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Opportunities for Low Indirect Land Use Biomass for Biofuels in Europe

Calliope Panoutsou [1,*], Sara Giarola [1], Dauda Ibrahim [1], Simone Verzandvoort [2], Berien Elbersen [2], Cato Sandford [3], Chris Malins [3], Maria Politi [4], George Vourliotakis [4], Vigh Enikő Zita [5], Viktória Vásáry [5], Efthymia Alexopoulou [6], Andrea Salimbeni [7] and David Chiaramonti [7,8]

[1] Centre for Environmental Policy, Imperial College London, London SW7 1NE, UK; s.giarola10@imperial.ac.uk (S.G.); d.ibrahim@imperial.ac.uk (D.I.)
[2] Wageningen Environmental Research, Wageningen University, 6708 PB Wageningen, The Netherlands; simone.verzandvoort@wur.nl (S.V.); berien.elbersen@wur.nl (B.E.)
[3] Cerulogy, London SE8 4BL, UK; cato@cerulogy.com (C.S.); chris@cerulogy.com (C.M.)
[4] EXERGIA Energy and Environment Consultants S.A., GR-106 71 Athens, Greece; m.politi@exergia.gr (M.P.); g.vourliotakis@exergia.gr (G.V.)
[5] Institute of Agricultural Economics (AKI), H-1093 Budapest, Hungary; vigh.eniko.zita@aki.gov.hu (V.E.Z.); vasary.viktoria@aki.gov.hu (V.V.)
[6] Centre for Renewable Energy Sources and Saving, Marathonos Avenue, 19009 Pikermi, Greece; ealex@cres.gr
[7] Renewable Energy Consortium for R&D (RE-CORD), Viale J. F. Kennedy, 182, Scarperia e San Piero, 50039 Florence, Italy; andrea.salimbeni@re-cord.org (A.S.); david.chiaramonti@polito.it (D.C.)
[8] Department of Energy “Galileo Ferraris” (DENERG), Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy
* Correspondence: c.panoutsou@imperial.ac.uk

Abstract: Sustainable biofuels are an important tool for the decarbonisation of transport. This is especially true in aviation, maritime, and heavy-duty sectors with limited short-term alternatives. Their use by conventional transport fleets requires few changes to the existing infrastructure and engines, and thus their integration can be smooth and relatively rapid. Provision of feedstock should comply with sustainability principles for (i) producing additional biomass without distorting food and feed markets and (ii) addressing challenges for ecosystem services, including biodiversity, and soil quality. This paper performs a meta-analysis of current research for low indirect land use change (ILUC) risk biomass crops for sustainable biofuels that benefited either from improved agricultural practices or from cultivation in unused, abandoned, or severely degraded land. Two categories of biomass crops are considered here: oil and lignocellulosic. The findings confirm that there are significant opportunities to cultivate these crops in European agro-ecological zones with sustainable agronomic practices both in farming land and in land with natural constraints (unused, abandoned, and degraded land). These could produce additional low environmental impact feedstocks for biofuels and deliver economic benefits to farmers.

Keywords: land use change; low ILUC; oil crops; lignocellulosic crops; advanced biofuels; sustainability; marginal land; degraded land

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1. Introduction

A strategic component of Europe's political agenda for sustainable biomass supply is the reduction of indirect land use change (ILUC) impacts associated with its use 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 (that is, fuels produced from feedstocks associated with significant levels of agricultural expansion into land with high carbon stock) [1–4].

The RED II also introduces the concept of certified “low ILUC-risk” biofuels, bioliquids, and biomass fuels. These are produced from feedstocks that avoid food and feed crop displacement through one of two additional pathways: (i) yield increases from improved agronomic practices, or (ii) cultivation of areas not previously used for crop production (including areas with natural constraints such as unused, abandoned, or severely degraded) [5,6]. These represent an important option to maintain current biofuel shares and further develop their sustainable market potential in Europe from 2023 onwards, especially for sectors with limited short-term decarbonisation alternatives such as aviation, heavy duty road transport, and maritime.

Indeed, there is a growing consensus in the EU [7,8] and beyond that the future holds significant risks for gaps in sustainable biomass supply. These gaps will continue to widen as RED II targets become more ambitious, RED II caps become more stringent, and as competition for, e.g., waste oils become more intense. Low ILUC-risk biomass can be seen as an opportunity to plug some of the supply gap by providing a new source of sustainable feedstock material.

The issues involved in the concept of low ILUC-risk concern land and crop productivity and agronomic practices; as such, they are strongly related to agriculture and its role as a sink and a source of Greenhouse Gas (GHG) emissions, as well as the mosaic of wider sustainability goals surrounding soils, pollution, biodiversity, and rural communities. In the policy sphere, sustainable carbon cycles [9] and the “Fit for 55” EU policy package [10] (including amendments to RED II) will further refine regulatory and support measures for sustainable biofuel development [11], whereas the Common Agricultural Policy (CAP 2023–2028) reinforces climate change mitigation as a key objective for the agriculture sector [12].

The rationale of the low-ILUC concept is rooted in the principle of additionality. A consignment of feedstock can be low-ILUC only if there is evidence that it would not have been produced without the advanced biofuel sector. If such evidence is absent, there is a risk that using the material for biofuels will drive up total demand and hence incentivise unintended agricultural expansion.

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. This paper aims to consolidate this knowledge base by providing a meta-analysis of the biophysical and economic opportunities for low ILUC risk biomass based on current research from six relevant European Union funded projects: Biomass Policies, S2Biom, MAGIC, PANACEA, SoilCare, and BIO4A (see Table 1). 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) [13], and can have yield increases from improved agricultural practices—both in conventional land and in land with natural constraints (unused, abandoned, or severely degraded).

