Cerulogy

Golden Cropportunity?

The biofuel potential of intermediate crops and crops grown on severely degraded land for EU aviation and maritime fuel targets

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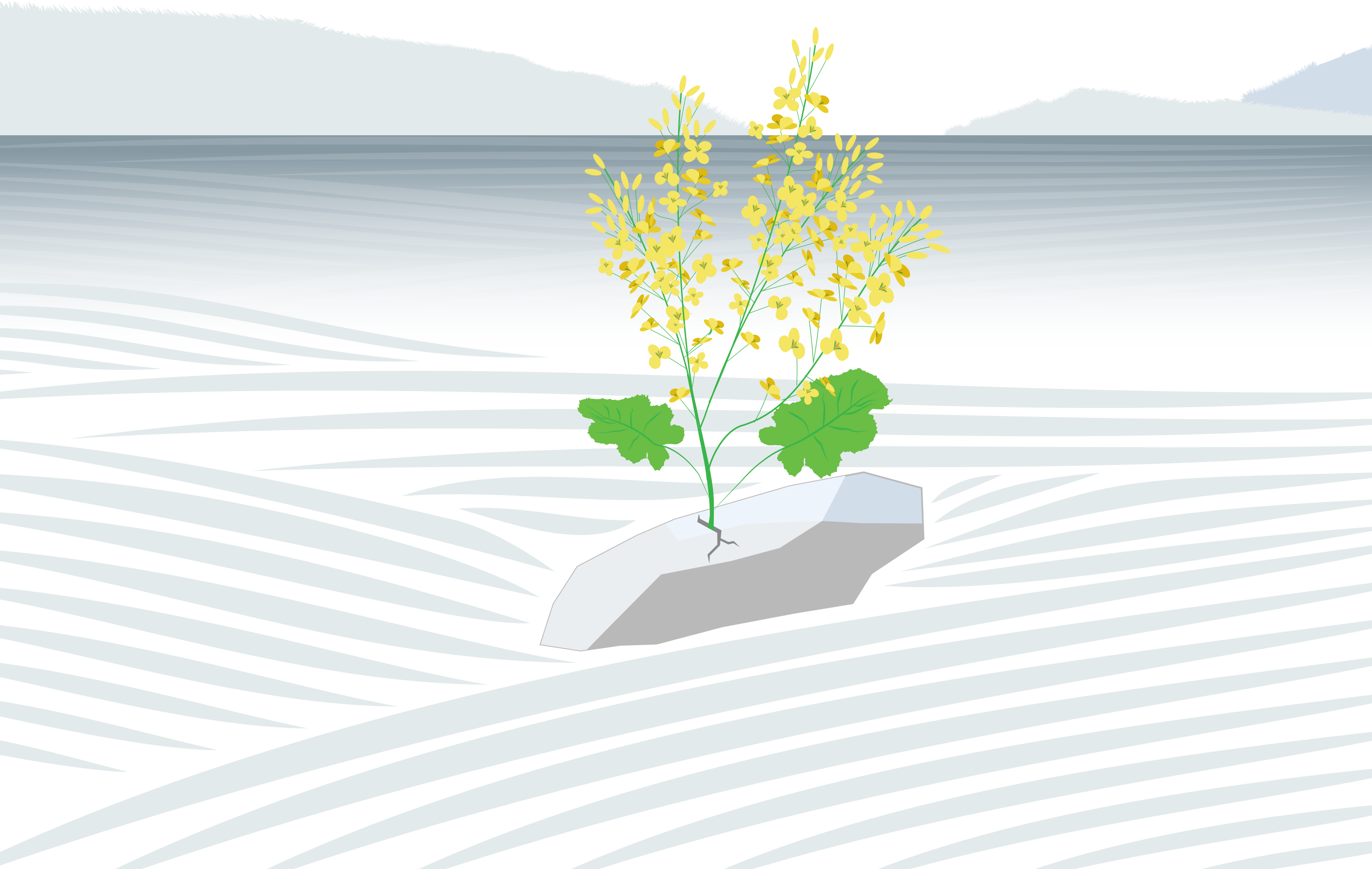
November 2025



Acknowledgements

This work was funded by Transport and Environment. We are grateful to the Tranport and Environment team for reviewing this report, and to Calliope Panoutsou for useful discussions.

Disclaimer

Contents

Summary

The European Union (EU) has recently added two crop-based biofuel feedstock categories to Annex IX of the Renewable Energy Directive (RED), conferring on them extra incentives for production and use. In this report, they are referred to as 'intermediate feedstocks', which are crops grown between the main harvests on agricultural land, and 'SDL feedstocks', which are crops grown on severely degraded land. The overall intention of adding these appears to be to encourage the use of feedstocks that don't compete with food production and don't stimulate agricultural expansion; however, questions remain about the details of how these feedstocks are to be defined, and how their sustainability is to be assessed and guaranteed[1].

