energy based) with a 3.5% advanced biofuels sub-target (double-counted). This illustrates that the demand for advanced low-ILUC risk biofules can be expected to grow in the future as will the demand for low ILUC-risk biomass. In addition the amendment in the Fit for 55 package also introduces a new 2.6% sub-target for renewable fuels of non-biological origins (RFNBOs), including hydrogen.

The REDII introduces an exemption from the limits for biofuels, bioliquids and biomass fuels through an option to certify these as low ILUC risk under the Delegated Regulation (EU) 2019/807. An overview of the current REDII policy and how it currently provides opportunities for additional support to low ILUC risk biofuels is extensively described in the recently published BIKE paper (Panoutsou et al, 2022) and what follows here is copied directly from it. ‘The RED II provides two opportunities for additional support to be offered to low ILUC-risk certified biofuels. First, it allows for additional feedstock production systems to be made eligible to be counted twice towards targets by being added to the list in Annex IX. At present, none of the entries on Annex IX is conditional on low ILUC-risk certification, but in principle it would be possible for new entries with this type of conditionality to be added. Second, Article 26 (1) gives Member States leeway to distinguish between biofuels based on best evidence on ILUC emissions when creating national support systems. This would allow a Member State to provide a more favourable treatment under national legislation to biofuels that have reduced their ILUC impact by receiving low ILUC-risk certification. This opportunity is clear for oil, starch, and sugar crops, as the Directive includes estimates of ILUC for those feedstocks. For lignocellulosic crops, however, a Member State would need to argue that best evidence suggested that uncertified material was likely to be associated with non-zero ILUC emissions (contrary to the assumption enshrined in Annex VIII), as low ILUC-risk certification would not

[5] https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

deliver any prima facie emission benefit if a crop was already expected to have zero ILUC emissions'. *(Copied from Panoutsou et al., 2022).*

Amendments to the REDII are currently under discussion in the EC and the EP. These legislative updates proposed in July 2021, as part of the Fit for 55 package of new strategies and updates of climate and energy legislation, involve a revision of the current REDII. For advanced biofuels the most important changes proposed are that the sub-targets for advanced biofuels will be increased to 2.2 percent in 2030. And a new 2.6% sub-target for renewable fuels of non-biological origins (RFNBOs), including hydrogen, will be introduced.

Common Agricultural Policy

The current CAP and also the new CAP that is now in preparation, provide several opportunities to incentivise low ILUC-risk biomass production in EU areas. This is embodied in the pan-EU agro-ecological objectives of the CAP (e.g., Priority 4 on restoring and enhancing agricultural resources, and Priority 5 on efficient and low-carbon production).

Incentivizing the cultivation of crops on unused, abandoned, or severely de-graded land offers the opportunity to restore low quality land; this builds not only on existing farm income support, support to ANCs and greening payment measures, but also more general rural development funding regulation. The CAP is also structured to be flexible to the needs and conditions of the different EU Member States and regions: national governments can design their Strategic Plans (for the new CAP) to exploit the alignment between their own environmental objectives and the low ILUC-risk system (alongside other residual based biofuel pathways), while also introducing additional sustainability requirements on crop-based biofuels preferably creating win-wins on both farm income and wider environmental sustainability.

Producing specific, mostly perennial crops on agricultural lands with many natural constraints (e.g. in Areas of Natural Constraints (ANCs)) can intersect with other goals on soil health, carbon sequestration, and runoff control through improving ground cover. Low ILUC-risk production systems may therefore benefit directly or indirectly from provisions in the EU's Farm to Fork Strategy, Nitrates Directive, Pesticides Regulation, Habitats Directive, and Biodiversity Strategy, among others.

Table 2.1 CAP instruments that may help incentivize Low ILUC risk biomass production

RDP instruments	Other soft instruments (CAP and other)	Future policy expectations in new CAP
• Payments to Areas of Natural Constraints (ANCs) – (Pillar I and II)	• Sources from the European Cohesion fund: Investments can be made that strengthen the rural economy, including finding way of increasing the production of sustainable activities and the infrastructure that supports this.	Compared to the current CAP, conditionality rules are expected to be stricter to ensure additionality to current farming practices as is required in the European Green Deal/Farm to Fork. The conditionality will also introduce new GAEC measures: GAEC 2 (Preservation of carbon-rich soils such as peatlands and wetlands), GAEC 5 (Compulsory use of the new Farm Sustainability Tool for Nutrients,) and GAEC 8 (crop rotation, which replaces crop diversification under greening).
• RDP 8.2: Support for establishment and maintenance of agroforestry systems	• LIFE programme can provide financial support to achieve environmental/climate goals	Introduction of Eco-schemes in new CAP which enable farmers to voluntarily choose a scheme through which they are rewarded to take measures that

RDP instruments	Other soft instruments (CAP and other)	Future policy expectations in new CAP
		improve environmental and climate performance such as managing and storing carbon in the soil. MSs have to design and choose the Eco-schemes they want to introduce following minimal EU-CAP guidelines.
• RDP- RDP 1.1, RDP 1.2; RDP 2.1: RDP 2.3) all support for training, skill acquisition and demonstration activities for farmers and farm advisors and can be targeted to biodiversity friendly farming.	EU Missions in Horizon Europe: They will deliver impact by putting research and innovation into a new role, combined with new forms of governance and collaboration, as well as by engaging citizens. - Soil Deal for Europe: Mission objective is improved soil structure to enhance soil biodiversity.	Boosting the development of innovation projects and making these projects' results known and implemented is the key objective of an effective AKIS 2.0, following the cross-cutting CAP objective on 'modernisation' of the sector by fostering knowledge, innovation and digitalisation of agriculture and rural areas' (Art. 5 of the CAP Strategic Plan regulation). This innovation network can contribute to spread of case studies and other good practices on low ILUC-risk biofuel production within the European community
• RDP 9.1: Setting up of producer groups and organisations in the agriculture and forestry sectors	• EIP-AGRI: The EIP-AGRI brings together innovation actors (farmers, advisers, researchers, businesses, NGOs and others) in agriculture and forestry. • COPA: (the Committee of Professional Agricultural Organisations) represents over 22 million European farmers and their family members in a combined effort with its members to promote the best interests of the agricultural sector among the EU institutions and other relevant stakeholders. • COGECA: (the General Confederation of Agricultural Cooperatives) represents the general and specific interests of European agri-food, forestry, and fishery cooperatives among the EU Institutions and other socio-economic organisations contributing to European decision making.	Investing in these platforms like EIP-Agri, Copa- COGAGA will increase the organisations' efficiency and market bargaining power.
• The are several RDP measures that finance investments, marketing, development of new market products and collaborations between farmers that could help market biodiversity friendly products or organic products (e.g. RDP 3.1, 3.2, 4.1, 4.2, 9.1, 11.1 & 11.2).	• EIP-AGRI Thematic networks: Thematic networks are multi-actor projects which collect existing knowledge and best practices on a given theme to make it available in easily understandable formats for end users such as farmers, foresters, advisers and others e.g. Ecological approaches and organic thematic network. • BIOBRIDGES- Establishment of close cooperation among actors to boost the marketability of biobased products.	Funding for investments, knowledge-building, innovation and co-operation will in many cases be targeted at environment- and climate-related needs, though it will also serve other CAP objectives. These will enhance efficiency and promote uptake of biobased products. A significant breakthrough will be the support for investment in machinery for specialized biobased products to increase optimization and efficiency in production and conversion.

Examples of incentives under the current and also new CAP are summarized in Table 2.1.

To address the issue of bringing back abandoned and unused lands into production possibly through the introduction of low-ILUC risk biomass crops the payments in Areas of Natural Constraints (ANCs) may provide financial support. Payments to areas facing natural and other specific constraints are available under both Pillars of the CAP, although in the 2014-2021 period Member States have chosen to implement the measure predominantly under Pillar 2. The aim of the ANC measure is to 'contribute to maintaining the countryside as well as to maintaining and promoting sustainable farming systems' by 'encouraging continued use of agricultural land' (Regulation (EU) 1305/2013, recital 25). In 2019, 57.9% of UAA in the EU-27 was designated as ANC, ranging from 2.5% in Denmark to 100% in Luxembourg and Malta . Of this, 17.1% is designated as 'mountain' ANC, 32.6% as 'areas other than mountains facing natural constraints' and 8.1% as areas affected by other 'specific constraints'. The scale of disadvantage in different parts of the EU varies considerably even within these areas. Payments per hectare also vary greatly between Member States, but provide additional non-market, annual area-based payments to encourage continued use of agricultural land in mountain areas or in other areas facing natural or other specific constraints (such as steep slopes or poor soils) and act as a form of broadly targeted direct payment. In the DG-ENER study (Elbersen et al., 2020) it is shown that ANC payments can be effective in reducing land abandonment, particularly in more marginal and decentral locations where extensive and traditional land uses more often occur. It these payments are used by farmers in combination with development of market opportunities for Low ILUC biomass this support instrument can stimulate increased biomass supply.

In Pillar II of the CAP, there are several measures that can help enhance the viability of farms and rural areas that may stimulate (amongst others) directly or indirectly that taking up of dedicated non-food biomass cropping activities on unused, abandoned and degraded lands.

Several RDP measures offer opportunities for increasing cooperation and networking between farmers. These include support measures for vocational training and skill acquisition, demonstration activities and information actions, support for the use of advisory services, and training of advisors and setting up producer groups. There are also RDP measures that require collaborations in setting up plans, studies or making investments in areas of Natural Constraints, but also Natura 2000 areas. In the latter the introduction of dedicated biomass cropping should be avoided however, as the RED prescribes.

RDP measures that help achieve higher selling prices for environmentally- and biodiversity-friendly products and access to markets are also interesting. These cover support for new participation in quality schemes, setting up of producer groups and organisations. They also provide several other investment support options for information and promotion activities by groups of producers in the internal market, overall investments in agricultural holdings, in processing/marketing and/or development of agricultural products, and in forestry technologies and forest products.

The Agri-Environment and Climate measures (AECM) under the Rural Development Programme (RDP 4.4: Support for non-productive investments linked to achievement of agri-environment-climate) are effective for enhancing sustainable practices and mitigating land abandonment through providing additional income to carrying out particular management, provided it contributes positively to climate and environment, including biodiversity. The effectiveness of this measure will be different per EU country as there are differences in the design and targeting of the AECMs. Case studies in Elbersen et al. (2020) also highlighted the AECM as an important means of supplementing farm income and helping maintain land under agricultural production, but sofar not evidence was found that these have supported the large scale take up of dedicated . The AECM are particularly relevant to the adoption of new technologies and also increasing physical output.

The young farmer aid under (RDP 6.1) involves young farmers in taking up farming in remote areas where abandonment challenges occur. This funding requires the completion of a business plan and sometimes support is also provided as an interest subsidy on a loan (ECA, 2017).

The LIFE programme can provide financial support to achieve environmental/climate goals. These may directly or indirectly support bringing back land into active use or preventing it from becoming abandoned. Two types of fundings are provided: 1) grants of around 55-60% for traditional, integrated and preparatory projects; and 2) financial instruments, such as the Natural Capital Financing Facility (NCFF), which provides tailored loans and investments, backed by an EU guarantee.

In the case of introduction of biomass crops with support of all above mentioned instruments it is however important to also regulate carefully that the additional liquidity for farmers to make investments in dedicated biomass production may not that lead to certain intensification and specialisation activities which may have adverse effects on biodiversity (e.g. unsustainable application of nutrients, drainage and irrigation installations etc.). Bioenergy policies need to consider regional conditions and priorities along with the role of agricultural (crops and livestock) and forestry sectors (Faaij, 2018).

Policy instruments can help to incentivize the production of biomass on unused, abandoned and degraded lands. However, their effectiveness does not come alone. They should be accompanied by the development of significant market opportunities to obtain realistic prices for the low ILUC biomass. In the DG-Ener contract study (Elbersen et al., 2020) this was concluded. In this study the factors were put together that enabled and hampered the use of (agricultural) land for biomass for energy. The overview in Table 2.2 is copied from this study.

Table 2.2 Factors that enable (E) or hamper (H) the use of agricultural land for biomass for energy or other non-food uses production

Factor	EIP-Agri	Case studies *(with examples)*
Economic and financial	**(E)** Stable financial instruments and transparency; regional scale business models; collective approaches could be useful (in synergy with sustainable agricultural goals). **(H)** High costs of equipment and financing.	**(E)** Market prices and diversification of income were key reasons for adoption of biomass cropping (All case studies). **(H)** High investment cost (Latvia, Croatia), unstable market (Spain, Hungary).
Technical	**(E)** Investment in biogas storage capacity on farms. Pre-treatment technologies and costs need further development. **(H)** Other outputs of biogas plant (heat, digestate as fertiliser or purified biomethane) require multiple markets. Complex to match seasonality of biomass supplies to energy demand.	**(E)** Availability of biomass processing plants and supply chain (Romania). **(H)** Lack of biomass processing plants and supply chain (Hungary, Croatia). Absence of support for testing technologies (Latvia). Lack of technical knowledge and expert advice (Croatia).
Societal	**(E)** Social acceptance can be enhanced if benefits are demonstrated. Inclusive business models in regions can increase support. **(E/H)** Landscape impacts require attention.	**(H)** Lack of trust and cooperation within supply chain (Hungary).
Regulatory	**(E)** Stability in regulatory frameworks is needed, and a framework for sustainability of bioenergy.	**(E)** Local policy to replace coal with new biomass power plant (Portugal) **(H)** Unclear government policy on non-food industrial crops (Croatia).

Factor	EIP-Agri	Case studies *(with examples)*
Competition for natural resources	**(E/H)** Sustainability of increased feedstock production is a key issue, including how to avoid competition with food production.	Conflict over use of food crops for energy (France, Croatia). Not enough use of agricultural residues instead (France).

Sources: Elbersen et al. (2020) in which it was compiled from case studies and from additional information collected from Agri (2019).

Both the literature and the case studies used to compile Table 2.2 suggest that any scope for increasing biomass cropping is mostly dependent on the market. This again is influenced by the presence of an effective supply chain, including the availability of processing facilities. The case studies (in Table 3) suggest that, when farmers do introduce different crops, annual food crops, which can also be used for bioenergy (for example, rapeseed oil) or afforestation (not necessarily for energy production), are a more common choice than dedicated energy crops. The importance of economic factors was summed up by the case study in Hungary: 'The whole idea can't work unless the value chain including the processing line is built up. A market must be created for the utilisation of biomass growth.'

2.3 Unused, abandoned or degraded lands and overlap with areas of natural constraints

One of the options to produce low ILUC risk biomass is through growing non-edible crops on unused, abandoned and degraded lands as has already been envisaged in the EU Recast Renewable Energy Directive RED II (EC, 2018). Following the Delegated Act (2019) supplementing the Recast of the Renewable Energy Directive (RED II), Directive (EU) 2018/2001 these three types of land are defined as follows:

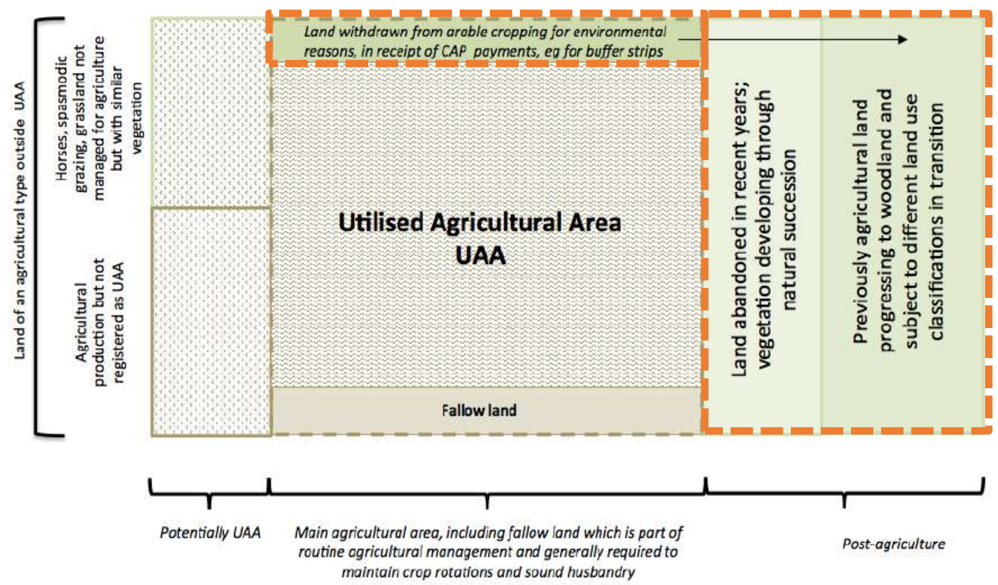
1) Unused lands; 'unused land' means areas which, for a consecutive period of at least 5 years before the start of cultivation of the feedstock used for the production of biofuels, bioliquids and biomass fuels, were neither used for the cultivation of food and feed crops, other energy crops nor any substantial amount of fodder for grazing animals;
2) 'abandoned land' means unused land, which was used in the past for the cultivation of food and feed crops but where the cultivation of food and feed crops was stopped due to biophysical or socioeconomic constraints;
3) 'severely degraded lands' means 'land that for a significant period of time has either been significantly salinated or presented significantly low organic matter content and/or has been severely eroded'

These categories seem to be straightforward, but the problem is that all these types of lands are not mapped nor is statistical data available directly on their extend.

For these three type of categories it is understood however that they often overlap with marginal lands to which it is also referred to as lands with natural constraints. The mapping of these marginal lands with low indirect land use changes in the EU has been much advanced in recent years in several EU projects (e.g. SEEMLA, MAGIC, MAIL, BIOPLAT, FORBIO), mostly involving the identification according to biophysical constraints. Some small progress was also made in mapping unused, abandoned and heavily degraded lands in selected regions in EU as part of FORBIO and MAGIC project. In spite of this, much progress is still to be made to map such areas in a reliable way to support the understanding of their extent, location and physical, technical and socio-economic potential to produce low ILUC biomass on them now and in the future.

The advances in mapping of all these categories of marginal low-ILUC lands both for current and future situations taking account of climate change effects will require complex spatial assessment approaches, including the use of new remote sensing data and analysis.

Figure 2.1 Agricultural land use transitions



Source: Allen et al. (2014).

For unused and abandoned lands we know that the land use classification of RED II does not acknowledge the complex process of reduced farming activity that leads to land abandonment in rural areas. The stages reflect a complex process of reduced farming activity over a continuum, ranging from land that is temporarily unused (overlapping here with fallow) to semi-abandoned land (managed only to comply with CAP cross-compliance requirements but not currently used for production) (see Figure 2.1). At the end of the range is land that is entirely abandoned and where management is withdrawn completely. It is important to realise that this last category of land loses its status as agricultural land and is also no longer eligible for direct payments under the CAP and no longer appears in agricultural land use statistics.

However, indirect evidence confirms that the abandoned land resource in the EU is quite large, particularly in certain regions. In the DG-Ener study (Elbersen et al., 2020) it was shown in an analysis of Eurostat Farm Structural Survey (FSS) data that for the period between 1975 and 2016 the utilised agricultural area (UAA) showed a total decline for all EU-27 and UK of almost 36 million hectares (18% of the UAA in 1975). Declines were seen over the whole period in all EU Member States, but the largest occurred in Bulgaria, Czechia, Estonia, Greece, Spain, Croatia, Italy, Cyprus, Latvia, Hungary, Poland, Slovenia and Slovakia. In this same study, a land cover flow analysis with Corine Land Cover data was made showing that in 18 years (2000-2018), 8% of the agricultural land went out of agriculture.

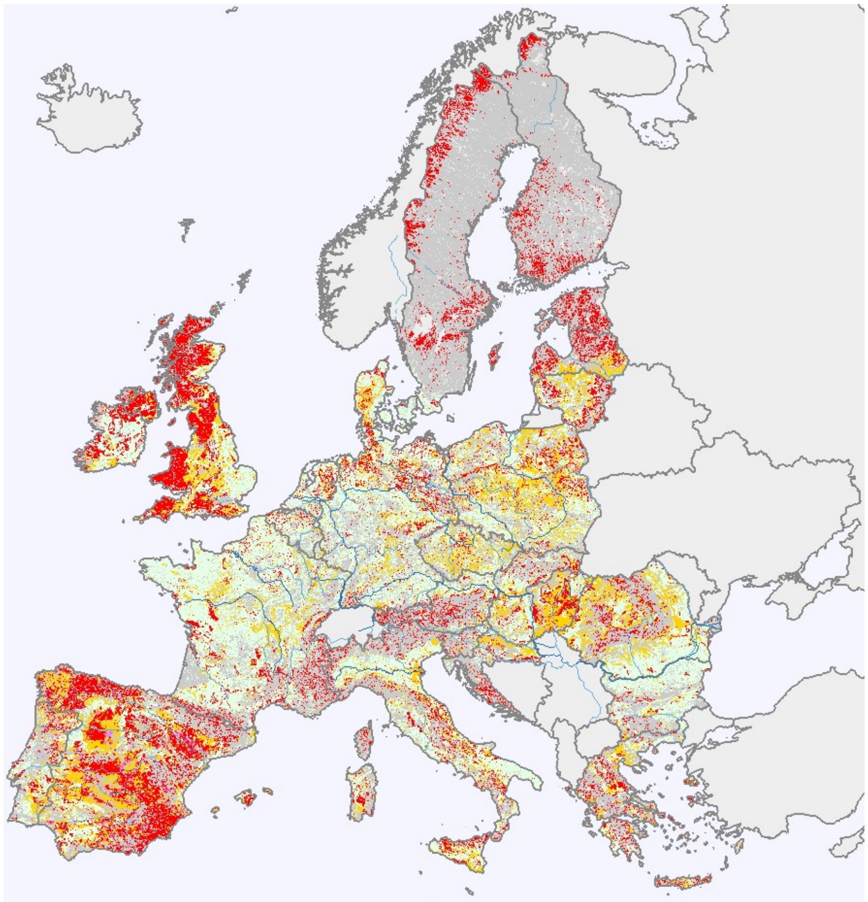
Also, for the short-term future, agricultural land abandonment is expected to continue as reported in Perpiňa Castillo et al (2021). In total for EU and UK, the net agricultural land projected to flow into abandoned lands by 2030 amounts to 4.8 million hectares, 600,000 hectares is projected to flow into forest and natural areas and only 18,000 hectares go to urban use. The frontrunner here is Spain where 1 million hectares of agricultural land between 2015 and 2030 are expected to be lost. The study by

Perpiňa Castillo et al (2021) also expects largest losses in the arable land taking up 70% of all abandonment in 2030 (around 4 million hectares), while permanent grasslands and permanent crops make up 20% and 7% respectively. This is an interesting development as it is more technically feasible to establish dedicated biomass crops on abandoned cropping land then on former permanent grassland. Conversion of permanent grasslands, even if already abandoned, may go together with large carbon and also biodiversity loss, if converted to cropping land. The processes that lead to land abandonment are complex. In Elbersen et al. (2020) 4 groups of factors were distinguished. natural constraints limiting the suitability for agricultural uses, socio-economic drivers at farm level, broader socio-economic drivers at regional level and drivers from policy (EU & national level). These factors can apply at the same time in the same location and work out very differently depending on the local context (Perpiňa-Castillo et al., 2020). Land abandonment in areas with natural constraints is a common phenomenon. However, usually natural constraints alone are not necessarily leading to land abandonment. If these constraints occur in combination with socio-economic constraints at farm and/or regional level, the chances for land abandonment are highest (Elbersen et al., 2020).

In MAGIC and SEEMLA projects areas of natural constraints were mapped (see Figure 2.2). MAGIC spatial assessment showed that in the EU & UK that 29% of land that was classified agricultural by Corine landcover (CLC)[6] was also classified as area of natural constraint. The most common constraint are poor rooting conditions, with 12% of the agricultural area. This is followed by adverse climate and excessive soil moisture occurring in respectively 11% and 8% of the agricultural land. The method to map natural constraints builds on the JRC work to identify Areas of Natural Constraints (ANCs) (Van Oorschoven et al., 2014 and Terres et al., 2014) and other land evaluation systems for agronomic suitability. The same natural constraint factors are also prescribed to be used by EU countries to map the Areas of Natural Constraints (ANCs) that can be made eligible of ANC payments under the first of second Pillar of the CAP.

[6] all land that was classified in an agricultural land cover class in at least one of the four Corine Land Cover (CLC) versions of 1990, 2000, 2006, 2012.

Figure 2.2 Areas of natural constraints, also referred to as marginal lands (in red in the map), as mapped in the MAGIC project. The orange area on the map are sub-marginal because the thresholds of marginality are near limit.