The paper consists of four sections. Section 2 outlines the methodology and baseline assumptions. Section 3 presents the results in two sub-sections. The first discusses the biophysical opportunities for (i) yield increases of a set of selected crops due to sustainable agricultural practices, and (ii) the adaptability and tolerance of these crops to be cultivated in unused, abandoned or severely degraded land. The second sub-section analyses the economic opportunities for European farmers from the understudy crops based on current market prices. Finally, Section 4 discusses the findings for biophysical and economic opportunities and the policy relevant context of this analysis.

Table 1. European research projects that formed the basis of the meta-analysis.

Project	Scope	Relevance to Low ILUC
Biomass Policies (www.biomasspolices.eu accessed on 4 April 2022)	Compiled cost supply information for oil, starch, and lignocellulosic biomass with geographic disaggregation at NUTS2-State level	Oil and lignocellulosic biomass crops Yields and cost information at national and regional level
S2Biom (www.s2biom.eu accessed on 4 April 2022)	Gathered cost supply information on fifty lignocellulosic biomass types for EU 27, UK, Western Balkans, Moldova, Ukraine and Turkey (NUTS3-level)	
MAGIC (www.magic-h2020.eu accessed on 4 April 2022)	Aimed to research the sustainable development of resource-efficient and economically profitable industrial crops grown on marginal lands	Yields and costs in land with natural constraints
PANACEA (www.panacea-project.eu accessed on 4 April 2022)	Was a thematic network for non-food crops into European agriculture as raw materials for bioenergy and bioeconomy	Yields and TRL level
BIO4A (www.bio4a.eu accessed on 4 April 2022)	Is investigating the use of biochar and co-composted organic matter in very arid soils in Spain, while applying at the same time sustainable rotations between food/feed and energy crops, i.e., barley and camelina	Cultivation in land with natural constraints and application of biochar
SoilCare (www.soilcare-project.eu accessed on 4 April 2022)	Identified and evaluated promising soil-improving cropping systems and agronomic techniques increasing profitability and sustainability across scales in Europe	Sustainable agricultural practices

2. Materials and Methods

The scope of this paper is to analyse options for low ILUC risk biomass crops in Europe as feedstock for biofuels. So far there is much agronomic research (at field and demonstration, precommercial, and sometimes commercial scales) on such crops, their biophysical traits, and modelling for their potential economic viability. The findings are important, but knowledge is fragmented, and most of the time presents case specific results without considering several possible options in a comparable manner. This paper aims to cover this gap and perform a meta-analysis of knowledge generated in recent European research projects on biomass feedstocks for biofuels, crops, and agricultural cropping practices that can provide technically and economically feasible low ILUC solutions until 2030.

We apply the low ILUC biomass definition of the European Commission's Renewable Energy Directive (REDII): (i) crop productivity increases by means of improved agricultural practices and (ii) cultivation in land with biophysical marginality (which often overlaps with the categories defined in the current REDII as unused, abandoned, or severely degraded). For both cases we consider only practices in the European agro-ecological regions that are feasible and profitable from an agronomic perspective, acceptable from a social and cultural perspective, and sustainable from an environmental perspective. The goals of this paper are to review:

- Identified biomass crops that show promise in fitting the low ILUC-risk criteria and have high technological readiness level (TRL) for 2030 while being adapted to European agroecological climatic zones, being suitable as feedstock for advanced biofuels and, where feasible, exhibiting good adaptability when cultivated in land with natural constraints;
- Observed attainable crop yield in conventional farming land and in land with natural constraints and potential yield increases that can be expected when sustainable agricultural practices are applied;
- Estimated production cost and profitability prospects for European farmers under current market price ranges.

The information is based on recent findings from the six European projects shown in Table 1. Figure 1 outlines the crop selection process, which filtered the crops from these projects based on their characteristics, technological maturity, and applicable management practices. These assessments were drawn from the Biomass Policies, S2Biom, MAGIC and PANACEA projects, which have performed modelling, field trials, and have consolidated knowledge for industrial and non-food crops in Europe [14–17]. As noted before, one pathway to additional agricultural harvest would be to bring unused agricultural land back into production. In the case of land that has been abandoned due to natural conditions (for example high local temperatures, water stress, or rocky soil), we seek to assess and select crops with good tolerance to these specific non-ideal growing conditions.