Demand for these feedstocks is expected to be high. The EU has established a market for alternative fuels through ReFuelEU Aviation, FuelEU Maritime, and in the overall transport sector through the RED. Crop-based biofuels, in particular those based on vegetable oil, are positioned as a relatively scalable solution for which production technology is already mature. When the new Annex IX crops are used to produce aviation or maritime fuels, they are to be considered 'advanced': i.e. positioned among the most sustainable feedstocks whose contribution to the overall transport mix is not capped, and which count towards a stretching RED sub-target alongside cellulosic biofuels.

This report highlights a number of oilseeds that are suited to different climates, land types, and agricultural rotations for production of intermediate and SDL feedstocks that would fall outside the RED's cap on food-and-feed-based biofuels. Proponents highlight that producing such crops could maintain and rehabilitate soil health, while bringing agri-ecological benefits; however, these purported advantages are not automatic, and must be considered on a case-by-case basis in the context of alternative land uses. Production of intermediate feedstocks may imply agricultural intensification in seasons where the fields would otherwise be left to rest under a non-productive cover crop; and encouraging the spread of farming onto unused severely degraded land may disrupt local ecosystems.

As with main crops, producing intermediate and SDL feedstocks requires agricultural inputs and energy expenditure. Illustrative lifecycle analyses in this report demonstrate that meeting the EU's strict biofuel emissions savings thresholds it is not guaranteed for a given batch of intermediate or SDL crop. Chemical inputs will have to be applied judiciously, and energy use in the lifecycle stages from cultivation to finished fuel delivery carefully planned and optimised[2]. In particular there is likely to be a tension between the potential to increase yield and improve project economics by adding nitrogen fertiliser and the need to minimise nitrous oxide emissions if the feedstock is to meet regulatory emissions savings thresholds. Moreover, climate change is expected to shift the viable growing ranges of various crop types and affect their yields: regional competition for productive land may therefore intensify in future, calling into question the suitability of different crop types and agricultural management practices.

This report maps land areas in the EU that may be viable for the production of Annex IX intermediate and SDL feedstocks. Map layers corresponding to crop viability, cover cropping practices, land salination, soil erosion, soil organic carbon content, and land use are

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[1] It is hoped that some of these will be addressed in a forthcoming update to Commission Implementing Regulation 2022/996.

[2] There are also risks of emissions 'leakages', for instance a farmer who over-uses fertiliser in the main season may achieve a spurious reduction of fertiliser use for an intermediate crop.

combined to produce a maximum land area estimate – see Figure 1. A review of research trials across agri-environmental zones provides approximate crop and oil yields, which, in combination with an indicative range of farmer uptake rate, is translated into an estimate for Annex IX crop oil potential. In the EU, this amounts to less than 2 Mt (million tonnes) per year, falling far short of the expected demand for biofuels for the aviation and maritime transport segments. The implication is that there will also be a need for other Annex IX biofuels, and in particular for cellulosic biofuels, if targets are to be achieved.

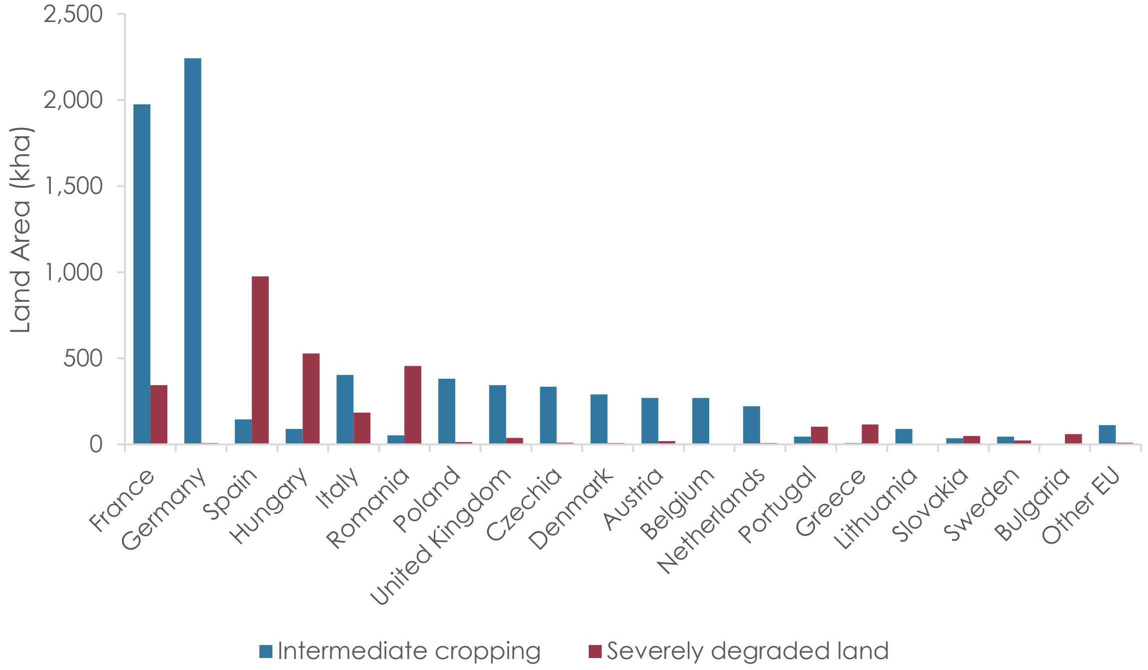

Figure 1 Estimate of maximum plausible land availability for growing Annex IX oilseed crops in the EU, in kilohectares, split between land suitable for intermediate cropping and severely degraded land