In the MAGIC mapping approach 18 single biophysical factors have been identified for the classification of severe limitations and these were grouped into 6 clustered factors:

1. Adverse climate (low temperature and/or dryness)
2. Excessive wetness (Limited soil drainage or excess soil moisture)
3. Low soil fertility (acidity, alkalinity or low soil organic matter)
4. Adverse chemical conditions (Salinity or contaminations)
5. Poor rooting conditions (low rootable soil volume or unfavourable soil texture)
6. Adverse terrain conditions (steep slopes, inundation risks)

The land units were identified with biophysical factors within the 20% margin of the threshold value of severity. This allows to map pair-wise limitations. When two factors are within this 20% margin the land units were classified from sub-severe to severe. Finally, a correction in the map was made by excluding areas where natural constraints were neutralized to enable high productive agricultural lands. Such land improvement measures include fertilisation, irrigation, drainage and creation of terraces.

Against these natural constraints, crops were further reviewed in MAGIC in relation to their capacity to cope with the different natural constraints dominant in the Agri-Environmental Zones (AEZ) (Metzger, 2020) in which they grow best. For further information between crop performance and natural constraints per AEZ see next chapter.

As to the REDII category of severely degraded land the same problems are encountered regarding its location and extend as with the unused and abandoned land categories. Very limited data exist on land degradation and REDII is not explicitly clear on what thresholds should be followed to classify land in this category. In the current Delegated Act (2019) supplementing the REDII reference is made to 3 factors which are significantly salinated, significantly low organic matter content and severely eroded.

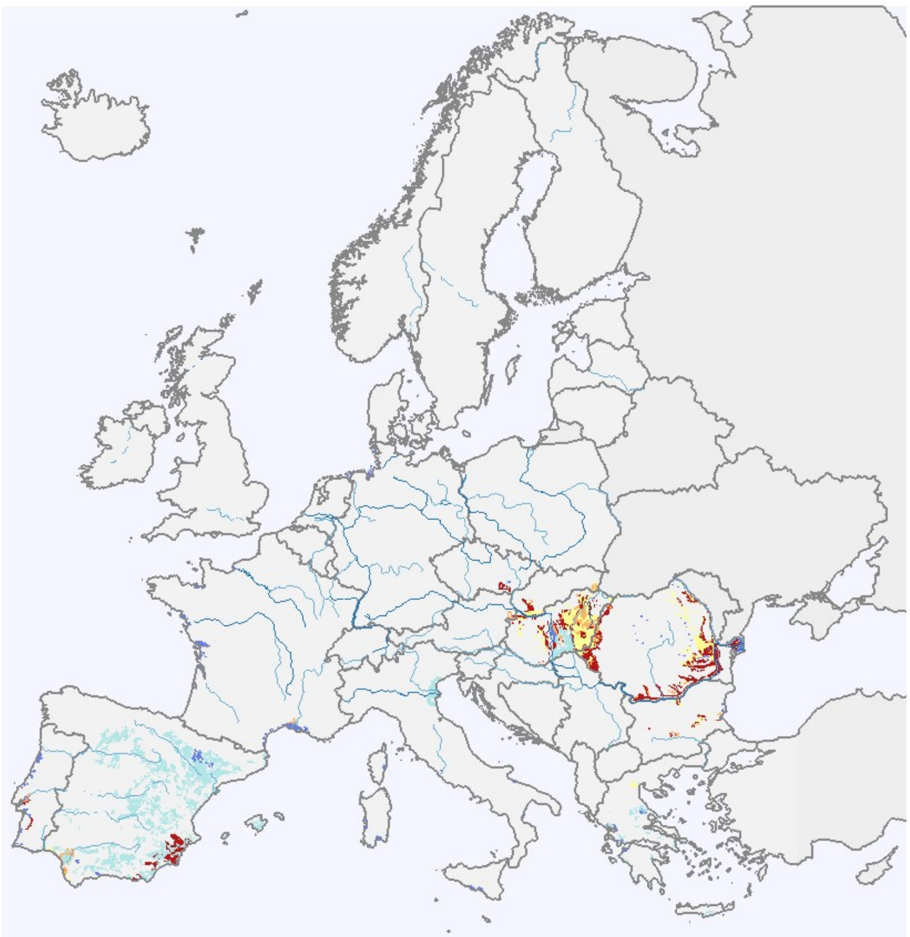


Figure 2.3 Areas with high salinity and/or sodicity with or without limitations on rooting (deep red in the map) (MAGIC, Elbersen et al., 2018). *The orange areas on the map are sub-marginal because the thresholds of marginality are near limit.*

As to salination we can follow the MAGIC ANC mapping which includes high salination levels as one of the 18 limiting factors and combines salinity and sodicity (determined by sodium levels) in one limiting group as both aspects affect plant growth in a similar and limiting way. The thresholds set for severe levels of salinity and sodicity follow what is recommended by JRC (Van Oorschoven et al., 2014 and Terres et al., 2014) for classifying lands in ANCs and amounts to 15 dS/m[7] or higher. For sodicity the threshold value for severe limitation is set at saturation with exchangeable sodium of more than 15% (ESP). Furthermore,

[7] deci-Siemens per metre (**dS**/**m**) of soil

lower salinity and sodicity thresholds, of 12 dS/m for salt and 12% for sodium, are also causing sever problems if they occur in soils with limited rooting depth. So for the mapping this combined limitation is also mapped as severe in MAGIC (see Figure 3). This combination is very problematic as limited rooting depth causes lower availability of nutrients and water and this is aggravated by salinity due to increased osmotic pressure of the soil moisture. The high salt content of the soil solution upsets the availability of plant nutrients. High levels of sodium (sodic) affect plant performance in sodic soils (toxicity) and causes soil structure deterioration, affecting soil stability and soil permeability and infiltration capacity (development of a soil crust). The areas where soil salinity and sodicity is problematic have been mapped in MAGIC (see Figure 2.3) and from this we know that roughly 1% of agricultural areas[6] in EU and UK have this constraint which may well reach around 2 million hectares of land. It can be expected that most of this land is still in use by agriculture, although exact data are not available, but salinity and sodicity is likely to be heavily constraining agricultural use especially in years that are very dry.

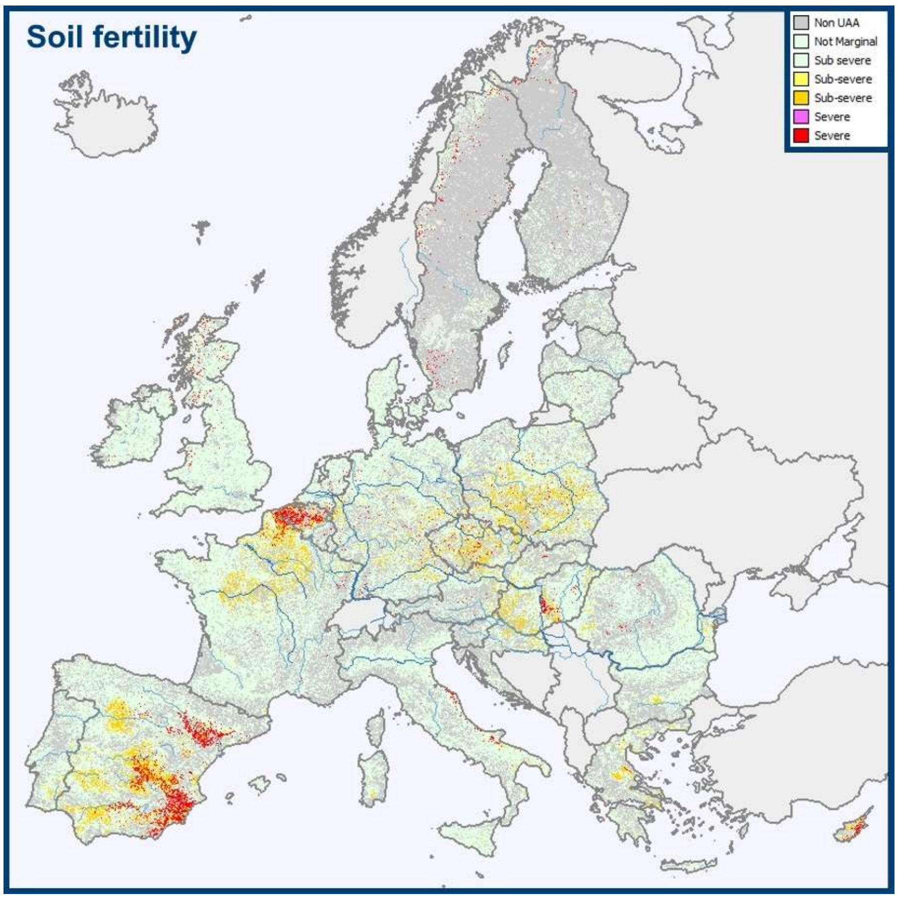


Figure 2.4 Areas with low fertility because of very low SOC levels (<0.5% in upper 30 cm soil) (in deep red on the map)(MAGIC, Elbersen et al., 2018). *The map shows all soils which have very low fertility levels, BUT excluding areas where this natural constraint is neutralized by very high levels of manure application*. *The orange areas on the map are sub-marginal because the thresholds of marginality are near limit.*

For the REDII category of severely degraded land that is coping with significantly low organic matter content the MAGIC results may also give some indication of where this is occurring and how much land this may cover. The thresholds set for severe levels of low organic carbon in MAGIC which was the main factor determining overall low fertility is soil organic carbon < 0.5% (in upper 30 cm soil). According to the MAGIC mapping exercise 2.9% of agricultural areas[6] in EU and UK have this constraint which may well reach around 7 million hectares of land. The area of land with this natural constraint is largest in the Mediterranean and northern boreal and nemoral zones. Belgium and southern and eastern parts of the Netherlands also had many sandy soils with very low SOC levels, but these constraints have been neutralised already for several decades because of high manure applications to support production of grass and forage maize on these lands (see Figure 2.4).

As to lands that are severely eroded which also comply with the REDII category of severely degraded lands it is clear that not reliable and spatially explicit data are available. What complicates their identification further is that REDII does not exactly specify at what level of erosion classifies lands in this category. At EU wide level soil erosion risk (by water and wind) is only mapped but spatially explicit data on real erosion levels is not available. Remote sensing data are however increasingly becoming available which provide good opportunities to detect soil erosion is larger areas (e.g. Lukyanchuk et al., 2020; King et al., 2020).

3. Crops suitable for unused, abandoned and/or degraded lands

3.1 Introduction

In the EU projects MAGIC and PANACEA the knowledge and understanding of crops that can cope well with different natural constraints has been improved strongly. In this chapter we will first give an overview of all crops (both annuals and perennials) studied in both projects and present their main characteristics in terms of relevance for producing biofuels from, the typical agricultural practices, TRL levels, their climatic suitability and the way they cope with different natural constraints. In chapter 4 we then discuss the different yielding capacities these crops may have in normal non-constrained conditions and under influence of different natural constraints.

3.2 Overview of crops and their main characteristics

Based on the information generated in MAGIC and Panacea projects a selection of crops was made that are adapted to European agro-ecological zones (AEZ) (Metzger, 2020), and can be grown both in conventional land and in land with natural constraints (unused, abandoned, or severely degraded). An overview of the selected crops, their main characteristics, their suitability for biofuel feedstock, their TRL level (following the requirements presented in Table 1) is presented in Table 4.

The selected crops are devided in oil and lignocellulosic crops. In the selection there are also crops that can be used for both production of oil and lignocellulosic material are cardoon, industrial hemp and Sunn hemp.

Oil crops

Oils mostly contained in the different seeds of the crops presented in Table 3.1 are the lipids needed to produce biobased substitutes particularly on the short term in the ‘hard-to-abate’ transport sectors of heavy duty, maritime, and aviation. The biobased jet fuel can be made from hydrotreated vegetable oil (HVO), the biobased hydrocarbon fuel substituting diesel, and hydrotreated esters and fatty acid (HEFA). Until 2030–2035 is it estimated the HEFA will be the dominant type of renewable jet fuel, and lignocellulosic biofuels will emerge at a large scale only after 2035.

The selected crops that produce the lipids and that are also suitable to cope with many different natural constraints are several crops closely related to rape seed: Ethiopian mustard, Camelina. Other suitable crops with interesting opportunities to become more widely cultivated in Europe are crambe, safflower, cardoon and castor.

Ethiopian mustard is well adapted to the Mediterranean climate and can be grown there as either a winter or spring annual crop. It is suggested to grow it as a spring crop in areas with cold winters due to low frost resistance, while in areas with mild winters, it can also be grown as a winter crop. Like with rapeseed, Ethiopian mustard is tolerant to water stress which is attractive with declining water availability in an increasing number of regions in Europe. The crop also seems to respond well to phytoremediation (Panoutsou et al., 2018), which provides opportunities to grow it on contaminated land and simultaneously rehabilitating the land and providing feedstock for biofuels.

Table 3.1: Overview of selected crops and main characteristics

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
Oil crop	Ethiopian mustard *Brassica carinata A. Braun*	A	Hydrotreated vegetable oil (HVO)/renewable diesel, HEFA (aviation, marine, heavy duty)	UAD, R, B	Ethiopian mustard is an annual crop closely related to rapeseed. 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. It originates from Ethiopia where it is cultivated as oilseed crop, while in southern Africa and in West and Central Africa it is grown as leafy vegetable. It is also used as a green fodder crop, green manure and as a cover crop. It has high seed yields. It is well adapted to arid and semi-arid conditions and saline conditions but cannot cope with frost. It has been proposed as an alternative oilseed crop to rape seed for the Mediterranean region and has been studied in several EU projects. The average yields range from 1.5-3.0 t/ha and oil content is around 40%. The oil is rich in erucic and linoleic acids and well-suited for biofuel production. It consists of 33% oleic, 37% linoleic and 21% linolenic acid compared to 61% oleic, 21% linoleic and 11% linolenic acid in rape seed oil. Seed cake that remains after oil extraction can be used as fertilizer or feed stuff. The oil is also used as cooking oil in Asia or for production of mustard.	++	+++
	Crambe *Crambe abyssinica L.*	A		UAD, R, B	Crambe is an annual spring oilseed crop and has a rather shortl cropping cycle. It originates from eastern Africa and was domesticated in the Mediterranean. In the last century it has been tested and cultivated in several projects in Europe (including northern regions), former USSR, Canada, USA, Pakistan, China. The number of crambe varieties available for commercial production is limited. The highest yields of Crambe have been reached on sandy loams. Crambe is well adapted to areas with mild winters and hot and dry summers. It has also been adapted to colder or drier areas and in Northern Europe and can be grown as a spring crop if sown once the risk of frost has passed. In the Mediterranean region it can be cultivated both as winter and spring crop. Crambe can be considered as drought tolerant and has similar fertilizer requirements as other spring oilseed crops. Seed yields vary widely between 1 and 5 t seeds/ha under varying environmental situations. Oil content varies between 36%-43% (dehulled). Crambe oil has a high percentage in erucic acid (higher then in rapeseed). Crambe appears to be a promising crop because of the many possible non-food uses of its oil (pharmaceuticals, detergents, cosmetic, ceramides, nylon and perfumes etc.). After pressing or extracting the oil, pressed cake or extracted oil meal is obtained, which can be fed to cattle, and to a very small extent to pigs.	++	+++
	Camelina *Camelina sativa L. (Grantz)*	A		UAD, R, I, CC, B	Camelina is native to southeast Europe and southwest Asia. It is naturally widespread in Europe either wild or cultivated. Cameline seeds can be used both for food and non-food products. In general, camelina species have a relatively short cropping cycle and are best adapted to cool temperate and semi-arid climates. Camelina grows very well on well-drained light (sandy), medium (loamy) and heavy (clay) soils. It is a winter	++	+++

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 952872

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
					crop but in mild climates, like the Mediterranean region, it can be grown also as spring crop. It used to be grown in Northern and Eastern Europe until 1940s when it was replaced by rapeseed. The last two decades camelina has been reintroduced at research level in Europe in several EU projects. Camelina has low nutrient requirements. It is considered as crop with high tolerance to drought and heat. Mean seed yields are around 2 t/ha. Oil content varies between 38% and 42%. 90 % of the camelina oil contains unsaturated fatty acids, including a 30-40% fraction of alpha linolenic acid, another 15-25% fraction of linoleic acid, about a 15% fraction of oleic acid and around 15% eicosenoic acid.		
	Cardoon	P		UAD, B	Cardoon is a perennial herb with an average range of height between 1 to 2.1 m. It produces both biomass and oil seeds. Cardoon is considered to be able to infiltrate its' root deep in the ground, creating a very large root system which provides the plant with the ability to regenerate, cope well with water deficit situations and is effective in erosion control. It is considered native to most countries of the western and central Mediterranean region but can also be found in central and western Europe. It requires a minimum of 450 mm of annual rainfall (or irrigation). It grows best at latitude range between 25º to 55º. Temperatures below 4ºC can damage the plant and high temperatures above 40ºC can also reduce yields. Above-ground biomass yields recorded through Europe showed a range of 15 to 21 tonne dm/ha/y. Seed yields range between 0.6-4.5 t/ha/y. Cardoon has been commonly used as green forage and also the production of paper. Seeds from Cardoon are increasingly used for liquid biofuel, biodiesel, other biochemical products, pharmaceuticals, and natural herbicides. The remaining lignocellulosic material can be used for biofuel production too.	+++	+++
	Safflower *Carthamus tinctorius L.*	A		UAD, R, I, B	Safflower is a branching thistle-like herbaceous annual (spring or winter) annual plant. Safflower is native to the Old World, and the genus occurs naturally in the Mediterranean, northeastern Africa, and southwestern Asia to India. It can be cultivated well in the whole of Europe and has been included in several EU research projects. It is cultivated for local uses for cooking and as a food colorant mostly in India, where half of world production takes place. 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%). The first are used as heat stable cooking oil to fry food and are also used in cosmetics, food coatings, and infant food. The high linoleic varieties are used primarily for edible oil products but also for paints. The crop has a deep taproot that can penetrate to 2-3 m and thus can draw moisture and nutrients from a considerable depth and thus can be grown on areas with low available moisture. It cannot survive on soils with standing water. Seed yields vary	+	++

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
					between 2 to 3.5 t/ha and oil content is between 34 and 36%. Safflower seeds contain 92-93 % unsaturated fat and as such considered as high quality edible oil.		
	Castor *Ricinus communis L.*	A		UAD, R, I, B	Castor is a valuable oilseed crop that can be either annual or perennial (small tree). The annual growing cycle is medium to long (varies from 180-120 days). Castor is indigenous to the southeastern Mediterranean Basin, Eastern Africa, and India, but is widespread throughout tropical and subtropical regions as an ornamental crop. It is commercially grown in India, China, and Brazil. In 2015, the global castor oil seed production was 1.8 million tons and the main producer was India with 1.55 million tons. Although the crop can be cultivated in the Mediterranean region, it is found only on experimental and demonstrative fields performs best in moderate temperature (20-26oC) with low relative humidity and clear sunny days throughout the crop season. Areas with temperatures higher than 40 C or lower than 15C are not conducive for castor cultivation. A frost free climate is mandatory. 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 improves survival under moisture stress. Moderately fertile soils are preferred as high fertility induces excess vegetative growth, prolonged flowering, and delayed maturity. Europe is one of the main importers of castor oil. Seed yields between 2-5 t/ha are being reported and oil content is quite high (50% or even higher). The oil is rich in ricinolic acid (12-hydroxy 9-octadecenoic acid) (85%). Castor oil has numerous chemical and medicinal applications and, in the international market, has more than 700 non-food uses.	+	++
Lignocellulosic crop	Willow *Salix spp. L.*	P	Ethanol, methanol, butanol, Synthetic fuel Hydrotreated bio-oil/biocrude (aviation, marine, heavy duty, Fischer Trophs diesel, to pyrolysis oil to FT diesel.	UAD, AF, B	Willows are fast-growing large trees or shrubs with an approximate height from 13 to 21 m. But in plantations they are usually grown in Short Coppice Rotations (SRC). It is native in almost every country in Europe and is commonly cultivated in most of Europe as it can be used for biomass production for biofuels, energy and biomaterials. Willows are considered to be riparian or alluvial species that endure the exposure of roots and waterlogging while preventing erosion and flooding. Willow species have the ability to remediate erosion, mine spoil, industrial waste, dredge spoil, ore smelters, sewage sludge, petroleum spills, oil shale waste disposal, nuclear waste and landfills.	++	+++
	Poplar	P		UAD, AF, B	Poplars are fast-growing trees with more than a dozen cultivars and hybrids including Aspen trees. Poplars are medium to large trees with straight trunks and an upright growth habit. Many cultivars reach up to 30 meters in height at maturity. Many poplar species are native to Eurasia. Poplar is together with willow, the most common species in SRC plantation for biomass (for bioenergy) in Europe. The natural distribution of poplar extends from the tropics to the northern hemisphere's latitudinal and altitudinal limits of tree growth. This tree species has been studied a lot in several EU projects. Poplars are adaptive to varying levels of soil moisture but	++	+++

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
					the optimum is for easy draining soil that remains moist, but does not remain wet for a long period of time. Poplar is temporarily tolerant to flooded soils. It will also tolerate dry soil and drought conditions for short periods, but it may drop its leaves because of that, affecting the growth. Poplar is a fast-growing species and nutrient-rich soils help to ensure optimal growth. Feasible annual yields in Europe range between 10-18 tdm/ha. The biomass from poplar has the same uses as for willow, but is not so widely applied for bioremediation as willow.		
	Biomass sorghum *Sorghum bicolor L.*	A		UAD, R, I, B	Sorghum is an annual herbaceous warm-season (C4) crop. The commercial sorghum varieties are divided into six groups: grain sorghum, forage or fodder sorghum, fiber sorghum, broom sorghum, sweet sorghum and biomass sorghum. Grain sorghums cultivars cultivated for food and feed consumption. Fiber sorghum cultivars have high fibre content and can potentially be used as fiber or energy crop. The broom sorghums cultivars have long and elastic branches and mainly used for brooms. The biomass sorghum cultivars have high ligno-cellulosic biomass yield and can best be used to provide biomass for advanced biofuels. Sorghum 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 and biomass) had been included in several EU research projects. Typically, sorghum needs between 550 to 800 mm of water to achieve good yields, (i.e.20-25 tdm/ha). The major advantage of sorghum is that it can become dormant, especially in vegetative phase, under adverse conditions, and can resume growth after a relatively severe drought. Sorghum is considered very efficient in utilizing water and soil nutrients because of its large fibrous root system. 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 and it can be cultivated, apart from grain, for sugar juice from its stalk for making syrup or ethanol, bagasse and green foliage, which can be used as excellent fodder for animals, for gasification, for second-generation bioethanol production, as organic fertilizer, for paper manufacturing or for co-generation. In Europe sorghum is obtaining increasing attention as a promising crop for the production of raw material for 2nd generation bioethanol and biogas (instead of maize) and as fodder.	++	+++
	Tall wheat grass *Agropyron elongatum (Host.) Beauv.*	P		UAD, B	Tall wheatgrass, is a perennial grass that can become up to 3m tall. It is native to Southern Europe (Greece, Italy, France, Spain, Portugal, Croatia and other European countries), however it is sustained from reports that its origin is from Turkey and Asia. A few varieties of crossbreads have been examined for biofuels, biomass and feedstock uses. Most of the trial are found in Europe and US. Tall wheat grass can adapt in many different climate conditions, since it has genes to regulate and hold its root growth when under drought conditions . Usually, it needs approximately 300-	+	++

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
					400 mm precipitation on annual basis. It performs well when in soils that are waterlogged in winter and dried out in summer since this is its natural habitat. Tall wheatgrass is commonly used for hay, pasture and grazing, due to its high yield potential and good forage quality. It is also used for erosion control. Notably, it is planted as forage on saline and sodic soils where few other species will survive as it is considered to be one of the most saline tolerant grasses commercially available. The species is also used for cross-breeding in wheat and other plants, since it has many insect, fungi and disease resistant genes.		
	Miscanthus *Miscanthus × giganteus J.M.Greef , Deuter ex Hodk., Renvoize*	P		UAD, B	Miscanthus × giganteus is categorized as a perennial grass, that is sterile and thus can only multiply by rhizomes. Since its' root system is able to penetrate deep in the ground and normally produces branches up to 1.2 m in the ground. Miscanthus' stems are erect up to 2.2 m, at the establishment year and can grow to 3.8 m after the second year of cultivation. Miscanthus is able to produce biomass up to 15 years after establishment. Miscanthus originates from East Asia and has been introduced to Europe in the 1930's, initially it was cultivated as an ornamental plant. By the end of the 1960's research focused on utilizing its fibers for building material production. Miscanthus combines high biomass yields with high survival percentage in marginal lands which makes it a promising biomass crop, thus there are a lot European research projects studying it. Miscanthus × giganteus, is the sterile descendant of Miscanthus sinensis and Miscanthus sacchariflorus thus, until today Miscanthus cultivar used for biomass production is based in a genotype harvested in Japan at 1935, although multiple breeding programs are currently investigating new genotypes of the plant that can achieve higher yields and environmental adaptability. Yields usually vary, from 10 tons per hectare in very marginal circumstances up to 36 tons per hectare in Europe. There is also a lot of interest to use it for phytoremediation and land restoration purposes.	+++	+++
	Switchgrass *Panicum virgatum L.*	P		UAD, B	Switchgrass is a C4 warm-season perennial grass with a lifespan 10-20 years. Seeds establish it. Switchgrass plants can reach heights from 0.5-2.7 m and have a deep root system that can reach up to 3 m depth. Switchgrass is native to North America, where it occurs naturally from 55°N latitude in Canada southwards into the US and Mexico. Initially, switchgrass was selected as a promising forage crop, and then it became a promising energy crop in USA (for lignocellulosic feedstock production (combustion, conversion to liquid or gaseous forms) in the beginning of the 1980s and a decade later, the research was started in Europe in several EU projects. Two main ecotypes have been classified; upland and lowland ones. Lowland ecotypes are taller than upland and they have longer bluish-green leaves. The upland ecotypes are better adapted to colder and drier habitats, while the lowland ones tend to thrive in warmer and wetter habitats and European research confirms that lowland ecotypes could	++	+++