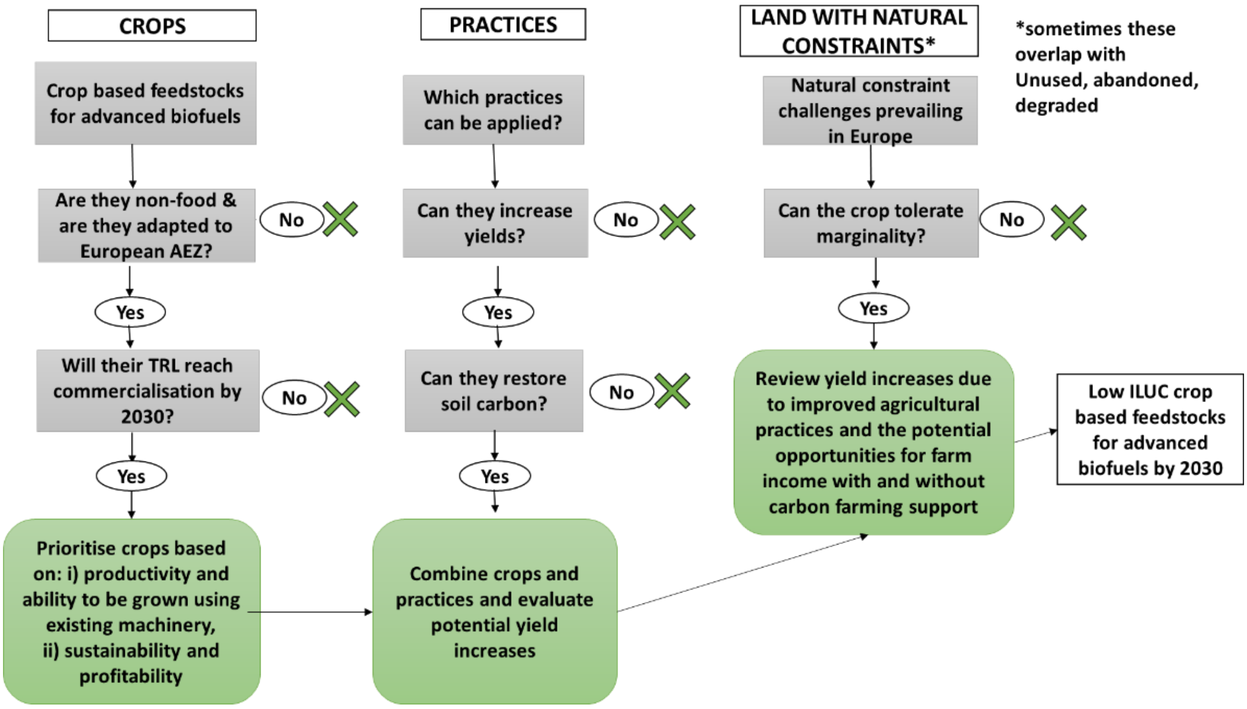

Figure 1. Methodological approach for the crop selection process.

The PANACEA project used the TRL [14] 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 2) 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 2 presents the scales of the TRL for the criteria used in assessing the crops. Only crops with expected TRL for 2030 above 7 are analyzed for the economic opportunities in the second part of Section 3.

The information and relevant metrics for sustainable agricultural practices and potential yield increases were based on research conducted within the MAGIC, SoilCare, and BIO4A projects.

Two categories of biomass crops suitable as feedstocks for advanced biofuels are reviewed in this paper. They include seven oil and nine lignocellulosic crops, and they are selected based on their adaptability to the European AEZ and their technological readiness level within the period 2020–2030 (see Figure 1). They are a combination of conventional and new species with improved traits for climate change related risks (e.g., drought, high temperature, etc.) [16,17].

Table 2. Technology readiness level (TRL) for the criteria used in assessing strengths for non-food biomass crops.

TRL		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
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

3. Results

3.1. Biophysical Opportunities for Low ILUC Risk Crops

Low ILUC risk biomass production is region and climate specific, and provisions must be in place for any risks due to projected climate change or human activity induced conditions [16].

Improving crop yields in conventional farming land is also subject to technical factors such as new crop varieties with improved resilience towards climate change risks (e.g., excessive soil moisture, prolonged periods of high temperatures and drought, etc.) as well as socio-economic challenges that relate to the human capital (e.g., knowledge of farmers for new methods of cultivation, etc.) and infrastructure (e.g., access to new machinery, access to capital for purchase of propagation material, fertilisers, etc.).

Restoration of land with natural constraints for cropping requires careful selection of species that are both adapted to the local agroecology and exhibit high level of tolerance to the prevailing biophysical constraints as well as assessment of agricultural practices [17,18].

Biomass crop production both in conventional land and in land with natural constraints, through improved agricultural practices that increase yield, requires careful planning, establishment, and management. Such practices also provide an opportunity to align with EU “Farm to Fork” and CAP goals surrounding low-input cultivation systems and enhancement of biodiversity [17–19].

3.1.1. Oil Crops

Today, lipids are needed to produce biobased substitutes in the hard-to-abate transport sectors of heavy duty, maritime, and aviation, namely, hydrotreated vegetable oil (HVO), the biobased hydrocarbon fuel substituting diesel, and hydrotreated esters and fatty acid (HEFA), the biobased jet fuel. Until 2030–2035 is it estimated the HEFA will be the dominant type of renewable jet fuel, whereas lignocellulosic biofuels and eFuels will emerge at large scale only afterwards [20,21].

Rapeseed (*Brassica napus*) is already used to produce biodiesel, and there is also interest from the chemical industry for the use of rapeseed HEAR [16,17,22] to produce ‘green’ chemicals. Rapeseed is also considered an effective break crop in cereal rotation because it results in higher-yielding cereal crops and weed control.

Ethiopian mustard is closely related to rapeseed (*Brassica carinata* L.). The plant is well adapted to the Mediterranean climate and can be grown 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 its low resistance to frost. In areas with mild winters, it can also be grown as a winter crop. Both rapeseed and Ethiopian mustard are tolerant to water stress and thus can be successfully grown in dry areas. They are also considered good crops for phytoremediation [17], offering a pathway for producing additional biomass from contaminated land and simultaneously rehabilitating said land.

Crambe (*Crambe abyssinica*), can be grown as a spring crop in central and northern Europe and as a winter crop that can tolerate mild winters in South Europe. This plant is tolerant to cold and dry weather, can be easily adapted to a variety of climatic conditions, and exhibits high productivity [16,17,23]. Crambe has a short-cycle winter crop and could be a good alternative as a crop 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 [24].

Camelina is a fast-growing crop that can be cultivated in central and northern Europe as a spring crop and in south Europe both as winter and 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) [16,17].

Cardoon is a thistle, a drought tolerant crop, and the oil from its seeds can be used to produce biodiesel. The crop is moderately tolerant to saline conditions and to drought stress. It has also been cultivated for the phytoremediation of soils contaminated with arsenic and cadmium [16,17,25].

Safflower is a branching thistle-like herbaceous (spring or winter) annual plant that best fits in the Mediterranean zone. The crop is tolerant to prolonged dry periods and high temperatures. It can be grown on land with natural constraints including land contaminated with heavy metals [16,17].

Castor is a hardy crop well adapted to south Europe. It can grow on land with natural constraints due to its high tolerance to drought, heat, and saline soil conditions. It is considered appropriate for dry farming [16,17].

3.1.2. Lignocellulosic Crops

Lignocellulosic crops have been cultivated for more than two decades throughout Europe. They exhibit high yields, have specific traits for bioenergy and biofuel uses, and can grow in land with natural constraints that does not compete for food/feed crops. As such they are considered eligible as feedstock for biofuels.

Willow can tolerate a great range of soils (e.g., wet sites, alkaline, saline, clay soils, etc.) and can remediate soil for land conservation practices, shelterbelts, and windbreaks. It can prevent soil erosion [16,26] and can also be used for biofiltration, constructed wetland, and wastewater treatment systems.

Poplar can be grown as a short rotation woody crop and harvested every two to five years. Researchers are working to breed improved varieties of poplars for bioenergy, carbon sequestration, phytoremediation, and watershed protection through the development of poplar genotypes with improved yield, higher pest resistance, increased site adaptability, and easy vegetative propagation.

Biomass sorghum is an annual herbaceous spring 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.

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.

Miscanthus can be grown across all Europe and is already cultivated at commercial 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, including land with natural constraints, because of its extensive root system [16,17]. It is tolerant to drought and can retain high productivity under drought conditions.

Giant reed is a common weed in the Mediterranean, and it is known to be invasive and out-compete other crops. It is drought tolerant and can also grow in saline, poor texture soil with steep slopes, as well as in contaminated lands for phytoremediation [16,17,27].

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.

3.1.3. Sustainable Agricultural Practices

The low-ILUC risk status for feedstocks involves the cultivation of crops that meet additional conditions and can be produced through smart, sustainable, and low input agricultural practices, which in return are expected to contribute to climate change mitigation and soil quality [28]. These include carbon sequestration through carbon farming. The term 'carbon farming' refers to land practices in agriculture and forestry leading to the storage of carbon from the atmosphere in biomass, organic matter, soils, and vegetation. Carbon farming is one of the mechanisms for the removal of carbon from the atmosphere that are proposed in the EU Communication on Sustainable Carbon Cycles [29]. Such practices include, among others, intercropping, cover crops, rotational cropping, and soil enrichment with biochar [30,31] that improve soil carbon stocks, organic fertilization, agroforestry that stores carbon in vegetation [32–34], and restoration of degraded land with perennial crops.

Five types of practices that support biomass production, carbon storage, and soil quality are addressed in this review, based on their occurrence in policy instruments of the EU. Each of these will now be discussed in turn.

Intercropping refers to a crop grown amidst a main crop or in between the planting rows of that main crop and intended to be harvested or to be supportive to the harvest of the main crop [35].

Cover cropping refers to a crop grown in between two main crop seasons [36]. A review of meta-studies on soil improving cropping systems reported that intercropping, mixed crops, and cover crops can increase yields [37–39]. Effects on nutrient cycling and resilience to stress were less clear. Legume cover crops could be a substitute for N-fertilisers, whereas other cover crops could decrease loss of N by leaching. The input of carbon to soils from cover crops depends on the biomass yield of the crop, which is determined by the species, time of seeding, winter hardiness, and availability of water [40]. Cover crops were reported to increase the soil organic matter content compared to fallow soils [39].

Data indicate that cover crops reduce soil penetration resistance by 0 to 29%. Cover crops also improve wet aggregate stability by 0 to 95% and cumulative infiltration by 0 to 190% but have insignificant impacts on bulk density, dry aggregate stability, saturated hydraulic conductivity, unsaturated hydraulic conductivity, and plant available water. The soils under the cover crop can be warmer in winter and colder in spring, summer, and autumn. Daytime soil temperature decreased by an average 2 °C, whereas night-time soil temperature increased by 1 °C, which also can induce changes in the soil organic carbon concentration [39,40].

Ten-year field trials using cover crops showed that the observed improvement in soil hydraulic function could be based on a more compensated distribution among macro to micropores, reducing soil compaction and increasing soil water retention and crop available water. The result could be less prone to runoff and drainage losses, compensating for the water competition [39–41].

Rotational cropping refers to the temporal alternation of different crop types (mown vs. lifted, monocots vs. dicots, annual vs. perennial) on a piece of farmland.

Crop rotation is the practice of growing a series of different types of crops in the same area in sequential seasons. Crop rotation gives various nutrients to the soil and replenishes nitrogen, for example, through the use of green manure, legumes, or cover crops in sequence with cereals and other crops. Crop rotation also helps to battle against erosion. Rotating crops helps to improve soil stability by alternating between crops with deep roots and those with shallow roots. Crop rotations can help prevent the accumulation of crop-specific pests and reduce the risk of pests developing resistance to ingredients used for crop protection [40,41]. Diverse crop rotations have the potential to deliver organic carbon to the soil derived from harvest residues, root residues, and root exudates. The effect is mainly determined by the amount and composition of the harvest residues [40].

Crop rotation achieved higher yields, less weed pressure, and higher soil C and N content in Poland in spring wheat [42] and in spring barley [43].

Data of 30 long-term experiments collected from 13 case study sites in Europe show that crop rotation had a positive effect on soil organic matter (SOM) content and yield and positively influenced earthworm numbers. Overall, crop rotation had little impact on soil pH and aggregate stability [44].

Farmers in Finland are worried about wet conditions in winter, more frequent heavy rains, and wet conditions during the harvest periods, which affect crop yields, nutrient leaching, and erosion. In response, specific crop rotations, including the use of deep–rooted crops (i.e., clover and oilseed), have been proposed by local scientists [45].

In Italy, adopting 2 or 3 year crop rotations (based on winter wheat and tomato) under future conditions led to an increase in soil organic carbon (SOC) by approximately 10% of the SOC content of the current system that is based on continuous wheat [46].

Agroforestry involves land-use systems and practices where woody perennials are deliberately integrated with crops and/or animals on parcels with the same land management, without the intention to establish a permanent forest stand. The trees may be arranged as single stems, in rows or in groups, and grazing may also take place inside parcels (silvoarable agroforestry, Silvo pastoralism, grazed or intercropped orchards) or on the limits between parcels (hedges, tree lines). The standing stock of carbon aboveground is usually greater than the equivalent land use without trees, and planting trees may also increase soil carbon sequestration [47–50]. Root systems of intercropped trees enable input of carbon to deeper soil layers compared to crops [39,40].