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
					yield more than upland ones when grown in Southern Europe. It grows best on well-drained fertile soils but tolerates acid and infertile soils conditions that could not be used by cool-season grasses.		
	Cardoon *Cynara cardunculus L.*	P		UAD, B	See above under oil crops.	++	++++
	Giant reed *Arundo donax L.*	P		UAD, B	Giant reed is a C3 herbaceous, tall, erect and perennial plant, reaching 10m in height. It produces creeping rhizomes below the soils (5-50 cm), having fibrous roots growing deep in the soils (more than 3.5 m). It has its origins from the Middle East and was then introduced to Mediterranean and Iran, before 1500 AD. It is recorded as the oldest invasive species, due to the many use opportunities (such as feedstock, building materials) which humans have welcomed. It is considered as an alien species across all Europe, while it is introduced to almost all countries around the globe. It has been studied in many EU projects. There are many varieties, some mostly used for ornamental purposes while others are more suitable for material uses and more recently for biofuel production. It can tolerate hard winters and extreme heats over 35℃, while it can tolerate and balance soil erosion and heavy rainfalls, since it can flourish in many pH and soil conditions. It is also commonly used for phytoremediation and decontamination.	++	+++
	Reed canary grass *Phalaris arundinacea L*	P		UAD, B	Reed canary grass is a C3 heterogamous, perennial, wind pollinated species, reaching up to 2m to 3m. Reed canary grass has its origins in Eurasia, and then it was spread across most of the continents. It is considered as native in Europe (except Iceland), North America and Asia. At the same time it is known that it has many invasive, adaptation abilities and a variety of genotypes, which makes it an aggressive species, also recorded as threat but also use for erosion control. There are several EU projects covering this species, particularly studied as biomass source for energy and renewable materials. In general, it grows best in mild climate and wet environments (e.g. wetlands, lakeshores, streams banks, floodplains), but can also cope well in dryer environments. Furthermore, it has proved strong adaptability to constraints like wetlands as well as in salty, contaminated soils, flooded areas, extreme temperatures and a range of 4 to 7.5 pH. Reed canary grass is used as fodder and forage crop, even if some parts of the plants have a toxicity, ornamental plant, a source of short fibers for paper production and has been widely tested for biomass production for energy and other biomaterials.	++	+++
	Industrial hemp	A		UAD, R, I, B	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. It originates from middle Asia from where it migrated to Eastern and Southern Asia.	+++	+++

	Name crop	Annual (A)/ perennial (P)	Relevant biofuels (sectors)	Systems and opportunities for low ILUC risk through sustainable agricultural practices*	Description (key characteristics), (*mostly based on MAGIC deliverable 1.5)*	Productivity/ability to use existing machinery	TRL in 2030 (see explanation in Table 1)
	Cannabis sativa L.				It has been first grown in China (5000 years ago) and from there it was spread to the whole world. The last years an increasing interest for industrial hemp has been recorded worldwide (www.eiha.org). In particular in Europe the area of its cultivation increased from 19,970 ha in 2015 to 34,960 ha in 2019. The main producer in Europe is France but an increase is seen in Italy, Italy, Netherlands, Lithuania, Estonia, Ukraine, Romania and Germany. Research on industrial hemp has been carried out in several EU research projects. It grows well after any type of crop in rotation, but it can even be grown for few years on the same field. It improves the structure of the soil due to its tap roots. It requires a mild, temperate climate and an annual water availability of 500-700 mm minimum. The hemp plant is sensitive to short day length which induces early flowering and this is very important factor in hemp yield determination. It requires long days (14-16 hours) during its vegetative phase. In Europe the mean yields in terms of dry stems is 7.5 t/ha and for fibers 2.5 t/ha. The seeds contain 32.5% oil, 70% is corresponding to polyunsaturated fatty acids. High-value bio-products can be produced from all plant parts (stems, leaves, seeds and flowers). The current main uses for it's fibers are paper and pulp, insulation mats, bio-composites and textiles. The shivs (the woody part of its stem) are used for 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 or for cosmetics and health care products. The flowers have numerous pharmaceutical uses from THC, CBD and other cannabinoids. Finally, from its leaves are being produced pharmaceutical products and tea bags.		
	Sunn hemp *Crotalaria juncea L.*	A		UAD, R, I, B	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 as green manure, fiber, lignocellulosic biomass and animal fodder crop. Both the stems, leaves and seeds can be harvested. Sunn hemp is native to India and Pakistan. In Europe Sunn hemp can be considered an alien crop. 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. Trial for this crop in Europe have been limited as only one EU project (BECOOL) covered it until now. High temperature with moderate humidity is preferable for Sunn hemp growth. Growth may be slowed by cool weather, and the plant is susceptible to freezing injuries when the temperature is below -2 ^{0}C. Sunn hemp is drought tolerant and, generally, no irrigation is necessary during the summer. When sunn-hemp is used for fibre or lignocellulosic biomass the harvesting should be done at the flowering stage. Seeds can be easily harvested with a combine when most of the pods (about 70-80%) are mature.	+++	+++

**intercropping (I), Unused, abandoned & degraded lands (UAD), cover cropping (CC), rotation (R), agroforestry (AF), biochar (B)*

Crambe (Crambe abyssinica), can be grown as either a winter or spring crop in Mediterranean and as a spring crop only in central and northern Europe. The crop is tolerant to cold and dry weather and can be adapted to a variety of climatic conditions. It can have a high productivity under the right circumstances (Alexopoulou et al., 2018 and Panoutsou et al., 2021). It is a short-cycle winter crop and can therefore be fitted in relatively easily as an alternative crop in a rotation system. The oil has great potential for biodiesel production due to its higher calorific value and oxidative stability as compared to soybean oil biodiesel (Souza et al., 2021).

Like the former oil crops, Camelina is also a fast-growing crop that can be cultivated in in south Europe both as winter and spring crop and in central and northern Europe as a spring crop. The crop has a short growing cycle that allows double cropping (catch crop) and can be grown in a wide range of climatic (throughout Europe) and soil conditions (even on dry land in Spain) (Alexopoulou et al., 2018 and Panoutsou et al., 2021).

The next three oil crops are different from the former in that both Cardoon and Safflower are thistle-like. They are both best adapted to a Mediterranean region as they are drought tolerant and high temperatures. Safflower is an annual plant that should be produced in a rotation system, while Cardoon is a perennial plant. Safflower is also suitable to be used for bioremediation of contaminated lands.

The interesting aspect of cardoon is that it can be harvested both for the seeds for oil and for the biomass to generate advanced lignocellulosic fuels from. Furthermore, because of its very deep rooting system in can cope with very arid conditions and is also an excellent crop in degraded lands coping with erosion. It is also salt tolerant at relatively high levels of salt according to which areas of natural constraints are classified.

The last oil crop is castor which can be both an annual and a perennial. The crop can cope with several constraints such as drought, heat, and saline soil conditions. But it also has a relatively long growth cycle to produce good quality oil seeds. It is therefore only suitable to grow it in South Europe. The oil content of the seeds is high and the composition is very attractive because of richness in in ricinolic acid (12-hydroxy 9-octadecenoic acid) and therefore has numerous chemical and medicinal applications beside the use for biodiesel generation.

Lignocellulosic crops

The selected lignocellulosic crops tested and grown in Europe in the last decades have generally high yielding potential in good agricultural lands and are able to cope with a wide range of natural constraints and climate conditions in Europe. The selected crops produce lignocellulosic biomass which can all be used as feedstock for biofuels such as towards ethanol, methanol, butanol, synthetic fuel, hydrotreated bio-oil/biocrude or pretreated to pyrolysys oil and then gasified in a Fischer Trophs process or gasified directly to biodiesel.

The woody crops selected are willow and poplar. Both can be grown as a short rotation coppice and harvested every two to five years, but medium rotation coppice systems are also possible with harvest cycles of around 10 years. Both have a distribution over the whole of Europe. Willow has a preference for moist soils, but can also handle water logged soils well as its natural environment is in riparian or alluvial areas and it is a good species to use for erosion control in wetter areas and is has been tested a lot and also already used for bioremediation of contaminated sites. Poplar tolerates a wider range of soil conditions but cannot cope as well with moist soils that remain wet or waterlogged for a long time.

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Biomass sorghum is an annual herbaceous spring warm season (C4) crop that can be cultivated throughout most of Europe. Temperature , however, is a limiting factor, so it is more suitable to the Mediterranean zone. Biomass sorghum has the advantage, contrary to seed producing and sugar sorghum, that not all growth stage need to be reached to produce a harvestable crop, which make it also suitable for intercropping. Even in the continental zone of Europe high enough yields can be reached with biomass sorghum in rotational and intercropping systems, provided short season varieties are used as was demonstrated in several projects in Germany (Jäkel & Theiss, 2017; Bracconier et al, 2014).

Tall wheatgrass is a tall, coarse, late-maturing bunchgrass. It is native to saline meadows and seashores, has high tolerance for drought, and has been cultivated in rainfed conditions. It is a perennial crop with a high regrowth capacity. It requires spring rainfall (April–June), however; if there is low precipitation in spring it will result in low biomass yields. As compared to other perennial grasses it is attractive in that is can tolerate extreme drought, high and low temperatures, high salinity, but its yielding capacity is significantly lower in Europe so far then for miscanthus, Giant Reed or switchgrass. This crop has been trieled and studied less in European environments then the other selected perennial grasses, hence explaining the lower TRL level in Table 3.1.

Miscanthus can be grown across all Europe and is already cultivated at commer-cial scale in several countries. The crop is considered beneficial for the mitigation of soil erosion and allows high level of carbon storage in soil due to high levels of plant residue from above and below ground.

Switchgrass can be grown successfully across Europe in different type of soils and ecological conditions and constraints. Its extensive root system supports the tolerance to drought and helps to retain high productivity even under drought conditions. To obtain optimal yields with switchgrass it is important to use the lowland and upland varieties in the right locations. In principle the lowland varieties have a higher yielding capacity but only in warmer and wetter environments, while the upland varieties are better adapted to both colder and drier habitats.

Giant reed is a common weed in the Mediterranean, and it is known to be invasive and out-compete other crops, but it is also able to give very high biomass yields provided it is grown under optimal conditions. Also with less optimal conditions it is well able to cope, such as drought, high salinity levels, poor texture and steep slopes, although this will decrease the yield level. It is also well suited to be grown in contaminated lands for phytoremediation.

Reed canary grass is a tall, perennial bunchgrass that commonly forms extensive single species stands along the margins of lakes and streams and in wet open areas, with a wide distribution in Europe.

The last two crops are the industrial and the Sunn hemp that produce fibre, lignocellulosic material and also oil seeds. Both are grown more for the biomass then for the oil. A wide number of (high value) bio-products can be produced from all plant parts, stem leaves, seeds and flowers). When used for biofuel production it is advisable to only use the lignocellose from the plant for this process and produce other higher value products from the remaining parts. Both crop types are short season and miliferous plants which are very beneficial to pollinators, particularly when introduced in rotational systems which prove less benefits to insects.

3.3 Selected crops and climate suitability

In the MAGIC project the climatic suitability of the different crops has been mapped carefully in order to better understand which crops can best be grown in the different AEZs and which natural constraints are most commonly occuring in the crops' climate suitable locations.

The thresholds for climatic suitability were determined in several sessions with all crop experts involved in the MAGIC project, for details please read chapter 6 in the updated MAGIC deliverable 2.6 (Elbersen et al., 2022). The thresholds were mapped assuming that the crop will be able to grow in the climate zone, but not necessarily that it reaches an optimal production level. The climate suitability is mapped according to the following factors:

1) Minimum length of growth season (days), linked to base temperature
2) Minimum length of growing degree days (GDD), linked to base temperature
3) Level to which the crop (above and below ground biomass) can survive different levels of killing frost (KF), assuming this frost occurring for at least 5 days in a row.
4) Minimum level of precipitation the crop needs during the growing season

In relation to annuals that produce seeds (or other storage organs) the growing season is scored more strictly as reaching maturing phase is crucial. For biomass crops it is acceptable if the minimal level of growth season and GDD is not completely reached as reaching maturity phase for harvesting the crop is not necessary for harvesting[8].

This resulted in 2 types of suitability maps per crop, one presenting the different climate limitations per factor and one more simple map of the suitable, marginal suitable and not suitable area for the crop as is illustrated for Biomass Sorghum in Figure 3.1 here and for all other crops in Annex I.

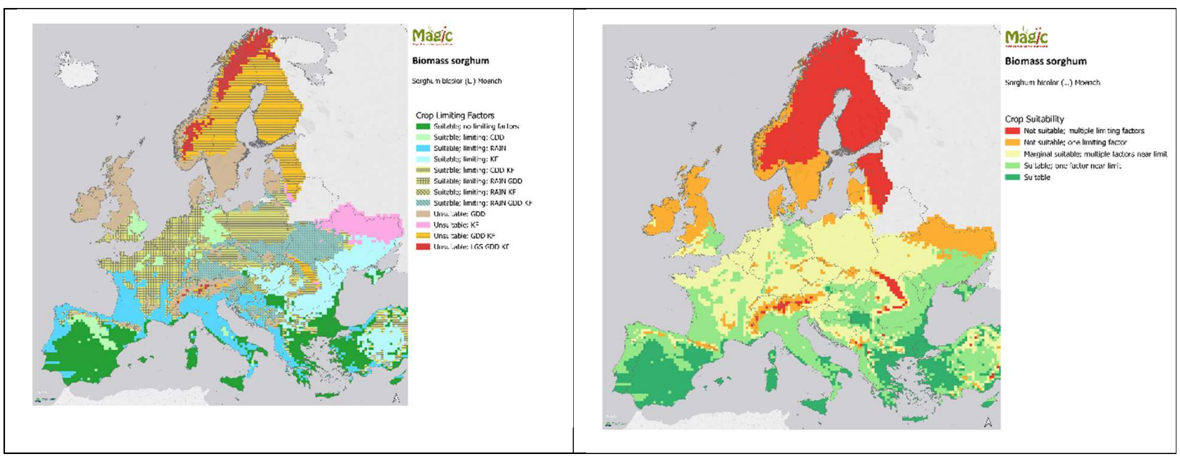

Figure 3.1 Climatic suitability for biomass sorghum in Europe (source: MAGIC Deliverable 2.6-updated, Elbersen et al., 2022)

Sorghum is typically a crop that thrives best in semi-arid (sub) tropical climate zones, but given the availability of many short season varieties and the fact that biomass sorghum can also be harvested before the final growth stage is reached (as biomass is the focus and no need to have mature seeds), it can also

[8] This implied that the mapping of the GDD for annuals allowed for mapping all areas meeting the threshold and those meeting still a 20% above/below the threshold. For perennials a wider area was mapped which scored 30% above/below the threshold. The areas mapped within the 20% and 30% thresholds respectively were classified as ' marginal suitable' because one or more factors are near limit.

be grown well in more northern regions like southeast England and northeastern Germany. In principle water needs in the growing season should be between 400-600 mm to obtain a good yield, but the crop can still manage to survive with lower precipitation levels, altough obviously, this will decrease the yield unless irrigation is used to compensate the water dificit.

The climatic suitability of all lignocellulosic crops selected is very wide covering practically the whole of Europe from southern Sweden to most southern Europe. Within this group, Tall wheat grass is the most tolerant of all lignocellulosic crops, followed by poplar, willow and Reed canary grass. Of course tolerance, does not imply that high yields can be reached for all these crops, they produce highest biomass yields when grown under optimal climatic circumstances which is with no or low water deficit and a sufficiently long growing season to perform all growing stages. The advantage of willow, poplar, and reed canary grass is that they already start growing when temperature is just above 0 0C. For Tall wheat grass it a bit higher at 4 0C but the number of growth degree days (GDD) is only 1200 which is together with sunn hemp and cardoon among the lowest of all lignocellulosic plants. Tall wheat grass, RCG, willow and poplar can also handle frost relatively well. Biomass sorghum, Giant Reed and Lowland switchgrass have a much higher base temperature in combination with a medium to long GDD requirement (see Table 1 in Annex I) which makes them suitable for a smaller area in Europe, particularly located in the Mediterranean and southern continental zones of Europe. Furthermore, they can only cope with mild frost. Upland Switchgrass, Miscanth0us and Industrial Hemp are somewhere in the middle with climatic requirements. Their base temperature is also at 6 0C , but their GDD are limited to around 1400-1500 and they can cope relatively well with frost, up to -10 0C for Switchgrass and Miscanthus, but only up to -5 0C for Industrial Hemp. Sunn Hemp has a relatively short GDD but with a high base temperature of 8 0C and no tolerance to frost. As an annual this should not be a problem provided the GDD are met. As to water requirements, the most drought tolerant lignocellulosic crops are tall wheat grass, Sunn Hemp and upland Switchgrass. Overall however, limited water availability will always significantly reduce the yield, but survival rates are higher in these most drought tolerant crops and presence of irrigation facilities is not vital.

Of the oil crops selected Camelina grown as a summer annual has the broadest climate suitability in Europe, this is then followed by Castor and Crambe and Ethiopian Mustard, also grown as a summer annual. Camelina and Crambe can also be grown as winter annual in many regions of the Mediterranean. Castor and Ethiopian Mustard however are more difficult to be grown as a winter crop because of the very long GDD requirements and the zero tolerance to frost (see Table 1 in Annex I). The best tolerance for frost among oil crops is for Camelina. Crambe, Camelina, Ethiopian Mustard are also very drought tolerant and too much water (rainfall), especially in the last growth phases, will even be harmful. Castor is less drought tolerant then most of the other oil crops.

3.4 Selected crops and ability to cope with marginal conditions in areas of natural constraints

The way the selected crops may cope with marginal constraints was extensively studied in the MAGIC project. The way crops respond to the different natural constraints that determine together the marginal lands, was expressed in yield reduction levels. Determining these yield reduction levels was done by all crop experts involved in the MAGIC project, for details please read chapter 7 in the MAGIC deliverable 2.6 (Updated 2022) (Elbersen et al., 2022).

The results of the MAGIC expert assessment of the influence of different natural constraints on yield potential is summarized for the selected crops in BIKE for adverse climate factors in Table 3.2 and for soil related natural constraints in Table 3.3.

Table 3.2 Effect of adverse climate conditions on yield, expressed in yield reduction (YR) factor*, based on MAGIC

Name (Latin)	*Common name*	*Low temperature: Length of growing season <195 days*	*Low temperature: Growing Degree Days (GDD<1575 T base 5^0 C)*	Dryness: **Annual precipitation (P) to annual potential evapotranspiration (PET) <= 0.6. (P/PET ≤ 0.6)**
Panicum virgatum L.	**Upland Switchgrass**	1	1	1
Panicum virgatum L.	**Lowland Switchgrass**	2	2	2
Camelina sativa (L.) Crantz	**Camelina (summer-annual)**	3	3	3
Camelina sativa (L.) Crantz	**Camelina (winter-annual)**	3	3	3
Sorghum bicolor (L.) Moench	***Biomass sorghum***	1	1	2
Crambe abyssinica Hochst x R.E. Fries	**Crambe (summer annual)**	3	3	1
Crambe abyssinica Hochst x R.E. Fries	**Crambe (winter annual)**	3	3	1
Ricinus communis L.	**Castor bean**	3	2	2
Miscanthus x giganteus & synancys	**Miscanthus**	2	2	2
Arundo donax L.	**Giant reed**	1	1	2
Agropyron elongatum (Host.) Beauv.	**Tall wheatgrass**	3	2	3
Brassica carinata A. Braun.	**Ethiopian mustard (summer annual)**	0	0	2
Brassica carinata A. Braun.	**Ethiopian mustard (winter annual)**	0	0	2
Phalaris arundinaceae L.	**Reed canary grass**	2	2	3
Cynara cardunculus L.	**Cardoon**	3	3	2
Salix spp.	**Willow**	3	3	1
Populus spp.	**Poplar**	2	2	2
Crotalaria juncea L.	**Sunn hemp**	1	1	2
Cannabis sativa L.	**Industrial Hemp**	2	2	2

* Score: 1 to 3 [YR=yield (actual) reduction]
1= YR>50%;
2= 25%< YR <50%;
3= YR < 25%;
0= Unfeasible

A length of growing season and growing degree days (GDD) complying with the marginal thresholds are having the largest yield reduction effects on Lowland Switchgrass, Biomass Sorghum, Giant reed and Sunnhemp. For an oil crop like Ethiopian Mustard the production becomes completely unfeasible in these marginal conditions because the groth season and GDD are relatively long for and oil crop and practically no seed yield results if not all growth phases can be reached. The opposite is the case for crops like Camelina, Crambe, Castor, Tall wheat grass, Cardoon, Reed Canary grass (RCG) and Willow which have either very short growing season requirements or already start growing well at relatively low temperatures. For willow and RCG for example the base temperature at which growth starts is just above 0^0 C.

Yield reduction effects of dryness levels within the marginal range are largest on crops like Lowland Switchgrass, Crambe and Willow. Crops like Camelina, Tall wheat grass and RCG have a good drought tolerance experiencing lower yield reduction effects under these circumstances.

Table 3.3 Effect of adverse soil and terrain conditions on yield, expressed in yield reduction (YR) factor*, based on MAGIC

Name (Latin)	*Common name*	Soil moisture FC >210d	Poorly or very poorly drained	Soil texture Coarse material >10%	Soil texture: Sand; loamy sand >40%	C Soil texture: clay>50%	Soil texture : OM>30% (30/100 cm)	*Shallow rooting: <35cm*	Salinity: >3.2 dS/m	Sodicity >4.8 ESP	Acidity pH<5.5	Slope >12%
Panicum virgatum L.	**Upland Switchgrass**	2	2	2	3	3	1	2	NA	NA	NA	3
Panicum virgatum L.	**Lowland Switchgrass**	3	2	2	3	3	1	2	NA	NA	NA	3
Camelina sativa (L.) Crantz	**Camelina (summer-annual)**	2	2	1	2	1	1	2	2	NA	NA	1
Camelina sativa (L.) Crantz	**Camelina (winter-annual)**	2	2	1	2	1	1	2	2	NA	NA	1
Sorghum bicolor (L.) Moench	***Biomass sorghum***	1	1	1	2	1	3	2	2	2	2	2
Crambe abyssinica Hochst x R.E. Fries	**Crambe (summer annual)**	1	1	2	2	3	NA	2	NA	NA	NA	2
Crambe abyssinica Hochst x R.E. Fries	**Crambe (winter annual)**	1	1	2	2	3	NA	2	NA	NA	NA	2
Ricinus communis L.	**Castor bean**	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Miscanthus x giganteus & synancys	**Miscanthus**	2	2	3	3	1	3	2	2	NA	3	1
Arundo donax L.	**Giant reed**	3	3	2	3	3	NA	1	3	NA	NA	2
Agropyron elongatum (Host.) Beauv.	**Tall wheatgrass**	2	1	3	3	1	NA	2	3	NA	3	2
Brassica carinata A. Braun.	**Ethiopian mustard (summer annual)**	2	1	1	3	3	3	2	2	NA	NA	2
Brassica carinata A. Braun.	**Ethiopian mustard (winter annual)**	2	1	1	3	3	3	2	2	NA	NA	2
Phalaris arundinaceae L.	**Reed canary grass**	3	2	2	3	2	2	3	3	3	2	3
Cynara cardunculus L.	**Cardoon**	1	1	2	2	2	NA	2	3	3	3	2

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Name (Latin)	***Common name***	Soil moisture FC >210d	Poorly or very poorly drained	Soil texture Coarse material >10%	Soil texture: Sand; loamy sand >40%	C Soil texture: clay>50%	Soil texture : OM>30% (30/100 cm)	*Shallow rooting: <35cm*	Salinity: >3.2 dS/m	Sodicity >4.8 ESP	Acidity pH<5.5	Slope >12%
Salix spp.	**Willow**	3	2	3	3	2	2	2	1	3	3	2
Populus spp.	**Poplar**	3	1	3	3	3	3	1	2	3	1	2
Crotalaria juncea L.	**Sunn hemp**	3	1	3	3	2	2	3	1	NA	3	3
Cannabis sativa L.	**Industrial Hemp**	3	1	3	3	2	2	3	1	NA	3	3

* Score: 1 to 3 [YR=yield (actual) reduction]

1= YR>50%;

2= 25%< YR <50%;

3= YR < 25%;

0= Unfeasible

The effects on yield reduction of marginal soil and terrain limitations are presented in Table 3.3 and show a wide diversity. For effects of long periods of standing water (Soil moisture FC>210 days) is a big problem for crops like Biomass sorghum, Crambe, and Cardoon while it is less of a problem for switchgrass, Giant reed, RCG, willow and poplar.