Review studies of agroforestry systems reduced surface runoff and soil, SOC, and nutrient losses by average values of 58%, 65%, 9%, and 50%, respectively. They also lowered herbicide, pesticide, and other pollutant losses by 49% on average. However, Mupepele et al. (2021) [51] called for a caution: only a few studies provide results based on strong evidence, and more detailed reporting on effects of agroforestry on soil quality aspects is needed. However, results from available studies do show that agroforestry can lead to benefits on biodiversity [51–54].

Soil enrichment can be achieved with biochar. The application of biochar produced from biowastes to soils could be a very good way to reduce demand for fertilisers (cutting dependency, costs, and pollution), sequester carbon, and enable relatively cheap and lasting amelioration of degraded land and sustainable and improved agriculture [30]. The pyrolysis process produces biochar as well as two additional materials, syngas and bio-oil, that may have commercial value as energy sources. Biochars differ depending on the feedstock, temperature, and residence time and have been effective tools of waste management, soil remediation, and may also offer mitigation of GHG emissions through carbon sequestration [31]. Due to the large variability of biochar, one type of biochar may not be suitable for all growing conditions and crops.

3.1.4. Crops and Yielding Potentials in Marginal Land

Growing biomass crops on marginal land, especially perennial grasses such as switchgrass and miscanthus, is expected to benefit the environment by increasing carbon sequestration [15–17,19] and reducing nonpoint source pollution compared with those from traditional crop land.

Researchers concluded that producing perennial grasses on marginal Mediterranean land is feasible and, if appropriately managed, will have relatively few non-desired environmental side effects. In Mediterranean areas, growing perennial crops can have lower negative environmental impact than wheat farming, and it also provides benefits regarding soil properties and erodibility [16,19]. The main reasons for this are lower levels of mechanisation (and thus soil disturbance) and year-round soil coverage of perennial crops, and deeper and well-branched rooting [19]. According Chimento et al. (2016) [55], an additional reason for miscanthus' ability to build up carbon in the soil is that it allocates high proportions of the assimilated carbon below ground as a carbon reservoir for growth in the spring. This was confirmed by Chimento et al. (2016) [55] and in field trials for miscanthus, switchgrass, giant reed, and three woody crops (willow, poplar, and black locust) that, compared to grain maize, on average built up 45% more SOC in the root zone. A meta-analysis study (Agostini et al. 2015) showed SOC storage for herbaceous perennials (miscanthus and switchgrass) of between 1.14 to 1.88 mg C ha/year and for woody perennials (willow and poplar) a range from 0.63 to 0.72 mg C ha/year. However, these authors emphasized that long-term field trial data (>25 years) are missing and are needed to confirm the long-term sustainable soil carbon enrichment (because the stability of recently built up SOC stores is uncertain).

Willows as well as herbaceous crops such as giant reed or miscanthus are appropriate crops for being grown under climate conditions in Ukraine, but also in Germany and Italy, whereas in addition willow can be also grown under temporarily or permanently water-saturated soil conditions [16,17,19].

The effect of perennials on building up SOC is particularly large in marginal land with low SOC levels [56]. Conversely, if biomass crops are established on land that already has high SOC levels, such as long-abandoned land with dense shrub and/or forest vegetation coverage or wetlands, this may lead to a serious decline in carbon (both above and below ground); that being said, in the context of low ILUC-risk production, there are already regulatory safeguards in place to prevent such land conversions.

It is worthwhile noting that the production of lignocellulosic crops in contaminated soils may cause the accumulation of heavy metals and other contaminants in the crops, hence compromising the quality of biomass [17].

3.1.5. Potential Yield Increases by 2030

The yield increase potential for the understudy crops has been estimated based on the meta-data analysis and information published from the projects noted in Table 1.

Figures 2 and 3 present potential yields increases for the crops based on the following assumptions:

- Baseline yields are the ones reported in Table 3.
- 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 (agricultural-outlook-2020-report_en.pdf (europa.eu)).
- The low and high increase rate because of the application of one or multiple sustainable agricultural practices (e.g., intercropping and biochar, etc.) is calculated as an average of 15% and 25%, respectively, between 2020 and 2030 based on the findings from BIO4A and SoilCare projects.

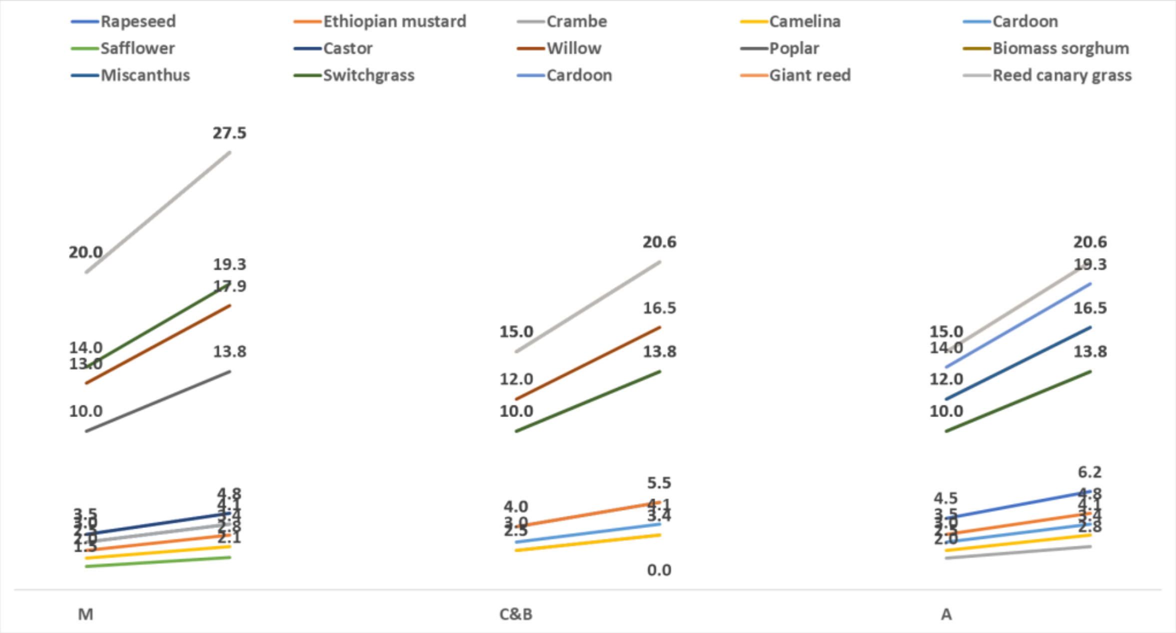

Figure 2. Estimated yield increases from the sustainable agricultural practices in farming land in the three AEZ. Details in Annex I (Tables A1 and A2).

Table 3. Technology biomass crops, relevant advanced biofuel types, agronomic suitability for the European Agro-Ecological Zones-AEZ (A: Atlantic, C&B: Continental and Boreal, M: Mediterranean) and opportunities for low ILUC risk through sustainable agricultural practices [intercropping (I), cover cropping (CC), rotation (R), agroforestry (AF), biochar (B)] and TRL levels for productivity and ability to be grown and harvested by existing machinery [16,17]. Details about the ranking in the last two columns (Productivity/Ability to use Existing Machinery and Expected TRL by 2030) can be found in Table 2.

		Relevant Biofuels (Sectors)	**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 Land with Natural Constraints)**			**Productivity/Ability to Use Existing Machinery**	**Expected TRL by 2030 ***
				A	C and B	M		
Oil	Rapeseed	Hydrotreated vegetable oil (HVO)/renewable diesel, HEFA (aviation, marine, heavy duty)	I, CC, R, B	4.5 (2)	4 (2.5)	3 (1.5)	+++	+++
	Ethiopian mustard		B	3.5 (1)	4 (1.5)	2.5 (1.5)	++	+++
	Crambe		B	2 (0.5)	2.5 (1)	3 (1)	++	+++
	Camelina		I, CC, R, B	2.5	2.5	3 (1)	++	+++
	Cardoon		B	3 (1.5)	3 (1.5)	3.5 (2)	+++	+++
	Safflower		I, B	na	2 (1.5)	1.5 (0.8)	+	++
	Castor		I, B	na	na	3.5 (1.5)	+	++
Lignocellulosic	Willow	Ethanol, methanol, butanol, Synthetic fuel Hydrotreated bio-oil/biocrude (aviation, marine, heavy duty)	AF. B	12 (9)	12 (9)	13 (8)	++	+++
	Poplar		AF, B	10 (8)	10 (8.5)	10 (7.5)	++	+++
	Biomass sorghum		I, R, B	15 (9)	15 (9)	20 (12)	++	+++
	Tall wheat grass		B	na	na	10 (7)	+	++
	Miscanthus		B	12 (8)	15 (9)	20 (9)	+++	+++
	Switchgrass		B	18 (10)	18 (10)	20 (12)	++	+++
	Cardoon		B	14 (8)		20 (10)	++	+++
	Giant reed		B	15 (9)	15 (9)	20 (10)	++	+++
	Reed canary grass		B	15 (9)	15 (9)	20 (10)	++	+++

* Only crops with expected TRL by 2030 above 7 are further analysed in the section.

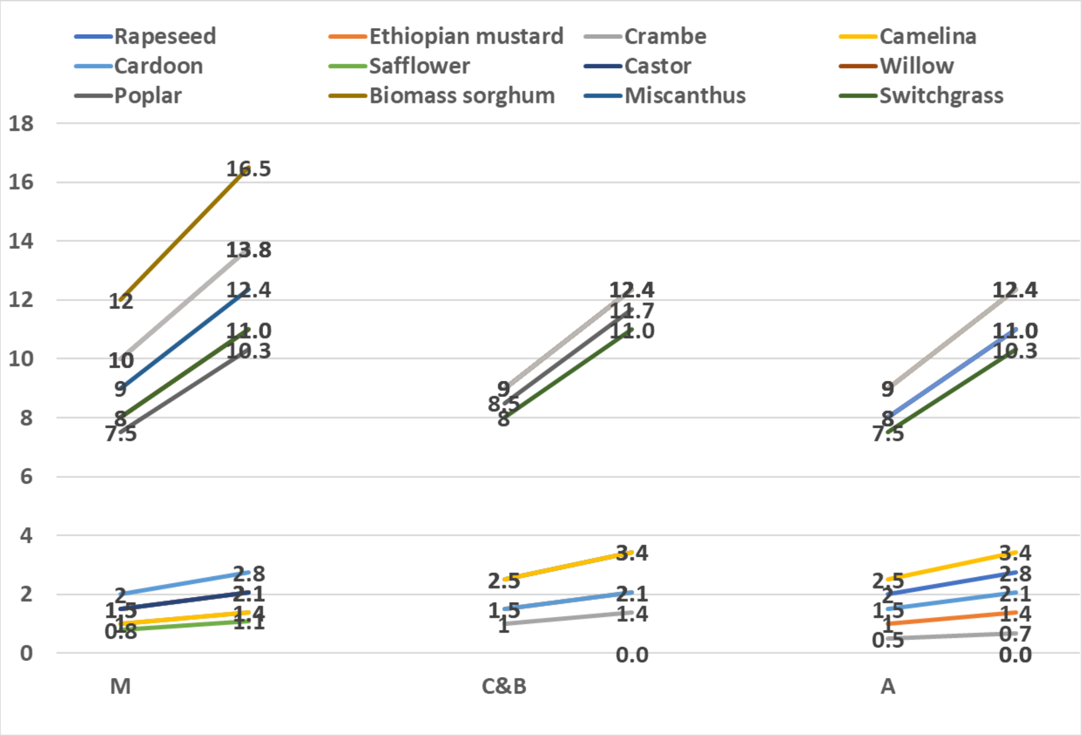

Figure 3. Estimated yield increases from the sustainable agricultural practices in land with natural constraints in the three AEZ [16,17]. Details in Annex I (Tables A1 and A2).