Badly drained soils at the moment in the growing season of a crop has a large yield reduction effect on all oil crops, including cardoon, but also on biomass crops like Biomass Sorghum, Tall wheat grass, Poplar and both types of Hemp. Giant reed is a crop completely adapted to wet conditions and is having no problems when grown on badly draining soils.

Soil textural limitations work out very differently, because of the wide diversity in types of soil textural limitations and crops. Soil texture limitations caused by presence of coarse material has the largest yield limitation effect in oil crops which are rotational crops which require frequent field management activities and mechanisation but is less of a problem in biomass crops, particularly Miscanthus, Tall wheatgrass, Willow, Poplar and Hemp.

A high content of loamy sand has a yield reduction effect on all crops, but is generally not a strong limiting marginal condition. A very high clay content is more limiting for many more crops, especially for camelina, biomass sorghum and miscanthus. High organic contents have a strong yield reduction effect on Switchgrass and Camelina. For several crops information on the effect is however missing in this marginal category. Shallow rooting conditions in the very marginal range are limiting Giant reed and poplar most strongly. The effects of salinity and sodicity on yields are not very complete for all crops, but for the crops with which the experts in the MAGIC project had experience we see that willow and Hemp experience high yield reduction in saline conditions, but less in sodic conditions, at least in the case of Willow. Cops that seem to be able to cope well with salinity are Giant Reed, Tall wheat grass, RCG and Cardoon and for many of these the same applies to high sodic levels.

Knowledge on high acidity effects on crop yields are also incomplete, but for the crops there is experience in field trials, we see that poplar’s yields levels are strongly adversely affected, while the opposite is the case for Willow, Hemp, Cardoon, Tall wheatgrass and Miscanthus.

Finally, steep slopes in the marginal range are expected to have the highest yield reduction effects in Camelina and Miscanthus which is likely causes by mechanisation limitations, particularly at establishment and harvesting of the crop.

The yield reduction effects coming from marginal conditions as discussed in the former are relative to the yield levels of the crops grown in optimal conditions. In the next chapter we will discuss that yield levels already measured in all the selected crops as derived from field trials implemented in the MAGIC project and in several other projects published in reports and scientific articles. It will become clear that yield levels under both optimal and marginal conditions do range strongly between the different crops, but particularly between the different types of biomass crops.

This project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 952872

4. Crop yielding capacity in unused, abandoned and or degraded lands

4.1 Introduction

One of the pathways to achieve value chains for advanced biofuel production with low ILUC-risk is to explore the possibility to grow industrial crops on unused, abandoned or degraded land. This is one of the forms of additionality of biomass feedstocks in the definition of the REDII. In the previous chapter, the suitability of crops for cultivation in these circumstances was examined. In this chapter we will estimate the yield performance of the selected crops in land with natural constraints. These may characterise unused, abandoned or degraded land, as was explained in chapter 2.

4.2 Method

Information on the yield performance of the selected industrial crops was derived from reviews and reports on the yield performance of industrial crops cultivated under favourable and unfavourable conditions with regard to climate and/or soil and terrain. The reviews and reports considered were compiled in the framework of the EU-project MAGIC[9] and the three review papers of Reinhardt et al. (2021ab and 2022). The conditions are referred to as respectively 'non-marginal' and 'marginal' from this point forward. The marginal conditions considered in the compilation are summarized in Table 1.

Table 1 Marginal conditions for the cultivation of industrial crops considered in the compilation of yield performance.

Category	Natural constraint	MAGIC – cluster of natural constraint (see section 2.3, Figure 2)*
Climate characteristics	Low temperature	Adverse climate (1)
	Drought	Adverse climate (1)
Soil and terrain characteristics	Unfavourable texture (heavy clay, sandy soils, stoniness)	Rooting (5)
	Compacted soil	Rooting (5)
	Low permeability to water/air	Rooting (5)
	Impeded drainage	Excessive wetness (2)
	Low soil organic matter content	Low soil fertility (3)
	Low soil fertility (alkalinity)	Low soil fertility (3)
	Soil acidity (low pH)	Adverse chemical condition (4)
	Contaminated soil	Adverse chemical condition (4)
	Shallow rooting depth	Poor rooting conditions (5)
	Steep terrain slope	Adverse terrain (6)

*In the MAGIC mapping approach 18 single biophysical factors have been identified for the classification of severe limitations and these were grouped into 6 clustered factors:

1. Adverse climate (low temperature and/or dryness)
2. Excessive wetness (Limited soil drainage or excess soil moisture)
3. Low soil fertility (acidity, alkalinity or low soil organic matter)
4. Adverse chemical conditions (Salinity or contaminations)
5. Poor rooting conditions (low rootable soil volume or unfavourable soil texture)
6. Adverse terrain conditions (steep slopes, inundation risks)

[9] https://magic-h2020.eu/ Horizon 2020 project, grant agreement No. 727698.

Data on observed average annual dry matter yield ($Mg.ha^{-1}$) and variation were collected in a database, together with the type of yield (above-ground biomass, stem, stalk, seed, grain), the agro-ecological zone in which the crops were grown and details on the field experiments and findings.

a. Review of yields for selected crops

Figure 4.1 shows observations on annual dry matter yield for the selected industrial crops under non-marginal and marginal conditions. Only crops were included for which more than two observations were available in non-marginal and marginal conditions. It should be noted that every record on the x-axis refers to a different source or field experiment, and therefore conditions of climate, soil and management differ between records. The reason is that the studies and reviews on field experiments consulted did not report yields for marginal conditions with reference values for the same trials under non-marginal conditions. This means that yields of a crop for marginal conditions cannot be directly compared to yields for non-marginal conditions. However, the range of values reported in the different studies can be compared between the marginal and non-marginal conditions, while acknowledging the variation in environmental and management conditions between the records.

Keeping this in mind, the graphs show that for most crops, the majority of observations of yield under marginal conditions are in the lower range of the values reported for non-marginal conditions. However, for some crops, the majority of reported yields are in a similar range of values under marginal and non-marginal conditions, or are even higher. This applies to hemp, reed canary grass, sorghum, switchgrass, willow and tall wheatgrass. This suggests that these crops could be suitable for areas with unused, abandoned or degraded land with such marginal conditions.

When we compare the maximum yield levels between the oil crops Camelina and Crambe (for Ethiopian Mustard not enough field trial data were derived), we see that Crambe can reach 5 ton seeds/ha in non-marginal conditions which is significantly higher then for Camelina (3 ton seeds/ha). In marginal circumstances the maximum in Camelina is however higher with 2.8 ton seeds/ha then for Crambe (2.2 ton seeds/ha).

For the biomass crops the highest minimum and maximum yields in non-marginal circumstances were observed in Giant reed (min 19 ton dm/ha and max 55 ton dm/ha), Miscanthus (min 10 ton dm/ha and max 41 ton dm/ha), Cardoon (min 10 ton dm/ha and max 36 ton dm/ha) and Willow (min 7 and max 30 ton dm/ha). Also in marginal conditions these crops still showed significant maximum yields of 37, 32, 20 and 44 ton dm/ha respectively, but also very low yields of almost 0 to 3 ton dm/ha.

On the lower end of yield levels found there are tall wheat grass (min 4 ton dm/ha and max 7 ton dm/ha) and RCG (min 4 ton dm/ha and max 14 ton dm/ha). However, for both crops it is also striking that the maximum yield found in marginal conditions was 14 ton dm/ha and 16 ton dm/ha respectively which is higher then the maximum yield in non-marginal conditions.

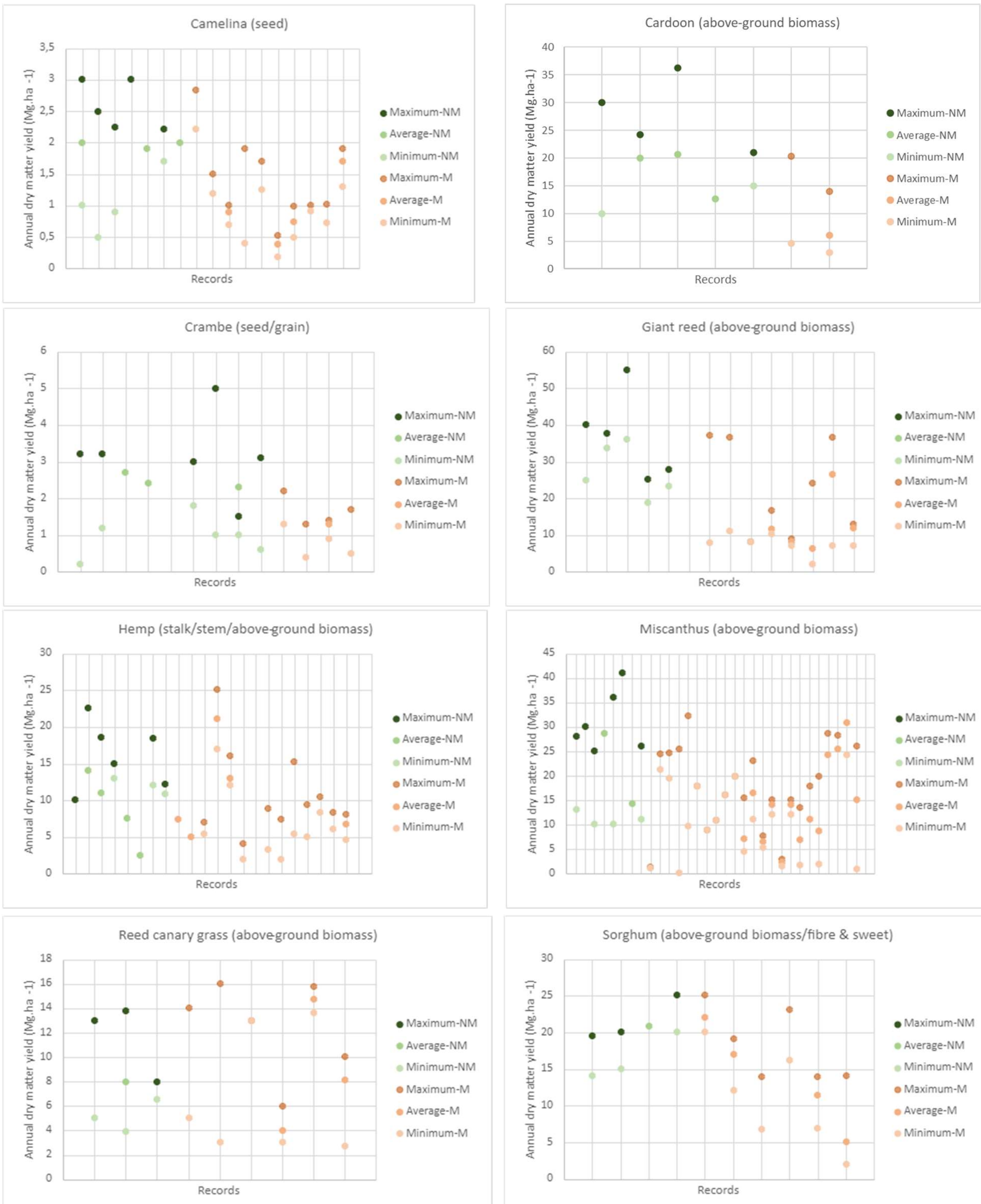

Figure 4.1 Yield of biomass crops under non-marginal (NM) and marginal (M) conditions, with average, minimum and maximum values given if available. Records on the x-axis are observations from different studies and agro-ecological zones.

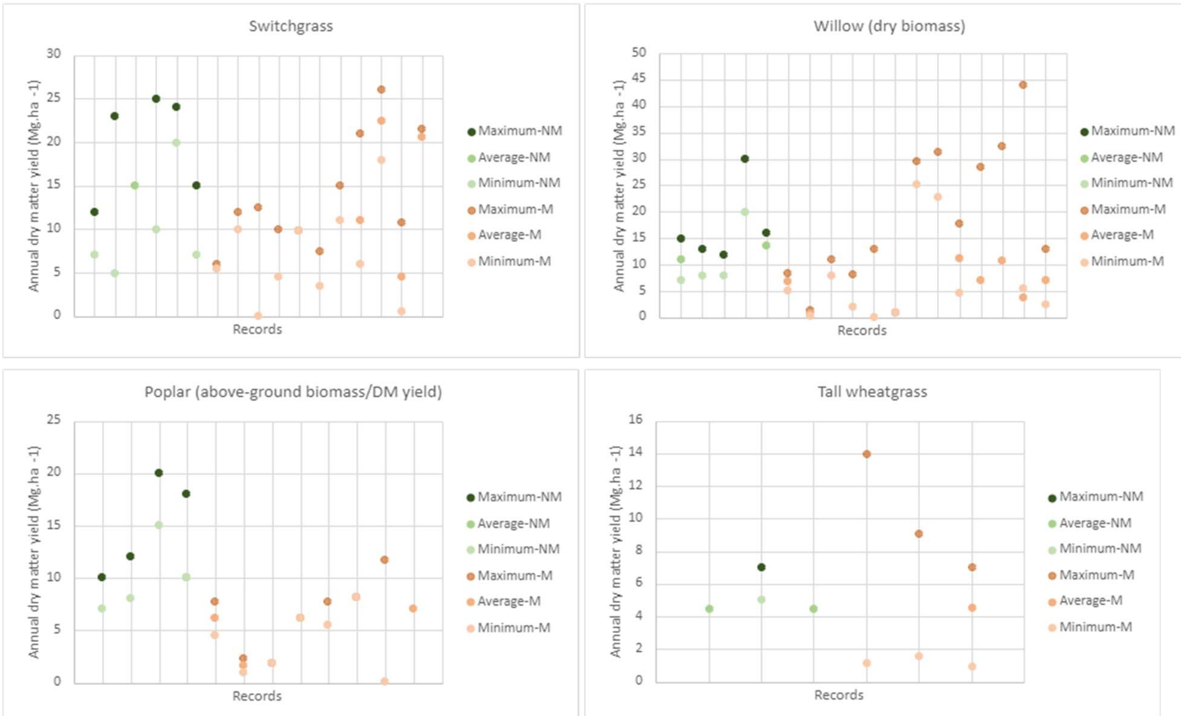

Figure 4.1 (continued) Yield of biomass crops under non-marginal (NM) and marginal (M) conditions, with average, minimum and maximum values given if available. Records on the x-axis are observations from different studies and agro-ecological zones. *Yields (t/ha Seeds for Oil Crops and t/ha Dry Matter Biomass for Lignocellulosic Ones) are annual average yield in Mg.ha-1. Castor is missing because of limited observations.*

If we look at the variation in yields reported for non-marginal versus marginal conditions reflected by the minimum and maximum values, we notice that the minimum and maximum yield performance (in above-ground dry matter biomass for biomass crops and in oil seed yield for oil crops) reported from the reviews appears higher for non-marginal conditions than for marginal conditions for most crops (Figure 4.1). However, there are exceptions as under marginal conditions, the maximum yield reported is approximately 50% higher for tall wheatgrass and willow and also RCG shows a significantly higher maximum yield in marginal conditions. This implies that for these crops, the marginal conditions do not necessarily depress yield at the upper end of the range of yield values obtained. When looking more closely to the conditions in the Willow trials with relatively high high yields these were high soil moisture, low organic matter unfavourable texture and stoniness. In Chapter 3 (Tables 3.2 and 3.3) it was already observed that willow can cope relatively well with these limitations. In case of tall wheat grass the yield observations were derived from marginal conditions related to dryness, low temperature and stoniness. These marginal conditions are not constraining yield levels very strongly in this crop as was also already discussed in the former chapter 3 (Tables 3.2 and 3.3).

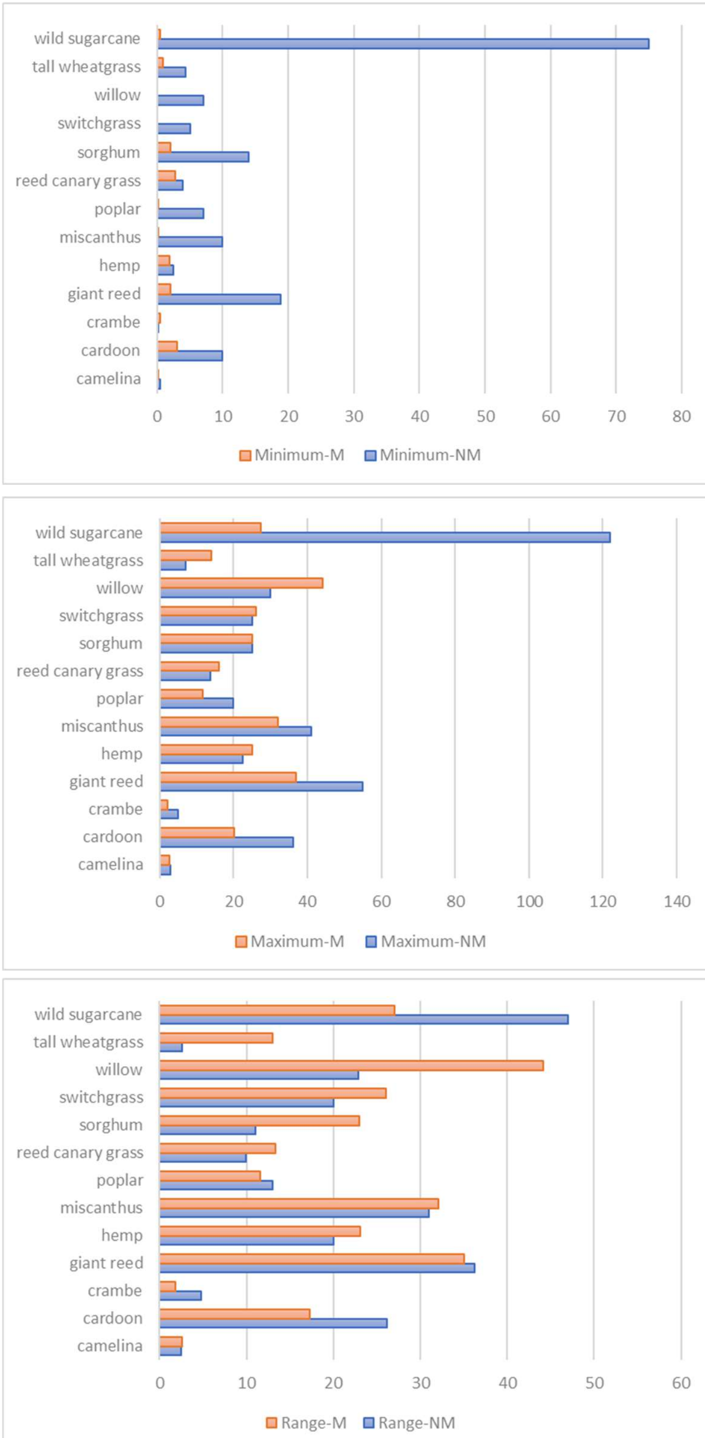

Figure 4.1 Minimum and maximum values and range of observations of yield of industrial crops under marginal (M) and non-marginal (NM) conditions. Yields (t/ha Seeds for Oil Crops and t/ha Dry Matter Biomass for Lignocellulosic Ones) are annual average yield in Mg.ha-1.

The range of yields reported in the field experiments is a measure of the variation that can be expected in the yield performance of the crops as a function of environmental conditions and management. Large ranges in yield values were reported for all crops under both non-marginal and marginal conditions, amounting to 40-100% of the maximum values of yields reported under both types of conditions. The large ranges probably reflect the diversity of agro-climatic conditions and management in the field experimental settings.

For some crops the range in reported yields under marginal conditions is larger than the range of yields reported for non-marginal conditions. This applies to hemp, reed canary grass, sorghum, switchgrass, willow and tall wheatgrass. This could indicate opportunities to achieve crop yields characteristic of non-marginal conditions under certain treatments.

Based on the review of results from the projects baseline yields of the selected crops could also be estimated per AEZ for normal and for marginal lands (i.e. land under natural constraints) as presented in Table 4.2.

Table 4.2 Baseline yields per European Agro-Ecological Zones-AEZ (A: Atlantic, C&B: Continental and Boreal, M: Mediterranean) as derived from published results from EU projects (MAGIC, Panacea, BIO4A)

		Agricultural Practices*	**Average Baseline Yields (t/ha Seeds for Oil Crops and t/ha Dry Matter Biomass for Lignocellulosic Ones) per AEZ** (in Parenthesis Yields in marginal Land (with Natural Constraints)**		
			A	C and B	M
	Ethiopian mustard	B, UAD	3.5 (1)	na	2.5 (1.5)
	Crambe	B, UAD	2 (0.5)	2.5 (1)	3 (1)
	Camelina	I, CC, R, B, UAD	2.5	2 (1)	3 (1)
	Cardoon	B, UAD	3 (1.5)	3 (1.5)	3.5 (1.5)
	Castor	I, B, UAD	na	na	3.5 (1.5)
Lignocellulosic	Willow	AF. B, UAD	12 (6)	12 (6)	13 (4.5)
	Poplar	AF, B, UAD	10 (8)	10 (7)	10 (4)
	Biomass sorghum	I, R, B, UAD	15 (9)	15 (9)	20 (12)
	Tall wheat grass	B, UAD	na	na	10 (7)
	Miscanthus	B, UAD	12 (8)	15 (9)	20 (9)
	Switchgrass	B, UAD	18 (10)	18 (10)	20 (12)
	Cardoon	B, UAD	14 (8)		20 (10)
	Giant reed	B, UAD	15 (9)	15 (9)	20 (11)
	Reed canary grass (RCG)	B, UAD	15 (7)	15 (7)	20 (7)

intercropping (I), Unused, abandoned & degraded lands (UAD), cover cropping (CC), rotation (R), agroforestry (AF), biochar (B)

**for map of AEZs see Annex II.

In the Atlantic zone, both under good and marginal circumstances the highest average yielding lignocellulosic crops are Switchgrass, Biomass Sorghum, Giant Reed and RCG. As to oil crops the best choice from an average yield perspective is Ethiopian mustard as summer annual, where the climate is suitable (see also Annex I), and Cardoon.

In the Continental and Boreal zones the best options for oil crops are Cardoon and Crmbe, where local climate allows (see also Annex I), both for marginal and non-marginal circumstances. For biomass crops the best choice in both marginal and non-marginal conditions given the average yield levels would be Switchgrass, Biomass Sorghum and Giant Reed.

The Mediterranean zone has the largest number of both oil and biomass crops to choose from. For oil crops under marhinal conditions Ethiopian mustard, Cardoon and Castor are expected to give the highest average yields. However if the marginal constraint is dryness, which is certainly an increasing problem in this AEZ, one can best choose Camelina which can best cope with this constraint. Another strategy would be to choose Camelina, Crambe or Ethiopian mustard as a winter crop to avoid the long drought summer period. This is however only possible in the most southern parts of the Mediterranean where also in winter GDD are sufficient (see Annex I).

As to biomass crops in the Mediterranean, there are many crops that can reach 20 ton dm/ha yields in non-marginal conditions and in marginal conditions above 10 ton dm/ha. However what the best choice is should again be determined by the locally present natural constraints. If it is dryness, the most widely present constraint in the Mediterranean, the best choice would still to choose a crop with an overall low average yielding level but with a good survival rate such as Tall wheat grass and RCG.

4.3 Potential Yield Increases by 2030

The yield increase potential for the selected crops has been estimated based on the meta-data analysis and information published from the projects MAGIC, Panacea and BECOOL.

Figures 4.3, 4.4 and 4.5 presents potential yield increases for the crops in the Mediterranean, the Continental & Boreal and the Atlantic AEZs. The yield projections towards 2030 are based on the following assumptions:

- Baseline yields are the ones reported in Table 4.2.
- Crop yield increases due to already foreseen genetic crop improvements in the varieties used is 10% between 2020 and 2030. This calculates an increase of 1% annually and is in line with the EU Agricultural Outlook, which presents the respective yield increases for cereals in Europe (agricultur-al-outlook-2020-report_en.pdf (europa.eu).
- The low and high increase rate because of the application of one or multiple sustainable agricultural practices (with the exception of UAP for which no yield increase is applied) as indicated per crop in Table 4.2 is calculated as an average of 15% and 25%, respectively, between 2020 and 2030 based on the findings from BIO4A and SoilCare projects.