At this point it must be noted that the highest yield entries for all crops in Figures 2 and 3 have been already achieved at demonstration and pre-commercial scale.

3.2. Economic

The cultivation of low ILUC risk biomass crops can offer an outlet to European farmers to diversify their crop production [57], improve agricultural practices, and restore soil while producing raw materials for low carbon fuels.

3.3. 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 3). The ranges of market prices used are:

- 300–450 €/tonne of oilseeds for oil crops.
- 50–100 €/tonne of dry matter for lignocellulosic crops.

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 and 5 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 Table 3). 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.

Table 4 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.

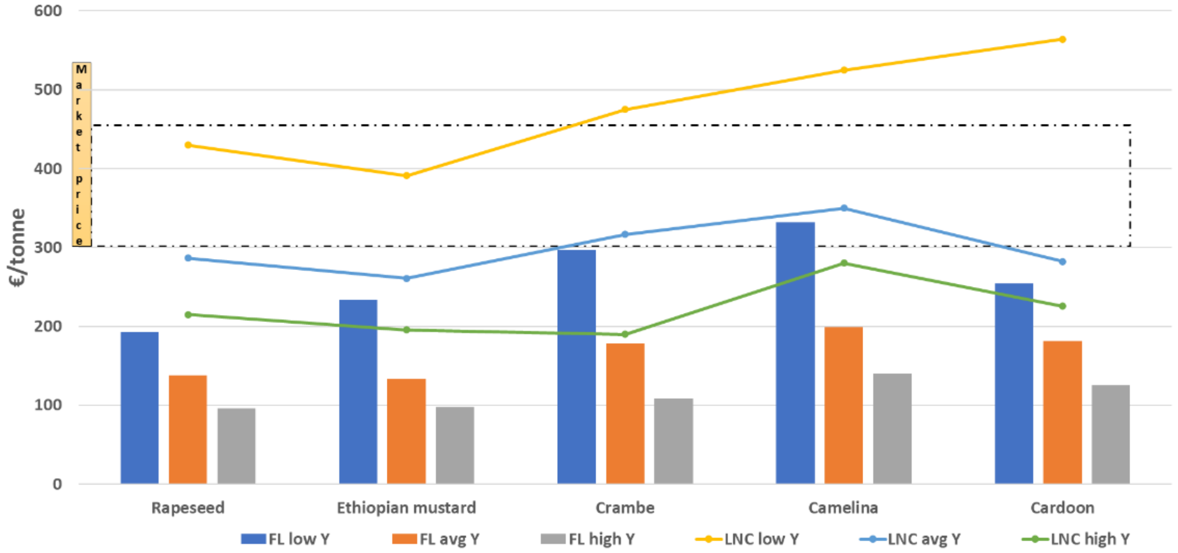

Figure 4. Oil crops production cost ranges in €/tonne seed (with yield increases) in farming land (FL) and in land with natural constraints (LNC). Details in Table 4.

Table 4. 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

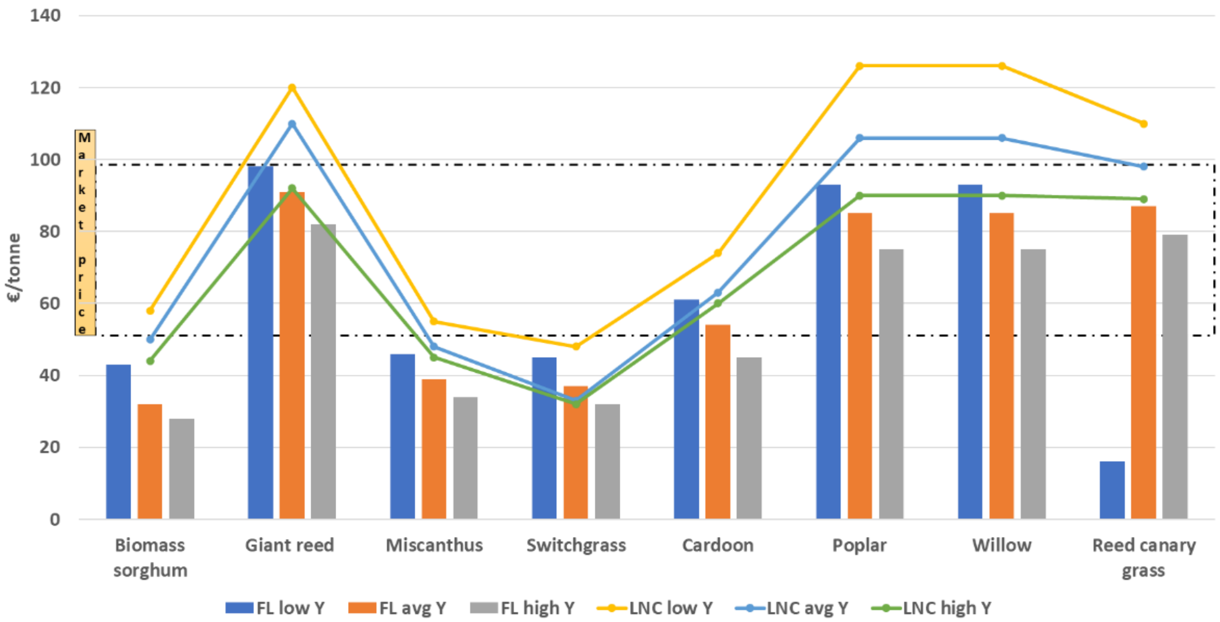

Figure 5. Lignocellulosic crops production cost ranges in €/tonne (with yield increases) in farming land (FL) and in land with natural constraints (LNC). Details in Table 4.