The projected results towards 2030 show for oil crops in agricultural land in the Mediterranean the highest yield levels to be reached for Castor (4.8 ton seeds/ha), followed by Crambe (4.1 ton seeds/ha), Camelina (4.1 ton seeds/ha) and Ethiopian mustard (3.4 ton seeds/ha). In the continental zone the highest yield for oil seed will be reached by cardoon (4.1 ton seeds/ha) and then by Crambe and Camelina wich are both projected to reach 3.4 ton seeds/ha by 2030. The climate in this AEZ does not allow for Ethiopian Mustard and Castor. In the Atlantic Ethiopian Mustard will be the highest yielding oil crop and will reach 4.8 ton seeds in 2030, but the area where it can be grown in this AEZ is more limited. The widely suitable oil crops for this AEZ with the highest yield potential would be Cardoon (4.1 ton seeds/ha).

When we look at projected yields for oil crops in marginal lands the highest projected yields in the Mediterranean would be for Cardoon (2.8 to seeds/ha) and Ethiopian Mustard (2.1 ton seeds/ha). In the continental a maximum projected yield would be reached by Cardoon (2.1 ton seeds/ha). In the Atlantic the best choice in marginal land for an oil crop would also be Cardoon (2.1 ton seeds/ha).

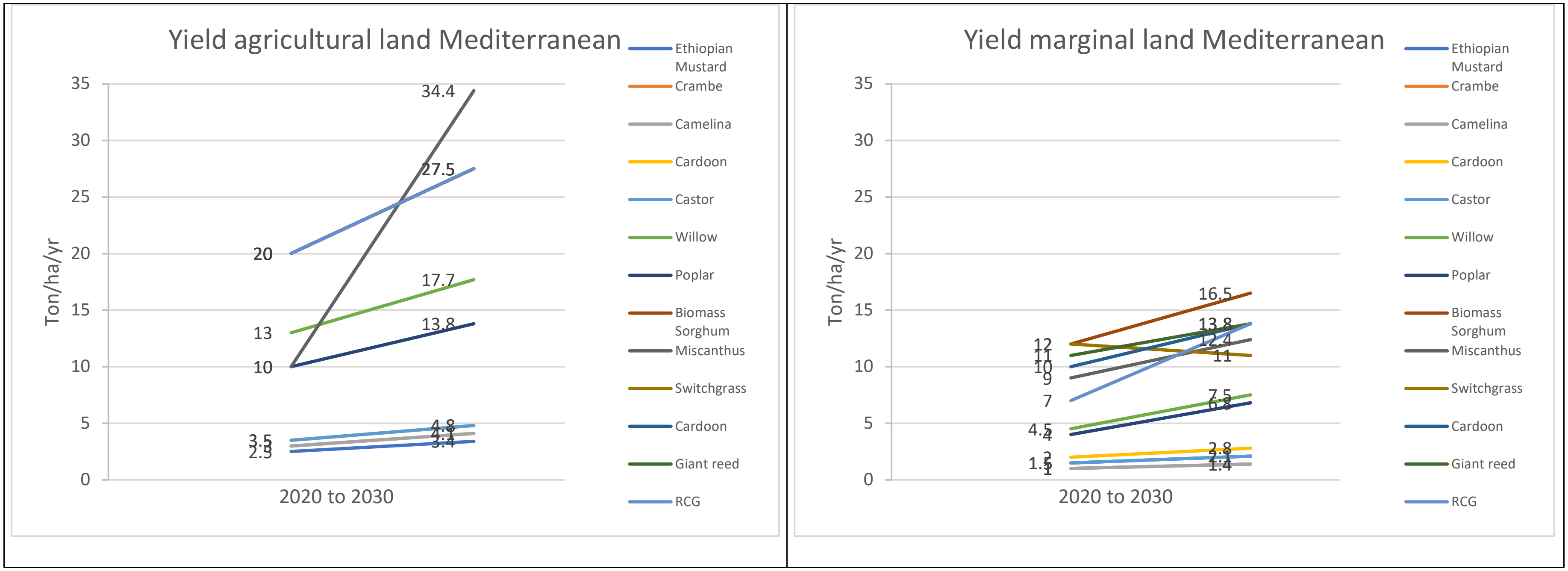

Figure 4.3 Estimated yield increases from the sustainable agricultural practices in farmland and in marginal land in the Mediterranean AEZ. Details in Annex III (Tables A1 and A2).

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 952872

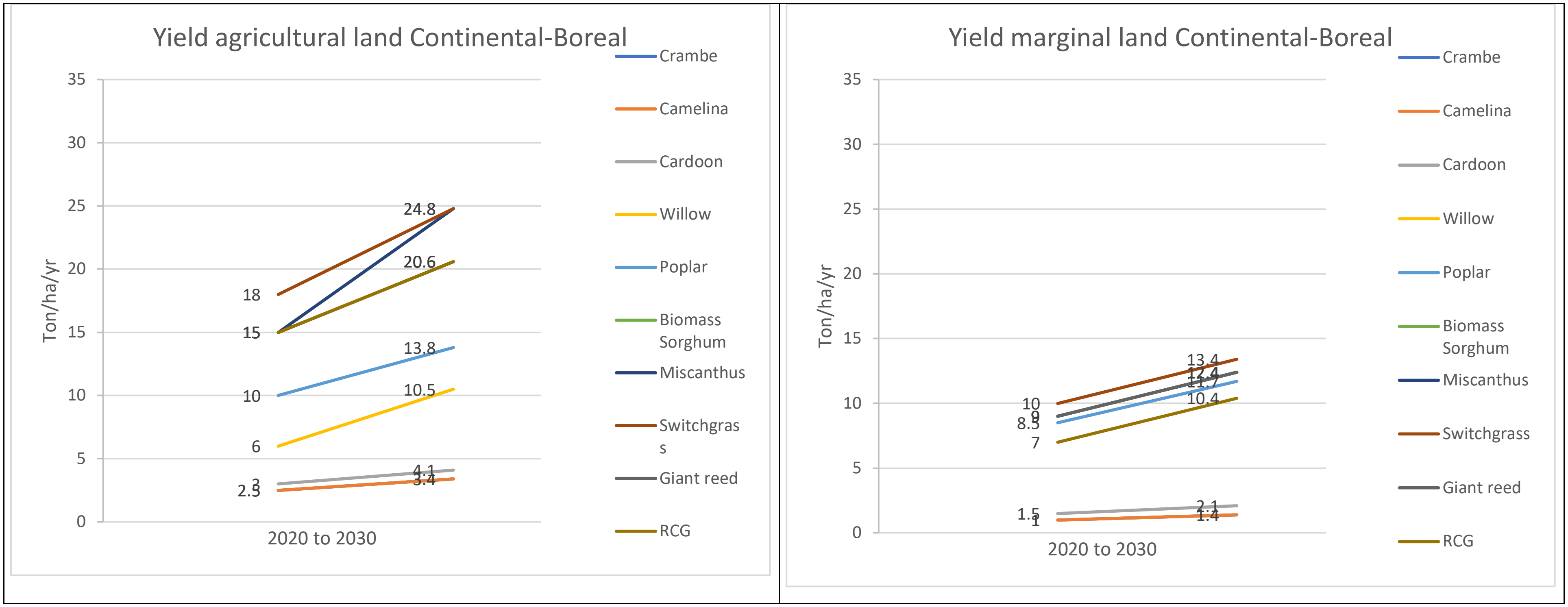

Figure 4.4 Estimated yield increases from the sustainable agricultural practices in farmland and in marginal land in the Continental & Boreal AEZ. Details in Annex III (Tables A1 and A2).

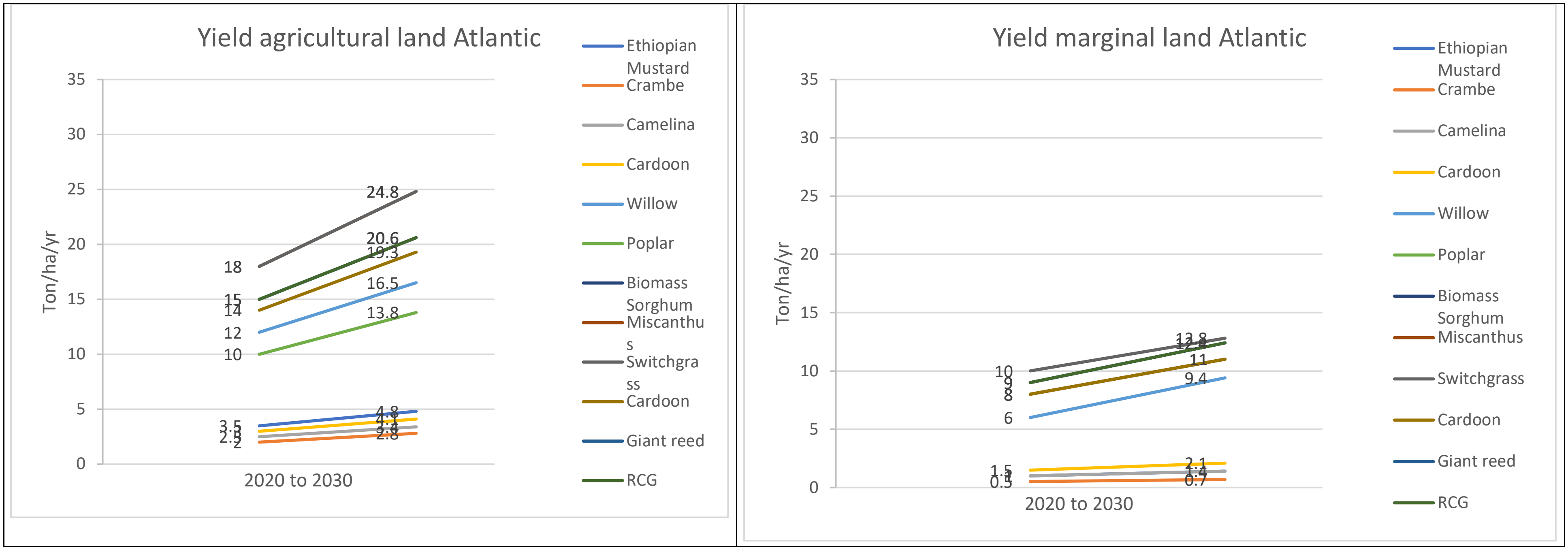

Figure 4.3 Estimated yield increases from the sustainable agricultural practices in farmland and in marginal land in the Atlantic AEZ. Details in Annex III (Tables A1 and A2).

For the biomass crops the current yields and the projected potential yields are generally higher in the Mediterranean AEZ as compared to the other two AEZ. In agricultural lands in the Mediterranean the highest yield projected is for miscanthus with 34.4 ton dm/ha. In the Continental and also the Atlantic AEZ the highest yield projected is for Miscanthus and Switchgrass with both 24.8 ton dm/ha in 2030. This of coarse is the situation in good conditions in good lands. However in marginal conditions the base line yields are lower and the yield projections for 2030 are generally more modest. In the Mediterranean the highest projected yields in marginal lands for biomass crops are found in Biomass sorghum with 16.5 ton/ha and for Cardoon, Giant Reed and RCG all at 13.8 ton/ha. In the Continental AEZ the highest maximum projected yield is lower then in the Mediterranean AEZ and is for Switchgrass with 13.4 ton dm/ha, closely followed by a combination of crops of biomass sorghum, miscanthus and Giant reed, which all have a projected yield of 12.4. In the Atlantic Switchgrass also reaches the highest maximum yield of 12.8 ton sm/ha followed by 12.4 ton dm/ha for biomass sorghum, Giant reed and RCG.

So projected yields for biomass crops in marginal lands are not sofar apart for crops like biomass sorghum, miscanthus, giant reed, RCG. The final choice for a crop in marginal circumstances should be lead by the yielding capacity in the specific marginal condition. In chapter 3 it was already shown that the type of condition a crop can cope wih can be very different per crop. Overall,it is therefore clear that the best choice under marginal circumstances is very much dependent on the type of natural constraint present.

4.4 Review of economic performance of crops

The cultivation of low ILUC risk biomass crops can offer an outlet to European farmers to diversify their crop production[10], improve agricultural practices, and restore soil while producing raw materials for low carbon fuels.

The work has been published in an open access article:

Panoutsou, C., Giarola, S., Ibrahim, D., Verzandvoort, S., Elbersen, B., Sandford, C., Malins, C., Politi, M., Vourliotakis, G., Zita, V. E., Vásáry, V., Alexopoulou, E., Salimbeni, A. & Chiaramonti, D. (2022), Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe. 1 May 2022, In: Applied Sciences (Switzerland). 12, 9, 4623. https://www.mdpi.com/2076-3417/12/9/4623

Ensuring a Viable Farm Income

Low ILUC risk feedstocks can offer opportunities for crop and income diversification through new markets and business models. Securing year-round feedstock supply for the biorefineries can contribute to additional income for farmers if the crops and cropping systems are integrated in a complementary manner to their current activities. This will ensure there are limited market distortions for currently cultivated raw materials while opening prospects for additional feedstocks from the same farm structures.

This paper presents a meta-data analysis for the production costs of the crops that are expected to reach TRL 7 and more by 2030 (Table 4.3). The ranges of market prices used are:

- 250–450 €/tonne of oilseeds for oil crops
- 50–100 €/tonne of dry matter for lignocellulosic crops

[10] C. Panoutsou, A. Singh, T. Christensen, L. Pelkmans. Competitive priorities to address optimisation in biomass value chains: the case of biomass CHP. Global Trans., 2 (**2020**), pp. 60-75, 10.1016/j.glt.2020.04.001

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 952872

These are based on the market price ranges for the last five years. They do not account for the high observed figures prevailing currently in the oilseed markets due to the war in Ukraine.

Figures 4.5 and 4.6 provide an overview of the production costs of the understudy crops (in €/tonne oilseeds and €/tonne lignocellulosic biomass, respectively) under the different yielding capacities (see Table4.2). The two figures also present the current ranges of market prices to understand the economic opportunities for the understudy crops in conventional farming land and in land with natural constraints.

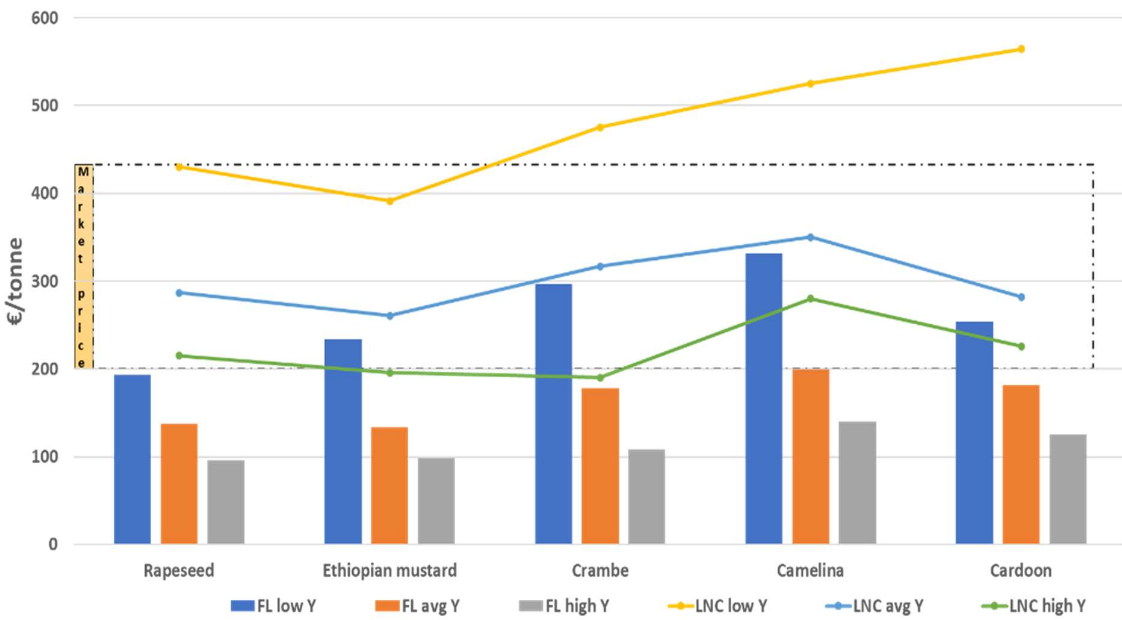

Figure 4.5 Oil crops production cost ranges in €/tonne seed (with yield increases) in farming land (FL) and in marginal land (Land with natural constraints (LNC)). Details in Table 4.2.

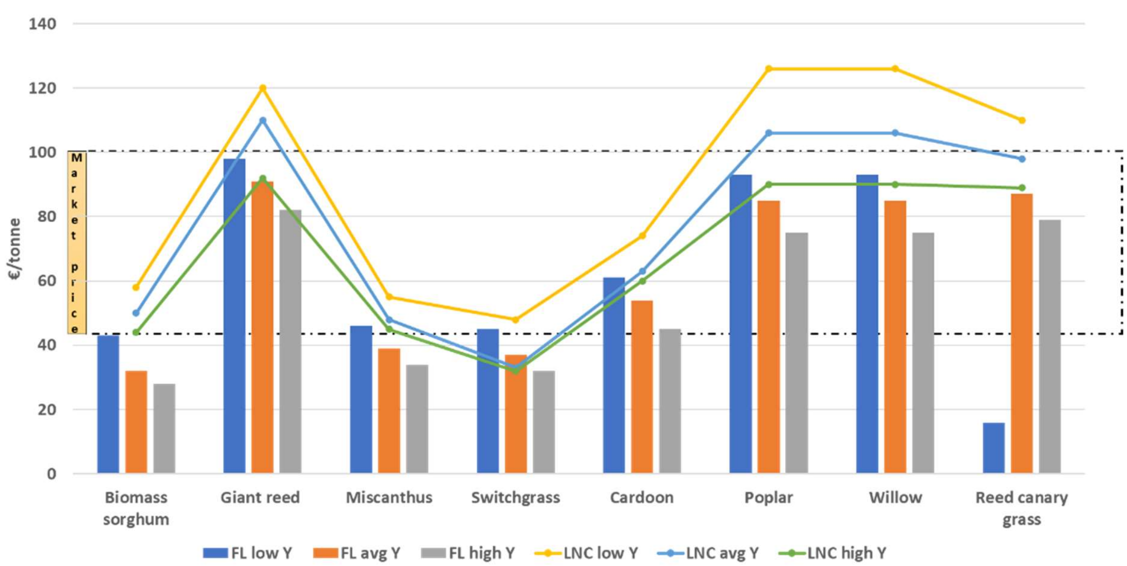

Figure 2.6 Lignocellulosic crops production cost ranges in €/tonne (with yield increases) in farming land (FL) and in marginal land (land with natural constraints (LNC)). Details in Table 4.2.

Table 4.3 below presents the profitability (i.e., the average market price minus the average production cost) of the understudy crops in conventional land and in land with natural constraints. In the case of oilseeds, camelina displays negative profitability even in farming land at the lowest yield range and at a market price of 300 €/tonne oilseeds. All other oilseed crops are profitable in conventional farming land for both market prices of 300 and 450 €/tonne oilseeds.

Table 4.3 Profitability of the understudy crops in conventional land and in land with natural constraints (in red the non-profitable entries).

	Profitability (€/Tonne Seed)											
	Farming Land						**Land with Natural Constraints**					
	Low Yield		**Average Yield**		**High Yield**		**Low Yield**		**Average Yield**		**High Yield**	
Market price	300 €/tonne	450 €/tonne	300 €/tonne	450 €/tonne	300 €/tonne	450 €/tonne	300 €/tonne	450 €/tonne	300 €/tonne	450 €/tonne	300 €/tonne	450 €/tonne
Rapeseed	107	257	162	312	204	354	**−130**	20	13	163	85	235
Ethiopian mustard	67	217	167	317	202	352	**−91**	59	39	189	105	255
Crambe	3	153	122	272	191	341	**−175**	−25	**−17**	133	110	260
Camelina	**−32**	118	101	251	160	310	**−225**	−75	**−50**	100	20	170
Cardoon	46	196	119	269	175	325	**−264**	−114	18	168	74	224
	Profitability (€/Tonne Dry Biomass)											
Market price	50 €/tonne	100 €/tonne	50 €/tonne	100 €/tonne	50 €/tonne	100 €/tonne	50 €/tonne	100 €/tonne	50 €/tonne	100 €/tonne	50 €/tonne	100 €/tonne
Willow	7	93	18	82	22	78	−8	108	0	100	6	94
Poplar	**−48**	52	**−41**	59	**−32**	68	**−70**	30	−60	40	**−42**	58
Biomass sorghum	4	96	11	89	16	84	**−5**	95	2	98	5	95
Tall wheat grass	5	95	13	87	18	82	2	98	17	83	18	82
Miscanthus	**−11**	89	**−4**	96	5	95	**−24**	76	**−13**	87	**−10**	90
Switchgrass	**−43**	57	**−35**	65	**−25**	75	**−76**	24	**−56**	44	**−40**	60
Cardoon	**−43**	57	**−35**	65	**−25**	75	**−76**	24	**−56**	44	**−40**	60
Giant reed	**−34**	66	**−37**	137	**−29**	129	**−60**	160	**−48**	148	**−39**	139
Reed canary grass	7	93	18	82	22	78	**−8**	108	0	100	6	94

None of the oilseed crops is profitable with the low yield option in land with natural constraints under a market price of 300 €/tonne oilseeds. Similar negative profitability is exhibited with a 450 €/tonne oilseeds market price for crambe, camelina, and cardoon as well as for crambe and camelina in the medium yield category. In all other cases, the oilseed crops are profitable.

Switchgrass, cardoon, and giant reed have similar performance at all yields with a market price of 50 €/tonne. In these cases, miscanthus has similar performance or is borderline profitable due to slightly higher yield per land unit. All lignocellulosic crops are profitable at a market price of 100 €/tonne in conventional farming land. Biomass sorghum is profitable in all cases except low yield in land with natural constraints and market price of 50 €/tonne.

At a market price of 100 €/tonne all the understudy lignocellulosic crops are profitable across yield categories in both conventional farming land and in land with natural constraints.

6. Conclusions

6.1 Integrated recommendations on crop performance per AEZ

The report examined yields for crops in agricultural land and land with natural constraints referred to as marginal land. The last category of land can strongly overlap with unused, abandoned, and degraded land as defined in REDII as land to which additionality may apply. At this point it is worth noting that the three REDII categories have not been mapped yet in a disaggregated manner due to the lack of respective statistical time series. As expected, crop yields are generally lower in such marginal lands, although this does not necessarily needs to be the case because certain crops are actually coping well with certain natural constraints. The crop choice is therefore a sensitive matter and will need to be tuned carefully to local characteristics of the land targeted.

Overall, the meta-analysis shows that there are many crops that are already or can reach the commercial level by 2030, are well adapted to the European agro-ecological zones (AEZs), and, when cultivated with sustainable agricultural practices, can deliver feedstock for biofuels while having traits that allow them to adapt to climate change risks and restore land with natural constraints and/or degradations.

In the Atlantic zone, both in agricultural land and in marginal land the highest average yielding lignocellulosic crops are Switchgrass, Biomass Sorghum, Giant Reed and RCG. As to oil crops the best choice from an average yield perspective is for Cardoon and Ethiopian mustard as summer annual, but this crop can only grow locally in a limited part of the Atlantic.

In the Continental and Boreal zones the best yielding oil crops are Cardoon and Crambe both for marginal and non-marginal circumstances. For biomass crops the best choice in both marginal and non-marginal conditions given the average yield levels would be Switchgrass, Biomass Sorghum and Giant Reed.

The Mediterranean zone has the largest number of both oil and biomass crops to choose from. For oil crops under marginal conditions Ethiopian mustard, Cardoon and Castor are expected to give the highest average yields. However if the marginal constraint is dryness, one can best choose Camelina.

As to biomass crops in the Mediterranean, there are many crops that can reach 20 ton dm/ha yields in non-marginal conditions and in marginal conditions above 10 ton dm/ha. However what the best choice is should again be determined by the locally present natural constraints. If it is dryness, the most widely present constraint in the Mediterranean, the best choice would still to choose a crop with an overall low average yielding level but with a good survival rate such as Tall wheat grass and RCG.

Overall, it is clear that the best choice under marginal circumstances is very much dependent on the type of natural constraint present. For oil crops one can conclude that a yield of more then 1.5 ton oil seeds is not easy to reach in marginal conditions in all AEZs. Oil seed yields are generally higher in the Mediterranean then in the other AEZs also because there is a wider choice of oil crops for this zone.

For biomass crops it was shown that certain crops even perform better under specific marginal conditions and this should guide the choice for a crop per marginal location. Dryness constraints for example are forcing the choice towards crops that can survive in these circumstances such as Tall wheat grass, RCG, but in general these are crops that are not among the high yielding crops. The review also showed however that there are several crops that can still give good yields in specific marginal conditions such as Willow, Giant reed and RCG that grow excellent in soils that are wet most of the year. Soil restoration or improvement or remediation is also an option with the reviewed crops. For example certain crops can cope well in soils that are salinated or have high acidity levels. Growing these crops on such soils may lead to improvements in the soil conditions to make soils suitable in the future to grow more profitable crops on it again.

The analysis of economic data and estimates confirms that most of the understudy crops can be profitable in farm land under current market prices both for oilseeds and for lignocellulosic ones. The cases where the crops are unprofitable refer mostly to the combination of low yields with low market price ranges and exist in both land categories. It is also important to clarify that production costs differ between farm land and marginal lands not only because of the 'lower yield' penalty but also because of the extra costs for restoring LNC that have to be factored in (such as more fertiliser, more labour, land rehabilitation, levelling, etc.).

Expected yield increases toward 2030 were also generated and these show that interesting yield increases towards 2030 can be reached in both oil and biomass crops, but generally these are not always enough to make crop production profitable in marginal lands. For oil crops this could be more challenging then for biomass crops where oil seed market prices remain low in combination with the relatively low yields these crops reach in most marginal soil and climate situations.

In agricultural land however, this would be different as with average and high yielding oil crops, certainly with Ethiopian Mustard and Cardoon, good profit levels are possible. Overall the high yield levels are very difficult to reach for oil crops in marginal lands. An exception would probably be Cardoon, but all other oil crops selected here are challenging unless niche situations are identified and REDII guidelines make low ILUC cetification possible. This could for example be the case where unused, abandoned or degraded lands have specific natural constraints for which oil crops exist that can cope well and still provide medium to high yields. Similarly this could happen if good agricultural land provides options for the introduction of oil crops in additionality practices such cover cropping, rotations or agroforestry systems (see also Deliverable 2.1).

In biomass crops the profitability levels are more easily reached then in oil crops. Overall conclusions show that a market price of 50 €/tonne will not make all biomass crops grown in marginal lands profitable, except for the crops that are on the higher end of the projected yields, such as miscanthus, giant reed, switchgrass, cardoon. However if the market prices is at 100 €/tonne practically all biomass crops can give some profit even in low yielding conditions which are generally applicable to marginal lands production.

Best strategy would always be to choose the crop that is best adapted to the local situation in order to create yields that are profiding profitable yields while complying with all low ILUC requirements to make certification possible.

Outlook and policies

Oil crops and lignocellulosic crops have distinct statuses under the RED II. If "produced on agricultural land as a main crop", oil crops fall under the RED II definition of food and feed crops. Despite the name, the RED II definition of a food and feed crop is not linked to edibility, and so an inedible oil crop grown as a main crop for bioenergy purposes would still count as a food and feed crop under this definition. Food and feed crop-based biofuels are counted once towards RED II targets, and there is a cap on their total use, which can vary by Member State. Oil crops grown as intermediate crops, however, are not identified as food and feed crops providing that their production does not "trigger demand for additional land". Low ILUC-certified oil crops grown in cover cropping or intercropping systems would therefore not be subject to the limitations on use applied to food and feed crops. If oil crops are grown on unused, abandoned or degraded lands their low-ILUC status in REDII is more challenging to prove, but no impossible and this will need to be further reviewed in BIKE also as part of work in WP1 on certification and in the case studies of BIKE.

Lignocellulosic material is treated more favorably under the RED II. Biofuels produced from lignocellulosic materials are treated as advanced and are eligible to be counted twice towards RED II targets, and there is no limit on the contribution of fuels from lignocellulosic material. The RED II includes 'provisional estimated' ILUC emissions values for different feedstock types, which inform decision making by the Commission and Member States. Oil crops are assigned a mean ILUC value of 55 gCO2e/MJ, but lignocellulosic crops are considered under the Directive to have no associated ILUC emissions. In the context of the RED II, low ILUC-risk certification is therefore more immediately relevant for oil crops than for lignocellulosic crops.

This report reviewed also some financial support instruments for enhancing the profitability of the understudy crops. There are, significant opportunities for governments to provide such support considering that agricultural subsidies account for a rather high share of agricultural income in many countries for traditional cropping systems. Financial interventions can be integrated in the greening measures within the Common Agricultural Policy, Rural Development Policy instruments, the Emissions Trading Scheme, the Sustainable Carbon Cycles Initiative, etc. From the findings presented in this report, it is evident that, with financial incentives tailored to the appropriate country, crop, land type and agricultural practice(s) combination, the understudy crops can provide profitable opportunities for European farmers in almost all cases and land categories.

Statistics

The proper understanding of opportunities for growing biofuel crops in line with the REDII policy guidelines is very much challeged by the lack of systematic statistical data colleaction. Recommendations in this regard are the following:

- Need to register in statistics the absence of management for several years in a row for land in agricultural domain (even when official agricultural land use status is lost).
- Detailed annual recording of yields per hectare at regional or field level is very informative. Helps to identify where marginalisation may lead to (further) abandonment.
- Degradation both on agricultural and other land should be recorded in statistical or spatial data sources.

Literature

Alexopoulou, E.; Christou, M.; Eleftheriadis (2018), I. Handbook with Fact Sheets of the Existing Resource-Efficient Industrial Crops (De-liverable D1.5); MAGIC Project Reports, Supported by the EU's Horizon 2020 Programme under GA No. 727698; CRES: Athens, Greece, 2018. Available online: https://magic-h2020.eu/reports-deliverables/ (accessed on 2 April 2022).

Allen, B., Kretschmer, B., Baldock, D., Menadue, H., Nanni, S., and Tucker, G. (2014). 'Space for energy crops – assessing the potential contribution to Europe's energy future.' Report produced for BirdLife Europe, European Environmental Bureau and Transport and Environment London; IEEP.

Braconnier, S. , S.Gutjhard, Trouche G., Reddy, B. , Rao R., Schaffert R., Parella, R., Zacharias A. , Rettenmaier N., Reinhardt G., Monti A, Amaducci S. , Marocco A., Snijman W. , Terblanche H., Zavala-Garcia F. , Janssen R., Rutz, D. (2014). Definition of new sorghum ideotypes to meet the increasing demand of biofuels.

EC (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0807 (accessed on 3 April 2022).

EC (2019a) 2055 Final. Commission Delegated Regulation Supplementing Directive (EU) 2018/2001 as Regards the Determination of High Indirect Land-Use Change-RISK feedstock for Which a Significant Expansion of the Production Area into Land with High Carbon Stock Is Observed and the Certification of Low Indirect Land **U**se Change-Risk Biofuels, Bioliquids and Biomass Fuels. 2019. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/2_en_act_part1_v3.pdf (accessed on 3 April 2022).

EC (2019b) 142. Report from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions on the Status of Production Expansion of Relevant Food and Feed Crops Worldwide. 2019. Available online: https://ec.europa.eu/transparency/regdoc/rep/1/2019/EN/COM-2019-142-F1-EN-MAIN-PART-1.PDF (accessed on 3 April 2022).

Elbersen, B.; Hart, K.; Koper, M.; Eupen, van M.; Keenleyside, C.; Verzandvoort, S.; Kort, K.; Cormont, A.; Klink, Giadrossi, A.; Baldock, D. (2020). Analysis of actual land availability in the EU; Trends in unused, abandoned and degraded (non) agricultural land and use for energy and other non-food crops. Wageningen 16 October 2020. Reference: ENER/C2/2018-440

Goh, B.H.H.; Chong, C.T.; Ge, Y.; Ong, H.C.; Ng, J.-H.; Tian, B.; Ashokkumar, V.; Lim, S.; Seljak, T.; Józsa, V. Pro-gress in utilisation of waste cooking oil for sustainable biodiesel and biojet fuel production. Energy Convers. Manag. 2020, 223, 113296. https://doi.org/10.1016/j.enconman.2020.113296.

Jäkel, k. & Theiss, M. (2017). Erfahrungen zum Sorghumanbau auf ertragsschwachen Standorten Vorstellung des FNR-Verbundvorhabens Sorghum. FIB e.V. Feldtag, 29. August 2017, Neu Sacro.

King, C., Baghdadi, N., Lecomte, V., Cerdan, O. [2020] The application of remote-sensing data to monitoring and modelling of soil erosion. Catena, 68, 79–93.

Lukyanchuk, K. A., Kovalchuk, I. P. & Pidkova, O. M.. (2020) Application of a remote sensing in monitoring erosion processes. Geoinformatics 2020. EAGE. Geoinformatics 2020 11-14 May 2020, Kyiv, Ukraine

Metzger, Marc J. (2018). The Environmental Stratification of Europe, [dataset]. University of Edinburgh. https://doi.org/10.7488/ds/2356.

OECD (2018), Effective Carbon Rates 2018: Pricing Carbon Emissions Through Taxes and Emissions Trading, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264305304- en.

Panoutsou, C.; Singh, A.; Christensen, T.; Alexopoulou, E.; Zanetti, F (2021). Deliverable D4.1 Training Materials for Agronomists and Students; PANACEA Reports, Supported by the EU's Horizon 2020 Programme under GA No. 773501; Imperial College London: London, UK, 2021. Available online: http://www.panacea-h2020.eu/wp-content/uploads/2021/04/D4.1-Training-manual-for-agronomists-and-students-update-.pdf (accessed on 3 April 2022).

Pelkmans L., Van Dael, M., Panoutsou, C., and Alakangas, E. (2016). D6.3 Policy options to mobilize sustainable non-food biomass resources for the biobased economy, December 2016, S2BIOM Project Grant Agreement n°608622

Perpiña Castillo, C.P., Jacobs-Crisioni, C., Diogo, V., and Lavalle, C. (2021). Modelling agricultural land abandonment in a fine spatial resolution multi-level land-use model: An application for the EU. Environmental Modelling & Software, 136, 104946.

Plevin, R.J., Beckman, J., Golub, A.A., Witcover, J., and O'Hare, M. (2015). Carbon accounting and economic model uncertainty of emissions from biofuels-induced land use change. Environmental science & technology, 49(5), 2656-2664.

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

Reinhardt, J., Hilgert, P., & von Cossel, M. (2021a). 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. (2021b). Biomass Yield of Selected Herbaceous and Woody Industrial Crops across Marginal Agricultural Sites with Shallow Soil. https://doi.org/10.3390/agronomy11071296

Souza, M.C.G.; de Oliveira, M.F.; Vieira, A.T.; de Faria, A.M.; Batista, A.C.F. Methylic and ethylic biodiesel pro-duction from crambe oil (Crambe abyssinica): New aspects for yield and oxidative stability. Renew. Energy 2021, 163, 368–374. https://doi.org/10.1016/j.renene.2020.08.073.

Terres, J.M., Hagyo, A., Wania, A., Confalonieri, R., Jones, B. Van Diepen K., and Van Orshoven J. (2014). 'Scientific contribution on combining biophysical criteria underpinning the delineation of agricultural areas affected by specific constraints. Methodology and factsheets for plausible criteria combinations'. JRC92686. doi: 10.2788/844501.

Van Orshoven, J., Terres, J.-M., Tóth, T., Jones, R., Le-Bas, C., Nachtergaele, F., Rossiter, D., Schulte, R., Van Velthuizen, H., 2012. Updated common bio-physical criteria to define natural constraints for agriculture in Europe. JRC Sci. Tech. Rep. Eur. Comm. Jt. Res. Cent. Inst. Environ. Sustain.-IES Luxembg. Available Online Httpmembers Iif Hutot3700abstrJVOJMTTT2012 Pdf. https://doi.org/10.2788/91182

Valin, H., Peters D., Van den Berg, M., Frank, S., Havlik, P., Forsell, N., et al. (2015). The Land Use Change Impact of Biofuels Consumed in the EU: Quantification of Area and Greenhouse Gas Impacts. ECOFYS, Utrecht, p. 261

Annex I Climatic crop suitability for all selected crops in Europe (Based on MAGIC climatic suitability mapping)

In the table the climate crop suitability thresholds are indicated against which the suitability levels per crop are scored.

After the table the crop suitability maps are presented for all crops. The maps on the left indicate per crop the climatic factors determining together the climatic suitability in the map on the right in which the final classification in five classes is presented ranging from suitable, marginally suitable and non-suitable.

Table 1 Crop suitability scores per climate factor

				Threshold of minimal GDD			Killing frost (°C)**			Threshold of minimal rainfall in growing season***					
		1=Annual/ 2=perennial	*Purpose: 1= (oil) seeds 2=biomass 3= combination*	*Minimum length of growth season (GS)**	*Minimum of growth degree days (thermal time)**	*Base temperature (°C)**	*-5 - 0 °C*	*-10 - 5 °C*	*< -10 °C*	*>1000 mm*	*1000-800 mm*	*800-500 mm*	*500-300 mm*	*300-200 mm*	*< 200 mm*
Panicum virgatum L.	Upland Switchgrass	2	2	126	1550	6	2	2	1	2	2	2	2	1	0
Panicum virgatum L.	Lowland Switchgrass	2	2	200	2300	6	2	0	0	2	2	2	1	0	0
Camelina sativa (L.) Crantz	Camelina (summer-annual)	1	1	90	1200	4	2	1	0	1	2	2	2	2	2
Camelina sativa (L.) Crantz	Camelina (winter-annual)	1	1	220	1300	4	2	2	2	1	2	2	2	2	2
Sorghum bicolor (L.) Moench	*Biomass sorghum*	*1*	*2*	120	1400	8	1	0	0	1	2	2	2	1	1
Crambe abyssinica Hochst x R.E. Fries	Crambe (summer annual)	1	1	110	1200	4	1	0	0	1	1	2	2	2	2
Crambe abyssinica Hochst x R.E. Fries	Crambe (winter annual)	1	1	150	1400	4	0	0	0	1	2	2	2	2	2
Ricinus communis L.	Castor bean	1	1	130	1200	8	0	0	0	2	2	2	2	1	0
Miscanthus x giganteus & synancys	Miscanthus	2	2	135	1500	6	2	1	0	2	2	2	1	0	0
Arundo donax L.	Giant reed	2	2	195	2200	**6**	**1**	**0**	**0**	**2**	2	2	1	1	0

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				Threshold of minimal GDD			**Killing frost (°C)****			**Threshold of minimal rainfall in growing season*****					
		1=Annual/ 2=perennial	***Purpose: 1= (oil) seeds 2=biomass 3= combination***	***Minimum length of growth season (GS)****	***Minimum of growth degree days (thermal time)****	***Base temperature (°C)****	***-5 - 0 °C***	***-10 - 5 °C***	***< - 10 °C***	***>1000 mm***	***1000-800 mm***	***800-500 mm***	***500-300 mm***	***300-200 mm***	***< 200 mm***
Agropyron elongatum (Host.) Beauv.	Tall wheatgrass	2	2	125	1200	4	**2**	**2**	**2**	**2**	2	2	2	2	1
Brassica carinata A. Braun.	Ethiopian mustard (summer annual)	1	1	140	2000	4	0	0	0	1	1	2	2	2	2
Brassica carinata A. Braun.	Ethiopian mustard (winter annual)	1	1	180	2200	4	0	0	0	1	1	2	2	2	2
Phalaris arundinaceae L.	Reed canary grass	2	2	82	1400	0	2	2	2	2	2	1	0	0	0
Cynara cardunculus L.	Cardoon	2	3	120	1200	8	0	0	0	2	2	2	2	1	0
Salix spp.	Willow	2	2	180	2000	1	2	1	1	2	2	1	1	0	0
Populus spp.	Poplar	2	2	180	2200	0	2	1	1	2	2	1	1	0	0
Crotalaria juncea L.	Sunn hemp	1	2	60	1300	8	0	0	0	2	2	2	2	1	0
Cannabis sativa L.	Industrial Hemp	1	2	90	1400	6	1	0	0	2	2	2	2	1	0

***Scoring minimum length of growth season and GDD:**

For annuals producing seeds:

0 >20% below threshold

1=20% + and - threshold

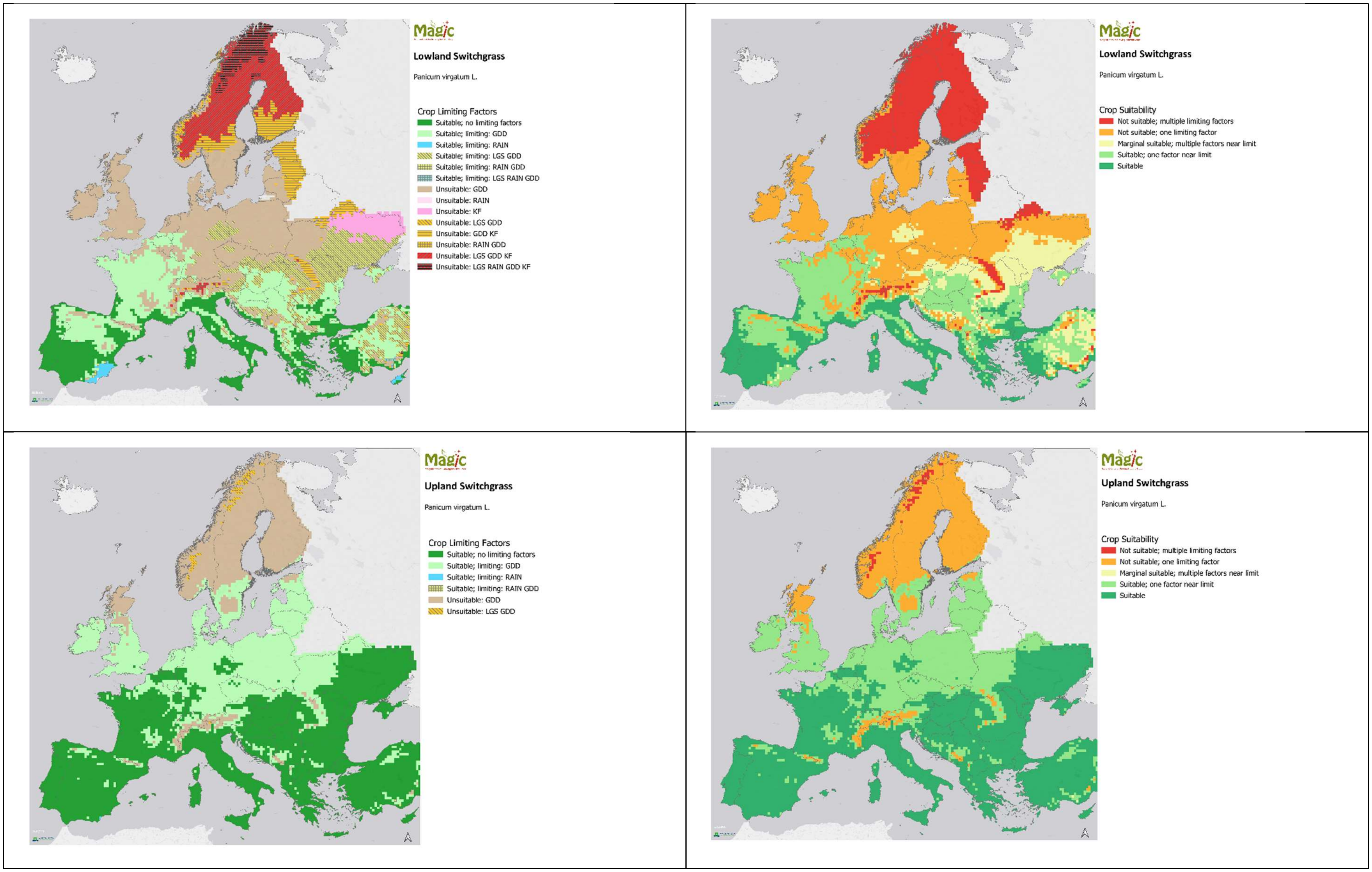
2= 20% above threshold

For perennials producing biomass:
0 > 30% below threshold
1=20% + and 30% - threshold
2= 20% above threshold

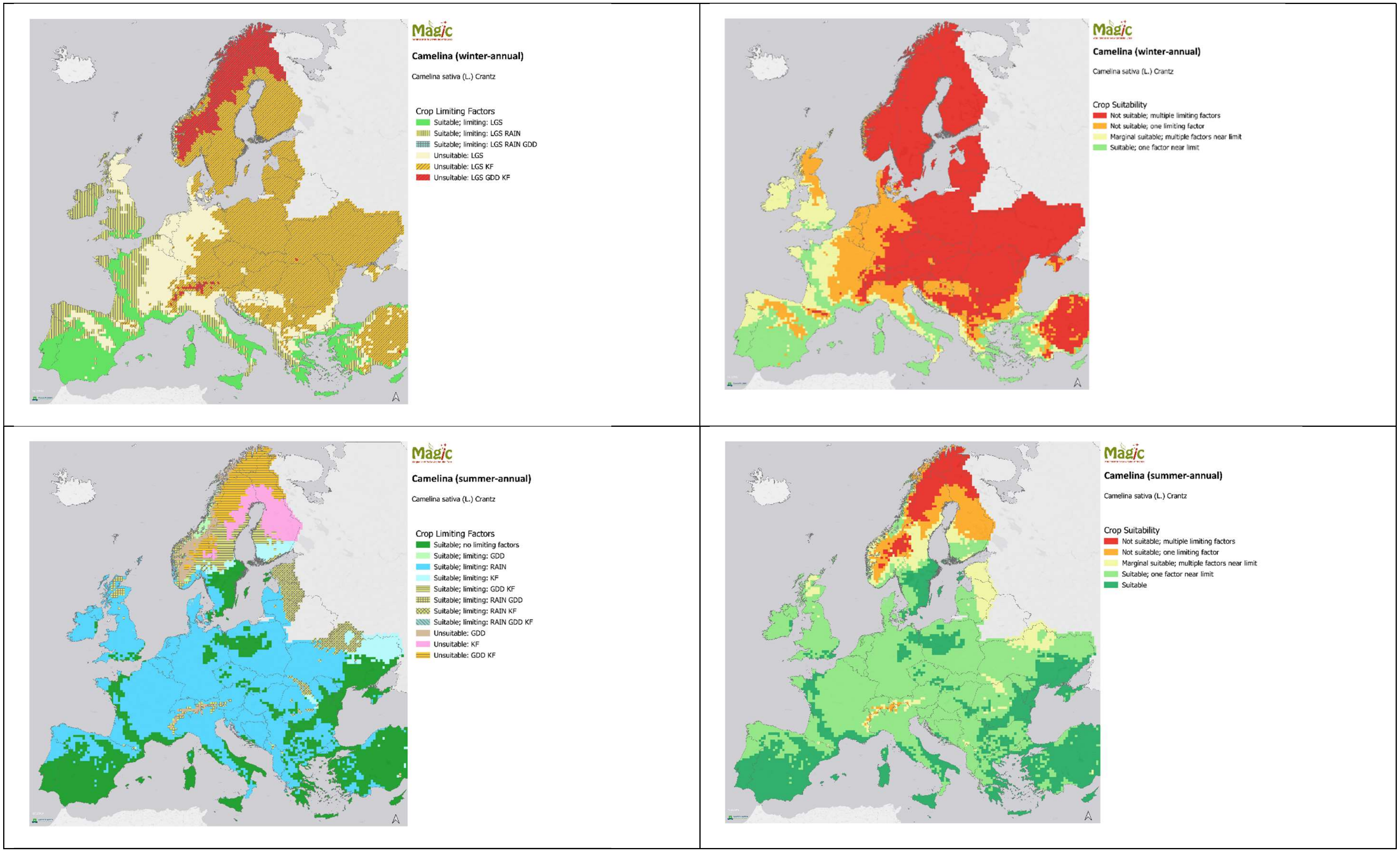
**** Killing frost:**
0= No go/
1= crop can still handle this frost/
2=crop can easily handle this frost/
* for perennials this limitation applies through the whole year. For summer annuals this applies during the growing season. So normally KF cannot be a big problem, unless it is the reason for the short Growth season.