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.

4. Discussion

4.1. Biophysical Opportunities

This paper evaluated a set of oil and lignocellulosic crops as suitable low ILUC risk opportunities for sustainable biofuels. 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, 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.

The yielding capacity of the crops is presented both for conventional farming land and for land with natural constraints (in both they can be cultivated as part of intercropping, crop rotation, agroforestry, and/or cover crops). It is worth noting here that the term ‘cover cropping’ often refers to crops that are not harvested but are intended to protect the structural aspects of soil fertility, reduce erosion, and prevent disease build up. If crops can be chosen that provide these services but can also be harvested for biomass feedstock, this could provide additionality. Cover crops can also be part of a crop rotation. Biochar is also considered in this paper and is the only practice that can be effectively combined with all the above to improve soil properties, enrich soil quality, and, as illustrated by the BIO4A project, increase crop yields.

The paper also examined yields for the same set of crops in land with natural constraints. The additionality in REDII defines such land as unused, abandoned, and degraded. At this point it is worth noting that the three latter categories have not been mapped yet in a disaggregated manner due to the lack of respective statistical time series. As expected, crop yields are significantly lower in such land types, and this is relevant to the crop and the agro-ecological conditions.

4.2. Economic Opportunities

The analysis of economic data and estimates confirms that most of the understudy crops can be profitable in conventional farming 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 FL and LNC 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.).

This paper did not analyse any financial support for the profitability of the understudy crops. There are, however, 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, the Emissions Trading Scheme, the Sustainable Carbon Cycles Initiative, etc. From the findings presented in this paper, it is evident that, with financial incentives tailored to the appropriate country, crop, and agricultural practice(s) combination, the understudy crops can provide profitable opportunities for European farmers in almost all cases and land categories.

4.3. Policy Context

The promotion of the low ILUC-risk concept by RED II could provide opportunities for the integration of new crop types and farming methods into the EU agricultural landscape, with climate, ecological, and economic advantages that go beyond bioenergy. The concept is relatively novel however, and its implementation and market role are still in flux. The RED II provides a well-defined market opportunity for low ILUC-risk certified palm oil, which is released from the restrictions on high ILUC-risk material. The value proposition for delivering low ILUC-risk certification of other crops is not yet clear, and the creation of value for low ILUC-risk projects may be dependent on Member State policy action.

4.3.1. Status in REDII

Oil crops and lignocellulosic crops have distinct statuses under the RED II, which affects the potential value proposition. 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.

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 gCO_2e/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.

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 deliver any prima facie emission benefit if a crop was already expected to have zero ILUC emissions.

4.3.2. Broader Policy Intersections

Beyond the energy-focused RED II, production of bioenergy feedstocks intersects with other areas of EU policy including decarbonization targets, agricultural policy, pollution control, biodiversity, rural development, and more.

Indeed, biomass production for a low carbon economy remains at the cornerstone of the European political aspirations for energy and agriculture. The European Green Deal and the Common Agricultural Policy (CAP) are 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.

There is also strong overlap between the low ILUC-risk concept and some of the pan-EU agro-ecological objectives embodied in 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 degraded land offers the opportunity to restore low quality land; this builds not only on existing farm income support and greening payment measures, but also more general rural development funding regulation. With these common goals in mind, the CAP is structured to be flexible to the needs and conditions of the different EU Member States: national governments can design their Strategic Plans to exploit the alignment between their own environmental objectives and the low ILUC-risk system (alongside other waste-based biofuel pathways), while possibly introducing additional sustainability requirements on crop-based biofuels.

Moreover, we have already seen how increasing agricultural yields through improved management practices—such as crop rotations and cover cropping—intersects 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.

5. Conclusions

Sustainable biofuels are an important tool for the decarbonisation of transport. This is especially true in aviation, maritime, and heavy-duty sectors with limited short-term alternatives. Their use by conventional transport fleets requires few changes to the existing infrastructure and engines, and thus their integration can be smooth and relatively rapid. Their feedstock provision, however, is interconnected with agriculture and must comply with sustainability principles for (i) producing additional biomass without distorting food and feed markets and (ii) addressing challenges for ecosystem services, including biodiversity and soil quality.

This paper consolidates knowledge from six recently finished and ongoing European research projects on biophysical and economic opportunities for low indirect land use change (ILUC) risk biomass crops for sustainable biofuels that benefited either from improved agricultural practices or from cultivation in unused, abandoned, or severely degraded land.

The findings show that there are several biophysical combinations of crops with sustainable agronomic practices in the European agro environment zones and significant opportunities to cultivate these crops both in farming land as part of rotations, intercropping, or agroforestry, as well as in land with natural constraints (i.e., unused, abandoned, and degraded) and overall deliver significant economic and socio-economic benefits. Main conclusions and policy implications from the work presented in this paper include:

- The restoration of land with mild or severe biophysical constraints can be very challenging as most cases require significant effort and material input to turn land to productivity. This can be particularly challenging in land with high contamination and may result in environmental risks, rather than environmental benefits. Future policy interventions must be in place to regulate the ratio of input/output and ensure sustainable low input practices are safeguarded.
- Land preparation in areas with natural constraint conditions can be very costly. There is need for financial support to farmers and landowners. The opportunities currently discussed in the carbon farming initiative and the options for including such activities to eco-schemes as beneficial for soil carbon are well suited.

Compliance of agronomic practices with sustainability and certification is critical to ensure that the cultivation of low ILUC risk biomass crops will be performed within planetary boundaries. It is important to ensure certification is reinforced and there is consistent monitoring of compliance to sustainability.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. 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 sustainable practices	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
	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

Table A2. 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 sustainable 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 sustainable 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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