*****Threshold of minimal rainfall in growing season:**
0= No go (0,1)
1=rainfall meets threshold of crop minimal precipitation need
2= Meets well with crop precipitation need

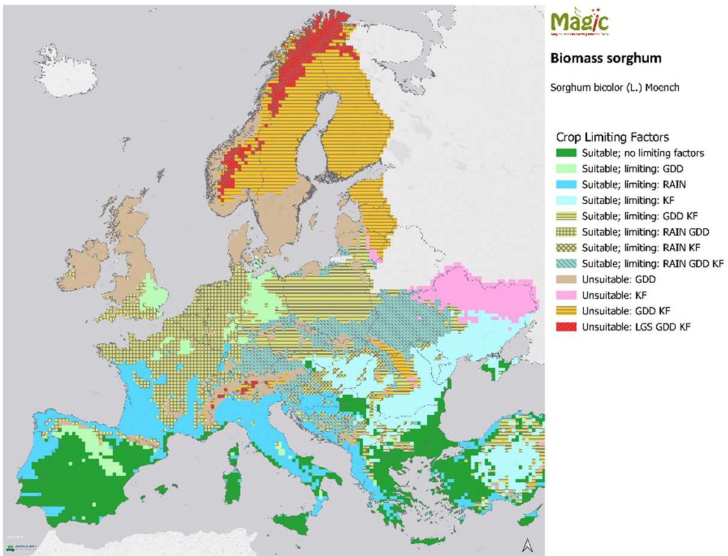
Map 1 Climatic suitability for Lowland and Upland switchgrass

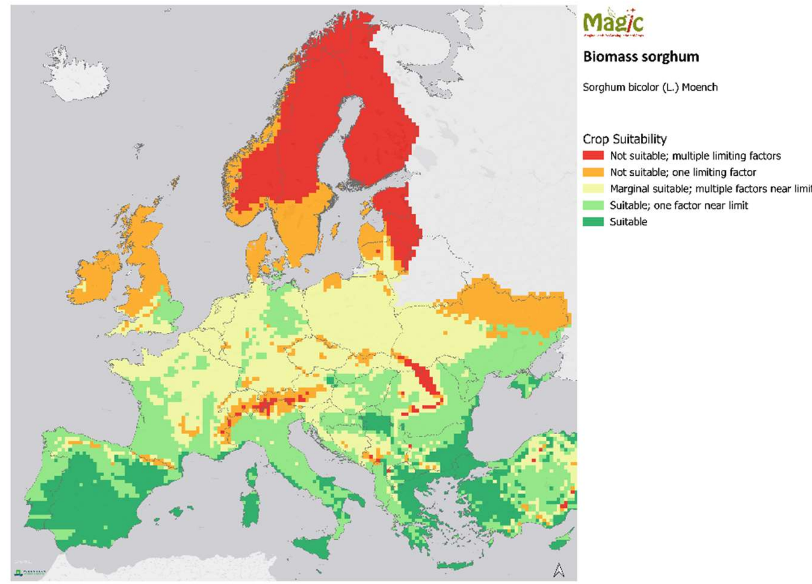


Map 2 Climatic suitability for Camelina as summer and winter annual

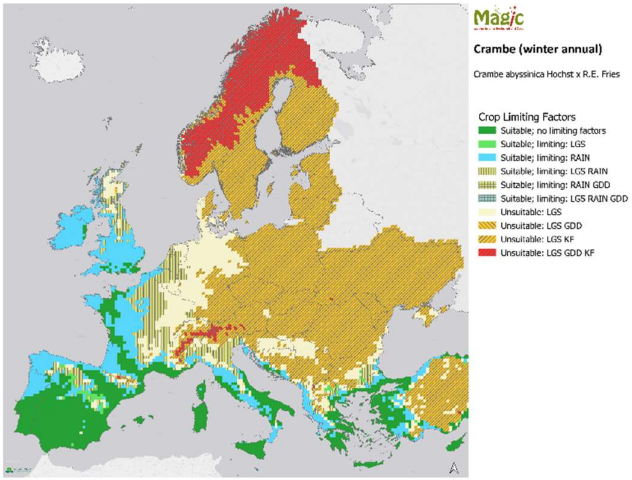


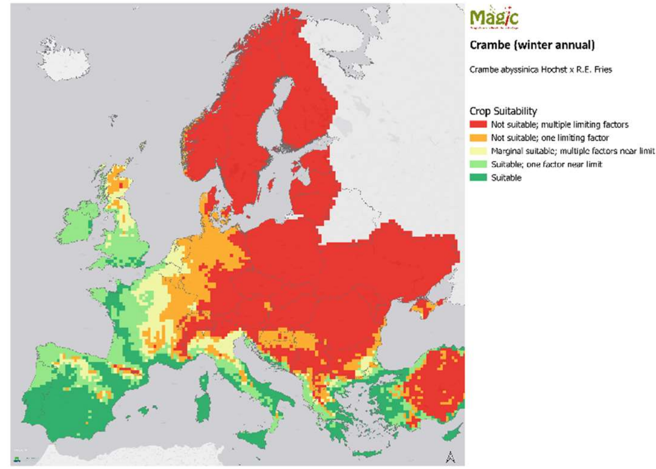
Map 4 Climatic suitability for biomass Sorghum

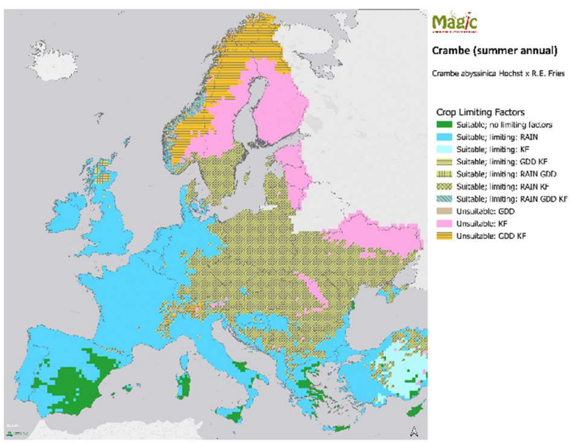


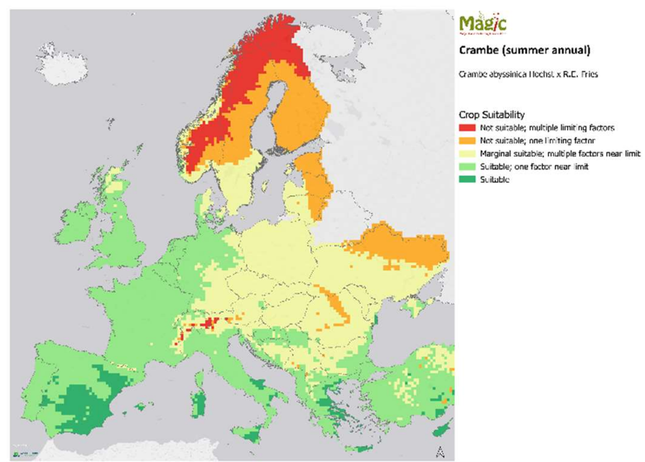


Map 5 Climatic suitability for Crambe as winter and summer annual

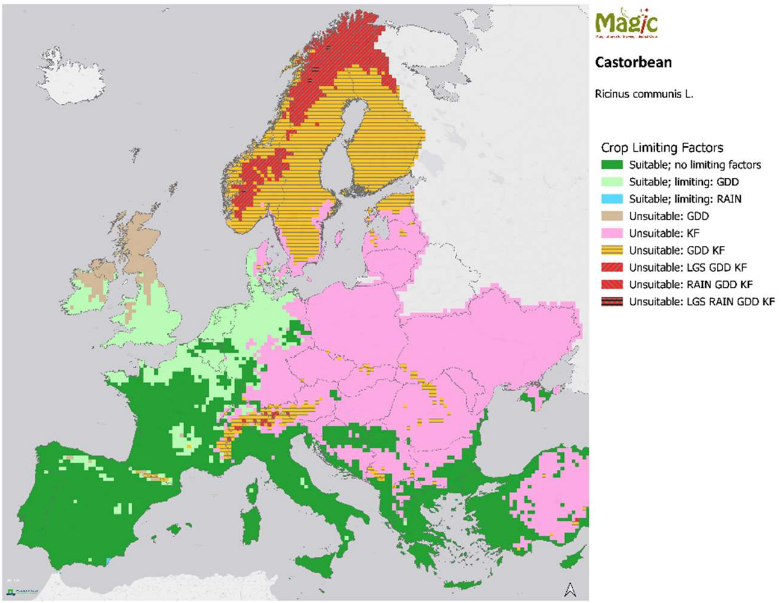


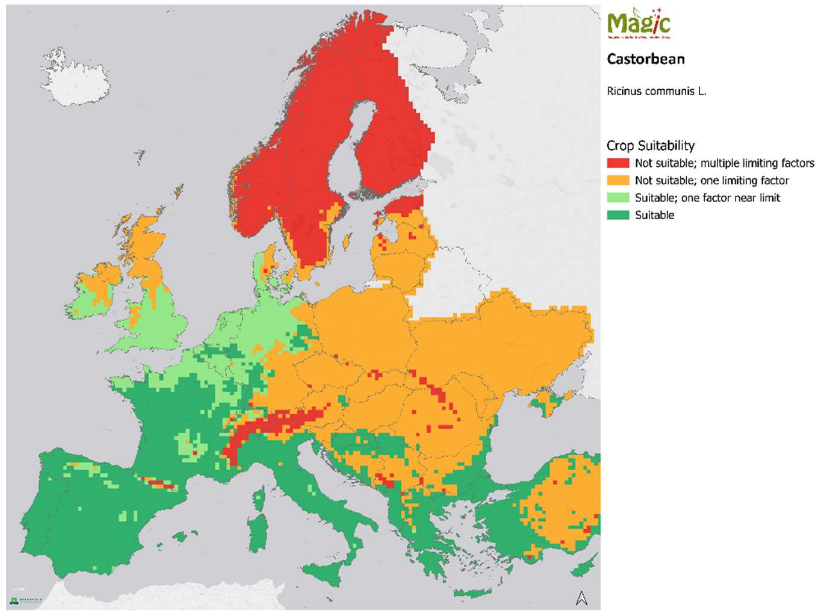




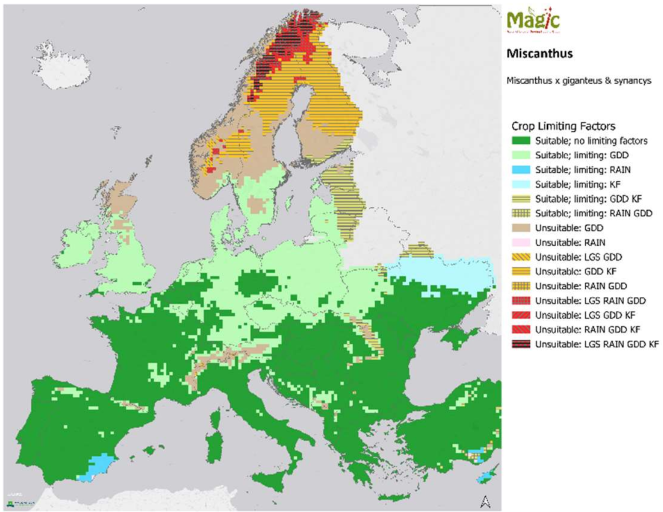


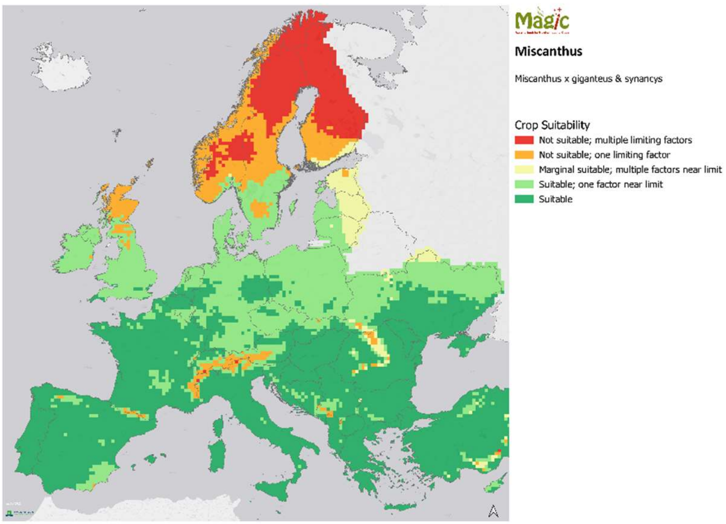
Map 6 Climatic suitability for Castor bean



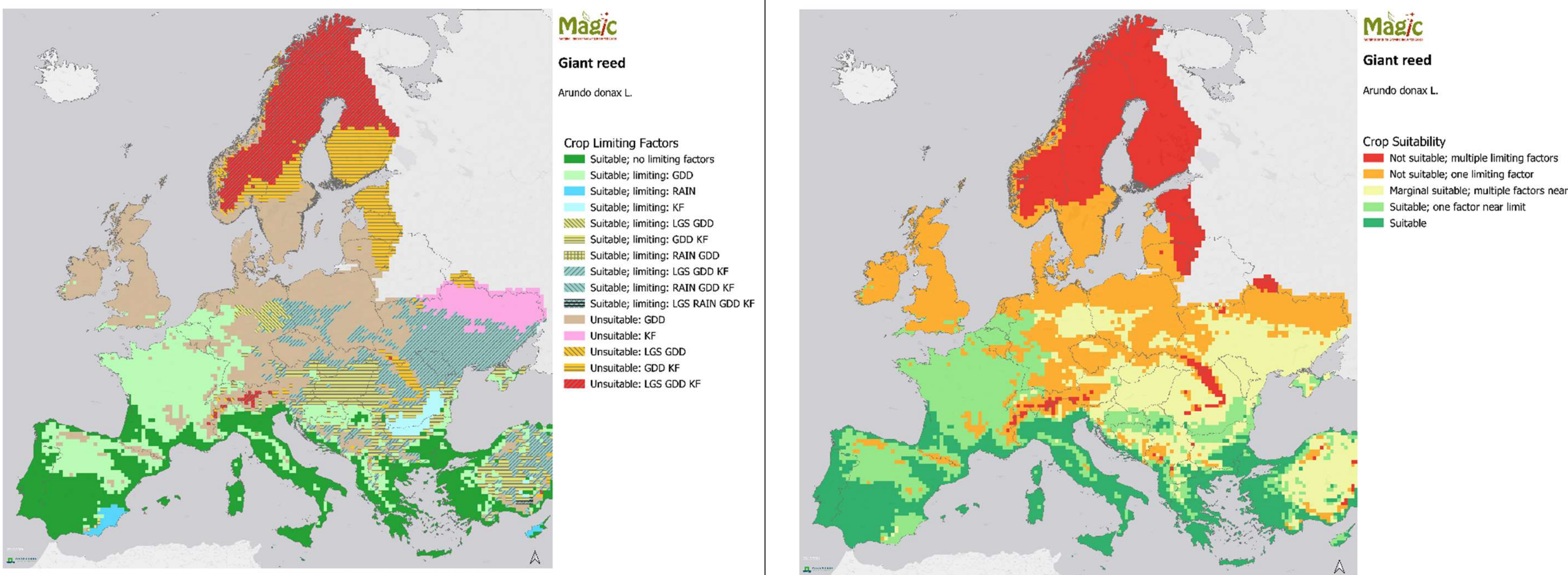


Map 7 Climatic suitability for Miscanthus

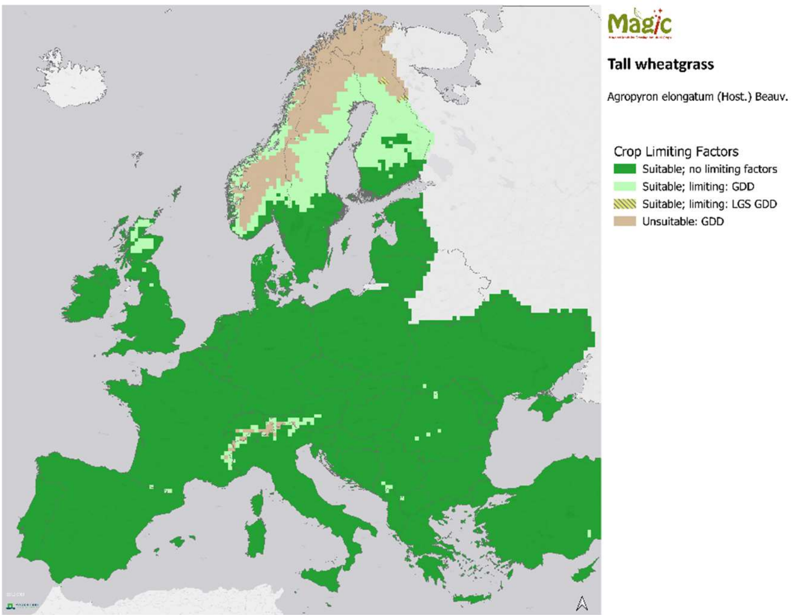


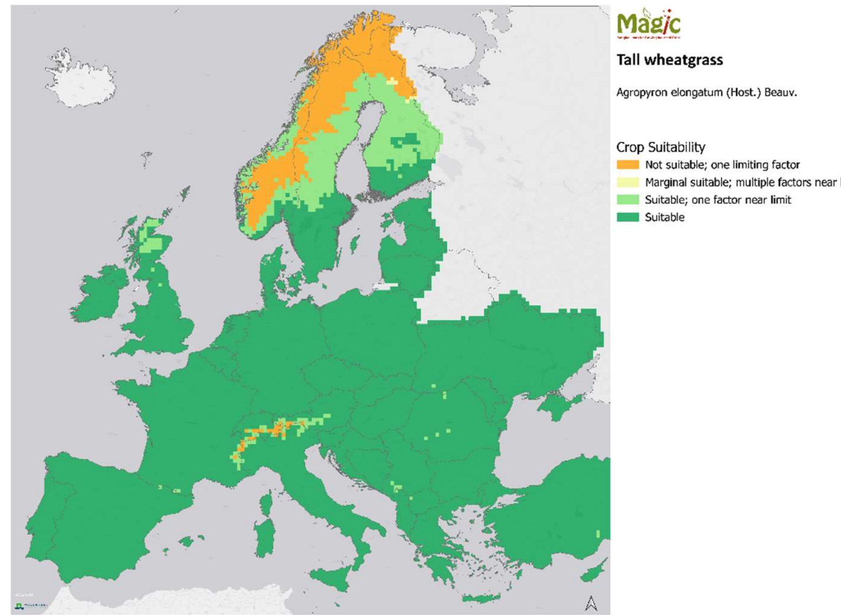


Map 8 Climatic suitability for Giant Reed (Arundo Donax)

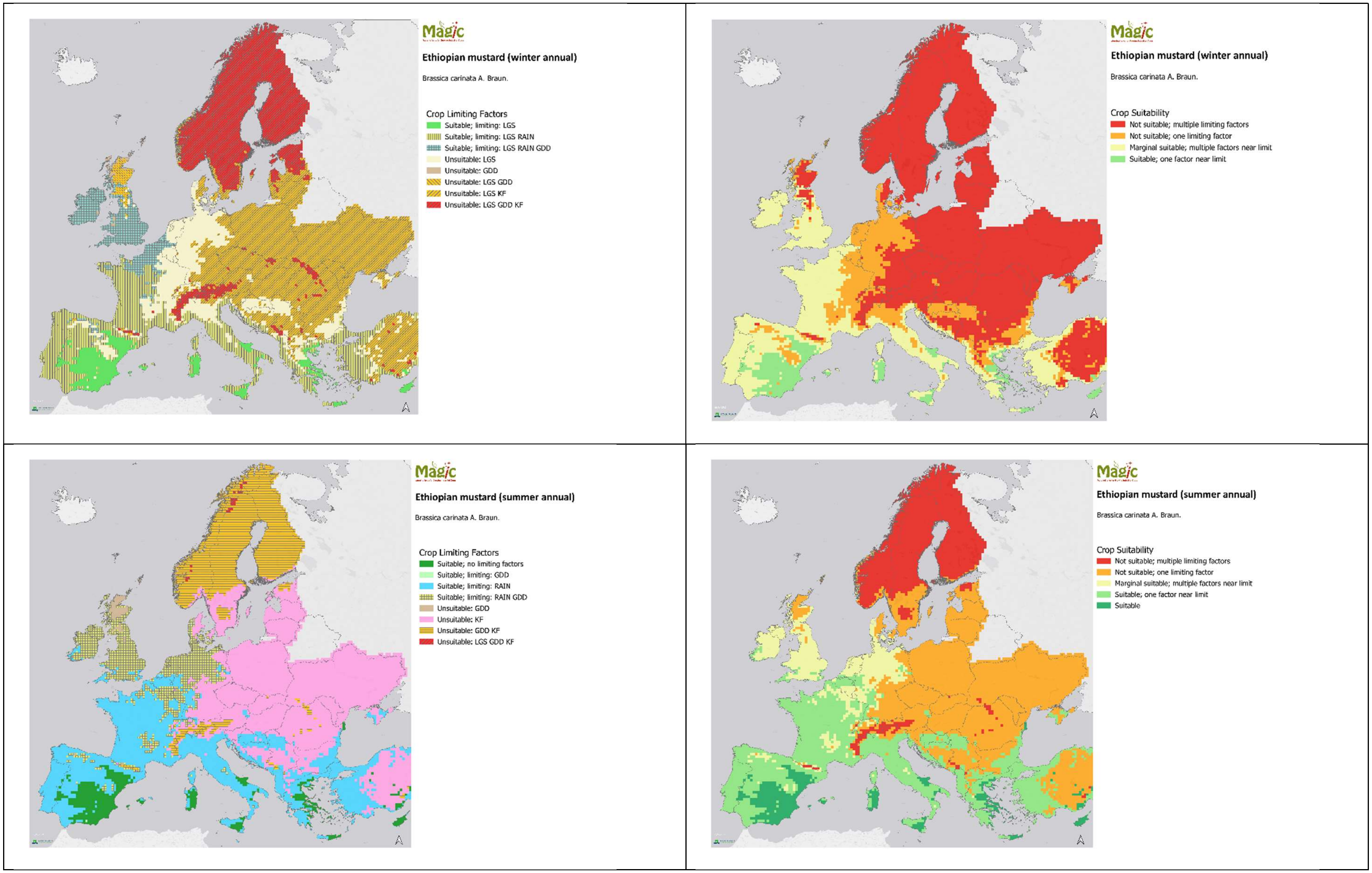


Map 9 Climatic suitability for Tall wheat grass

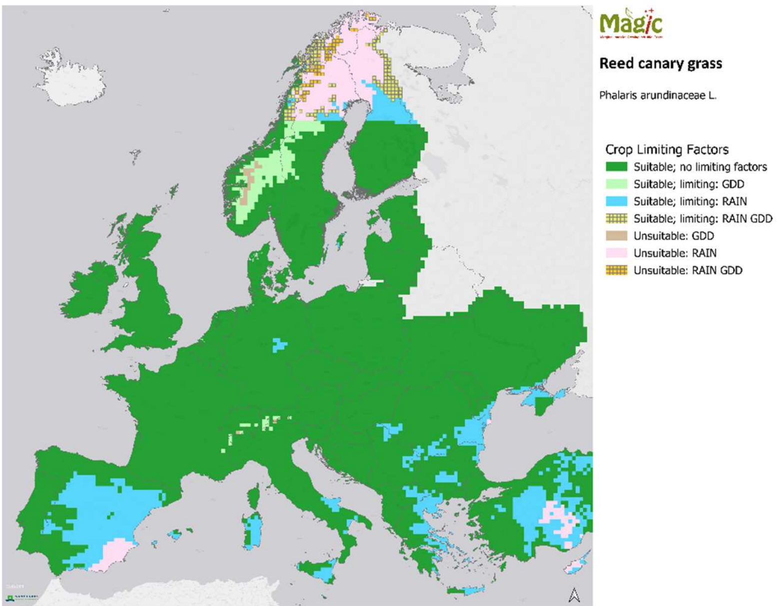


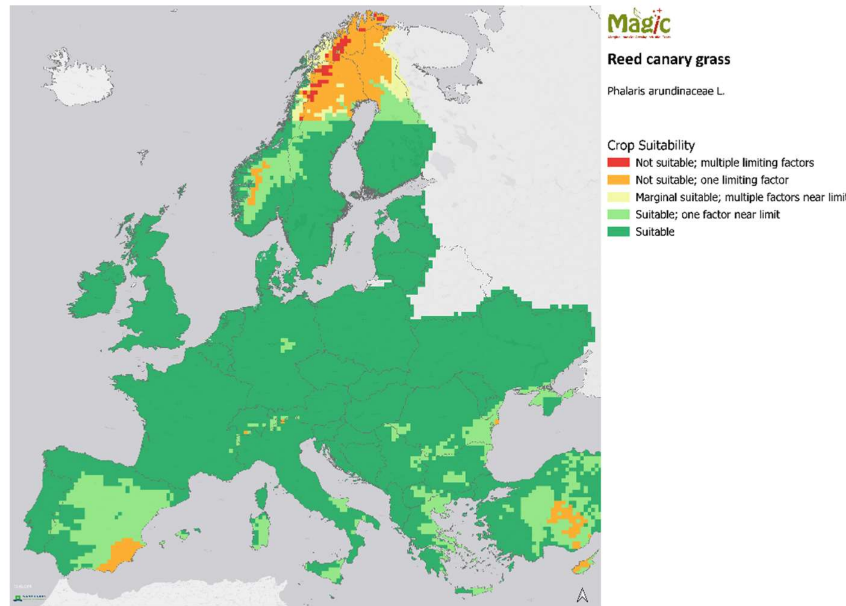


Map 10 Climatic suitability for Etheopian mustard as winter and summer annual

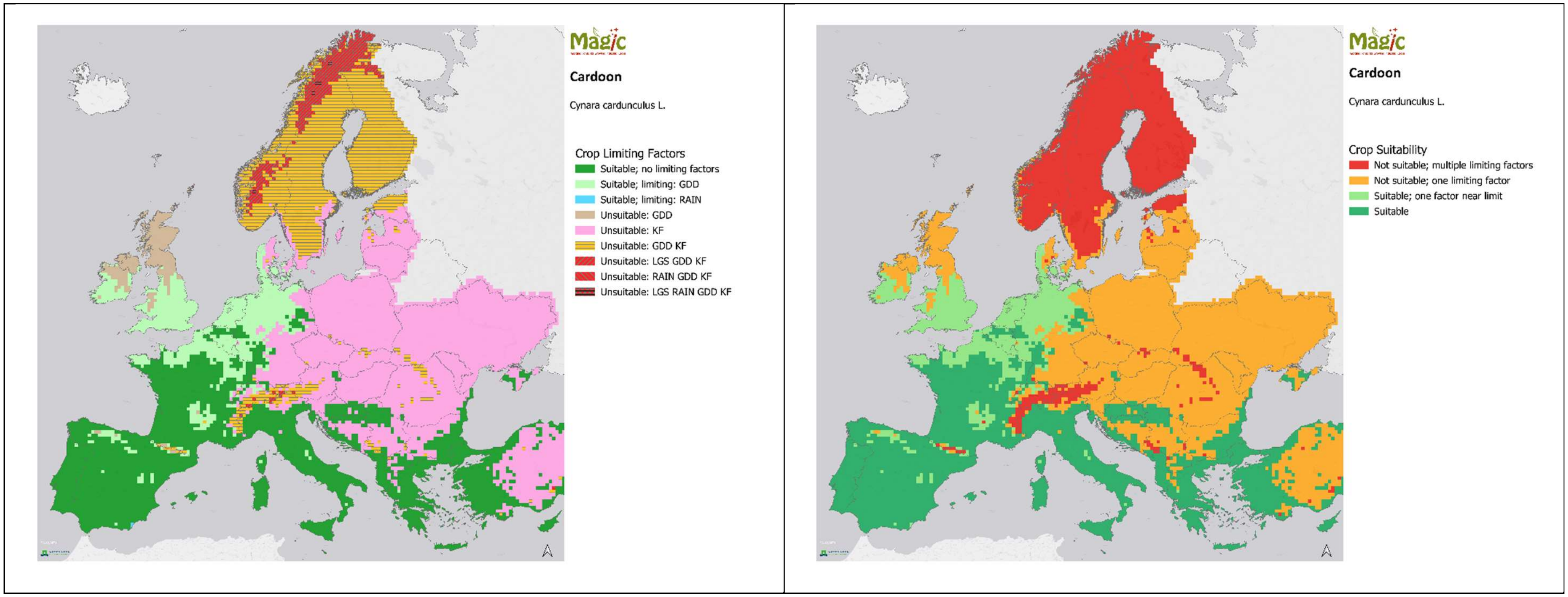


Map 11 Climatic suitability for Reed canary grass

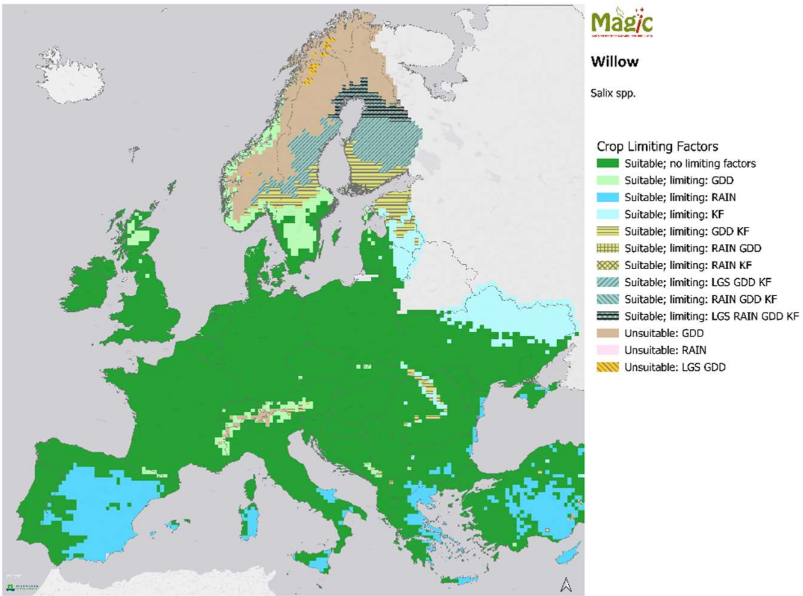


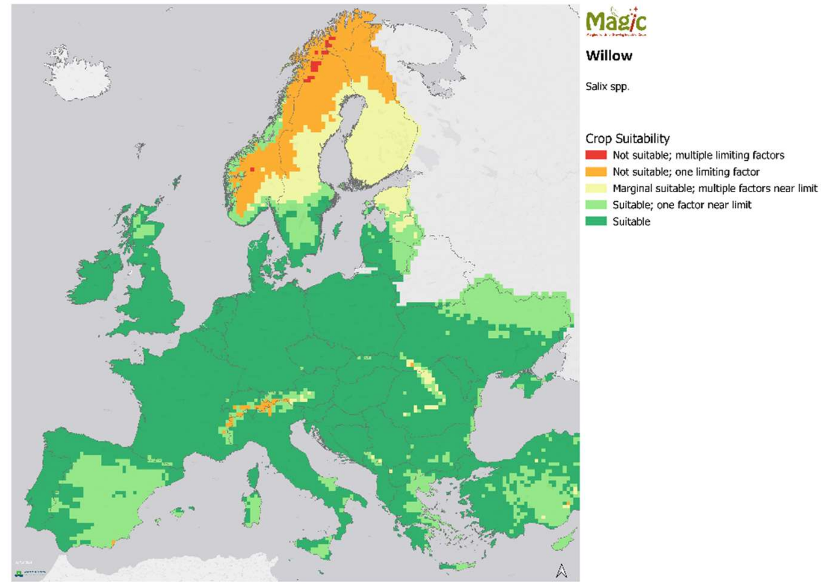


Map 12 Climatic suitability for Cardoon

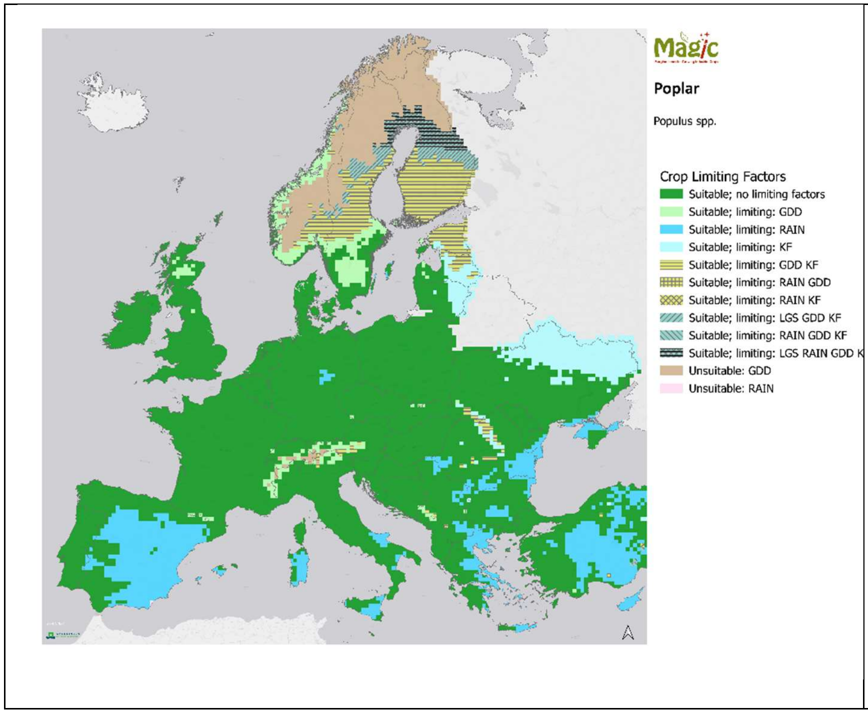


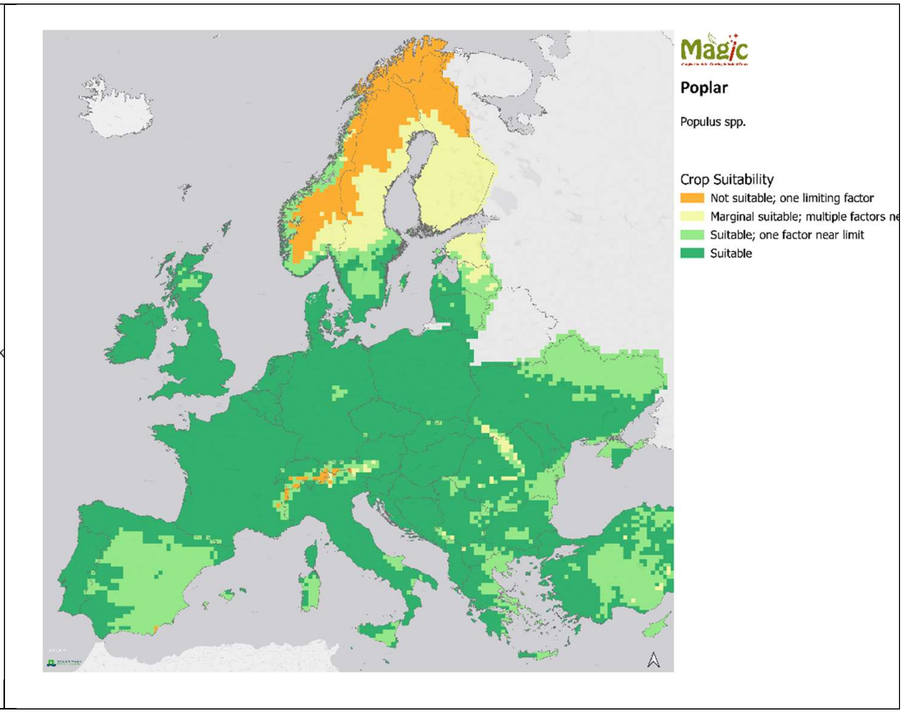
Map 13 Climatic suitability for Willow



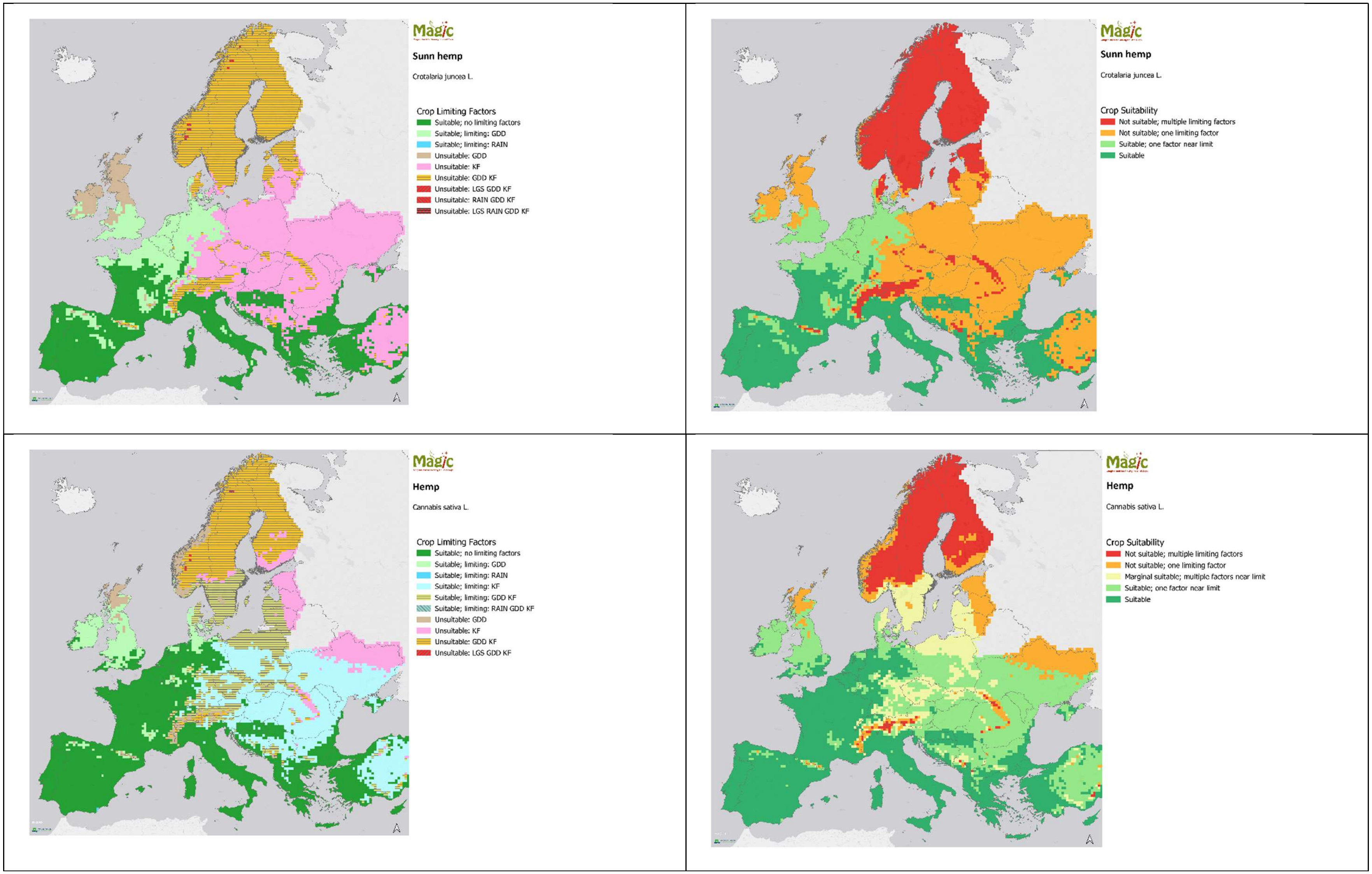


Map 14 Climatic suitability for Poplar

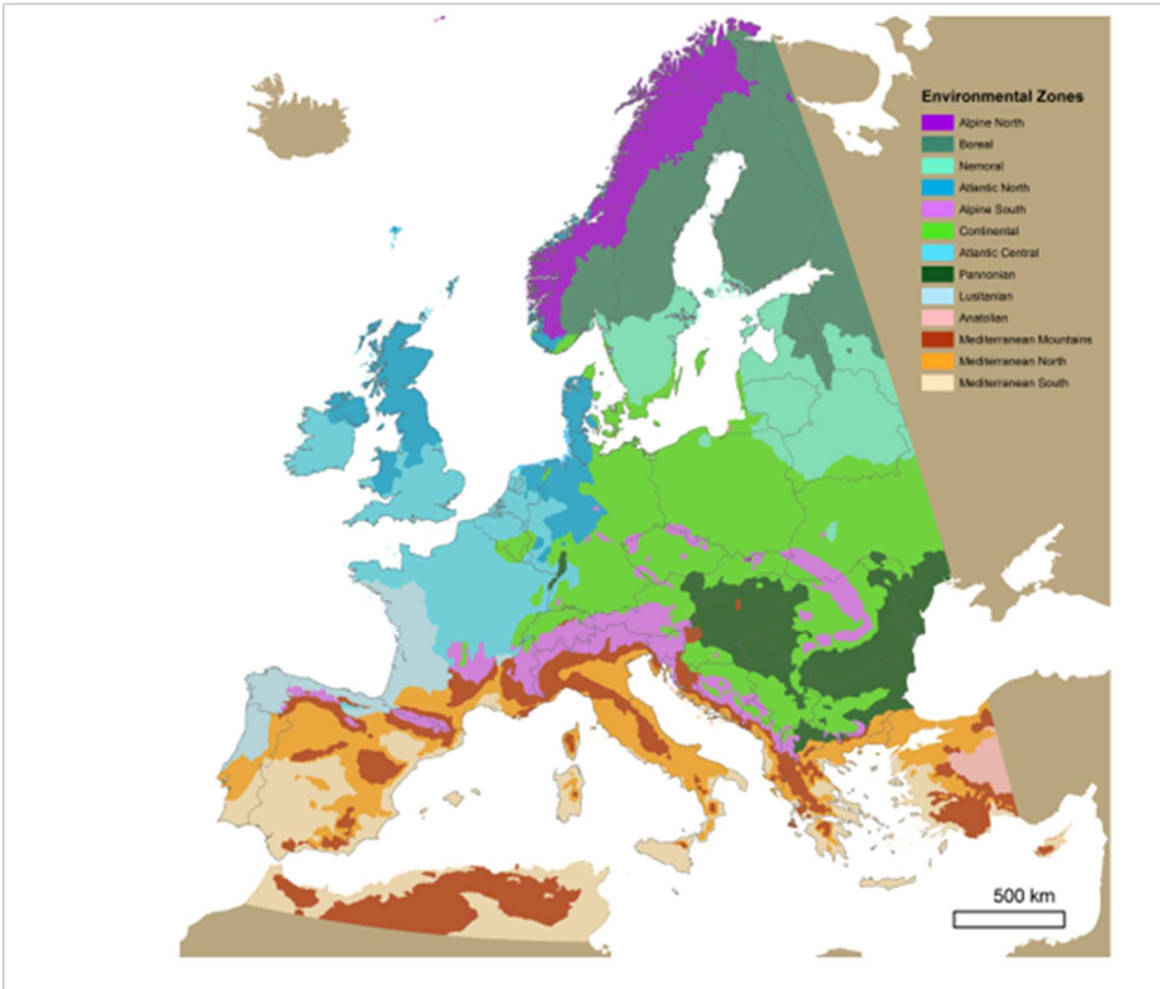




Map 15 Climatic suitability for Sunn hemp and industrial hemp



Annex II Environmental zination of Europe



Sources:
Metzger, Marc J. (2018). The Environmental Stratification of Europe, [dataset]. University of Edinburgh. https://doi.org/10.7488/ds/2356 (map contents)
Metzger M.J., Bunce R.G.H, Jongman R.H.G, Mücher C.A., Watkins J.W. (2005). "A climatic stratification of the environment of Europe". Global Ecology and Biogeography 14: 549-563 - https://doi.org/10.1111/j.1466-822x.2005.00190.x (description of the classification procedure)
https://datashare.ed.ac.uk/handle/10283/3091 (image)

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Annex III Yield increase assumptions per yield increasing measure

Table I Observed attainable yields and potential yield increases of the understudy crops in conventional farming land conditions.

		Rapeseed	Ethiopian Mustard	Crambe	Camelina	Cardoon	Safflower	Castor	Willow	Poplar	Biomass Sorghum	Miscanthus	Switchgrass	Cardoon	Giant Reed	Reed Canary Grass
Mediterranean	Baseline 2020	3.0	2.5	3.0	3.0	3.5	1.5	3.5	13.0	10.0	20.0	25.0	20.0	20.0	20.0	20.0
	Yield increase from improved varieties	0.3	0.3	0.3	0.3	0.4	0.2	0.4	1.3	1.0	2.0	2.5	2.0	2.0	2.0	2.0
	Low increase due to sustainable practices	0.5	0.4	0.5	0.5	0.6	0.2	0.6	2.1	1.7	3.3	4.1	3.3	3.3	3.3	3.3
	High increase due to sustainable practices	0.3	0.3	0.3	0.3	0.4	0.2	0.4	1.4	1.1	2.2	2.8	2.2	2.2	2.2	2.2
	Projected yield for 2030	4.1	3.4	4.1	4.1	4.8	2.1	4.8	7.9	13.8	27.5	34.4	27.5	27.5	27.5	27.5
Continental and Boreal	Baseline 2020	4.0	4.0	2.5	2.5	3.0	2.0	0.1	12	10.0	15.0	18.0	18.0		15.0	15.0
	Yield increase from improved varieties	0.4	0.4	0.3	0.3	0.3	0.2	0.1	1.2	1.0	1.5	1.8	1.8	0.0	1.5	1.5
	Low increase due to sustainabl	0.7	0.7	0.4	0.4	0.5	0.3	0.0	2.0	1.7	2.5	3.0	3.0	0.0	2.5	2.5

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		Rapeseed	Ethiopian Mustard	Crambe	Camelina	Cardoon	Safflower	Castor	Willow	Poplar	Biomass Sorghum	Miscanthus	Switchgrass	Cardoon	Giant Reed	Reed Canary Grass
	e practices															
	High increase due to sustainable practices	0.4	0.4	0.3	0.3	0.3	0.2	0.0	1.3	1.1	1.7	2.0	2.0	0.0	1.7	1.7
	Projected yield for 2030	5.5	5.5	3.4	3.4	4.1	2.8	0.3	16.5	13.8	20.6	24.8	24.8	0.0	20.6	20.6
Atlantic	Baseline 2020	4.5	3.5	2.0	2.5	3.0	0.0	0.0	12.0	10.0	15.0	18.0	18.0	14.0	15.0	15.0
	Yield increase from improved varieties	0.5	0.4	0.2	0.3	0.3	0.0	0.0	1.2	1.0	1.5	1.8	1.8	1.4	1.5	1.5
	Low increase due to sustainable practices	0.7	0.6	0.3	0.4	0.5	0.0	0.0	2.0	1.7	2.5	3.0	3.0	2.3	2.5	2.5
	High rate of increase due to sustainable practices	0.5	0.4	0.2	0.3	0.3	0.0	0.0	1.3	1.1	1.7	2.0	2.0	1.5	1.7	1.7
	Projected yield for 2030	6.2	4.8	2.8	3.4	4.1	0.0	0.0	16.5	13.8	20.6	24.8	24.8	19.3	20.6	20.6

Page Break

Table 2. Observed attainable yields and potential yield increases of the understudy crops in land with natural constraints.

		Rapeseed	Ethiopian Mustard	Crambe	Camelina	Cardoon	Safflower	Castor	Willow	Poplar	Biomass Sorghum	Miscanthus	Switchgrass	Cardoon	Giant Reed	Reed Canary Grass
Mediterranean	Baseline 2020	1.5	1.5	1	1	2	0.8	1.5	8	7.5	12	9	8	10	10	10
	Yield increase from improved varieties	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.8	0.8	1.2	0.9	0.8	1.0	1.0	1.0
	Low increase due to sustainable practices	0.2	0.2	0.2	0.2	0.3	0.1	0.2	1.3	1.2	2.0	1.5	1.3	1.7	1.7	1.7
	High increase due to sustainable practices	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.9	0.8	1.3	1.0	0.9	1.1	1.1	1.1
	Projected yield for 2030	2.1	2.1	1.4	1.4	2.8	1.1	2.1	11.0	10.3	16.5	12.4	11.0	13.8	13.8	13.8
Continental and Boreal	Baseline 2020	2.5	1.5	1	2.5	1.5			9	8.5	9	9	8		9	9
	Yield increase from improved varieties	0.3	0.2	0.1	0.3	0.2			0.9	0.9	0.9	0.9	0.8	0.0	0.9	0.9
	Low increase due to sustainable practices	0.4	0.2	0.2	0.4	0.2			1.5	1.4	1.5	1.5	1.3	0.0	1.5	1.5
	High increase due to sustainable practices	0.3	0.2	0.1	0.3	0.2			1.0	0.9	1.0	1.0	0.9	0.0	1.0	1.0
	Projected yield for 2030	3.4	2.1	1.4	3.4	2.1			12.4	11.7	12.4	12.4	11.0	0.0	12.4	12.4

Atlantic	Baseline 2020	2	1	0.5	2.5	1.5	NA	NA	9	8	9	8	7.5	8	9	9
	Yield increase from improved varieties	0.2	0.1	0.1	0.3	0.2			0.9	0.8	0.9	0.8	0.8	0.8	0.9	0.9
	Low increase due to sustainabl e practices	0.3	0.2	0.1	0.4	0.2			1.5	1.3	1.5	1.3	1.2	1.3	1.5	1.5
	High increase due to sustainabl e practices	0.2	0.1	0.1	0.3	0.2			1.0	0.9	1.0	0.9	0.8	0.9	1.0	1.0
	Projected yield for 2030	2.8	1.4	0.7	3.4	2.1	0.0	0.0	12.4	11.0	12.4	11.0	10.3	11.0	12.4	12.4

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