It can be expected that satisfying the EU's renewable energy targets would involve imports of both feedstocks and alternative fuels. A strong and stable policy value signal promoting Annex IX crops may influence farming practices and land uses around the world, with potentially millions of tonnes of intermediate and/or SDL feedstock flowing into the EU market every year. The current governance system in the RED III is not adequate to guarantee that producing this feedstock won't indirectly stimulate agricultural expansion. Given the practical difficulty of distinguishing vegetable oils grown under different conditions, it will also be challenging for certification bodies to robustly verify that a given batch has met the EU's requirements, with an ongoing risk that some batches may have been incorrectly labelled as Annex-IX-compliant. Rigorous interpretation and application of the rules will be needed to give confidence that the EU's new Annex IX feedstocks meet the intended level of sustainability.

1. Introduction

1.1. Policy context

The EU's Renewable Energy Directive (RED), now in its third iteration as RED III (European Union, 2023b), sets targets for the use of alternative transport fuels by EU Member States. It bestows special incentives on the use of biofuels made from feedstocks listed in its 'Annex IX': these incentives include double-counting towards renewable energy targets; an additional sub-target to motivate use of 'advanced biofuel' feedstocks listed in Part A of the Annex[3]; and a 1.2x energy multiplier for these advanced biofuels when used in the maritime and aviation sectors.

In the aviation sector, ReFuelEU Aviation (European Union, 2023a) sets rising quotas for the supply of alternative aviation fuels. Food-and-feed-based biofuels are excluded, and the contribution of other non-Annex-IX biofuels is capped at 3% of aviation fuel demand, leaving considerable room for Annex IX. On shipping, FuelEU Maritime (European Union, 2023c) requires vessel operators to comply with fuel emissions reduction targets. Food-and-feed based biofuels are excluded here too; and fuels which are able to report low lifecycle emissions – including biofuels form Annex IX – will be in high demand as the targets tighten over time. In short, the road, aviation, and maritime transport segments will all play a role in driving demand for Annex IX feedstocks.

Two newer feedstock categories added to Annex IX by European Commission (2024) warrant particular attention for their potential impacts on crop production, land use, and ecology. In this report, we will refer to them as:

> 'Intermediate feedstock': Intermediate crops grown in areas which normally only support one 'main crop' harvest;
>
> 'SDL feedstock': Crops grown on severely degraded land, other than 'food and feed' crops.

The full policy language is quoted in Appendix A.2, along with commentary on how specific eligibility criteria might be met. When intermediate and SDL feedstocks are used for the production of aviation fuels, they are to be counted in Annex IX Part A; otherwise they are to be counted in Part B[4]. We would anticipate that the combined value signal from ReFuelEU Aviation and inclusion towards the Annex IX Part A sub-target of the RED would lead biorefineries processing these feedstocks to optimise their product slate towards jet-compatible fractions (though there will inevitably be some proportion of naphtha and lighter hydrocarbons produced in tandem).

As cellulosic material – forestry residues, industrial by-products, energy crops, etc. – is already covered by other Annex IX categories, the effect of the new additions is to potentially bring

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[3] For example, cellulosic materials and industrial residues and wastes.

[4] The contribution of Annex IX Part B feedstocks is nominally capped at 1.7% of transport energy; but there is a strong precedent among Member States for raising this cap when it limits their ability to meet targets (Soquet-Boissy et al., 2024), so in this study we do not treat this as limiting use of Annex IX crops for non-aviation biofuels.

crops rich in sugar, starch, and oil into Annex IX. Of these, oilseeds are particularly relevant because conversion of vegetable oils to 'HEFA' ('hydroprocessed esters and fatty acids') jet fuel is a mature technology with existing capacity and because agricultural models already exist for off-season oilseed cultivation: billions of litres of vegetable oils like soybean and rapeseed are used each year for producing diesel- and kerosene-type drop-in fuels. But expansion of the intensive agricultural systems used to grow these crops is associated with greenhouse gas emissions and ecological harm, which offset and may potentially outweigh their contribution to reducing transport fossil fuel use (Phillips et al., 2024; Sandford, Phillips, et al., 2024). Oil crops such as the ones just mentioned have a particularly problematic track record, as demand for vegetable oil has stimulated deforestation and greenhouse gas emissions from land-use change in the tropics and beyond. The conditions under which oilseeds may be included in Annex IX should therefore be scrutinised – especially as allowing established conventional biofuel facilities access to incentives that have previously been targeted to next-generation technologies runs the risk of undermining investment in the latter.

This report examines the potential and the risks of the new Annex IX crop feedstocks in the EU biofuel mix, focussing on oilseeds (i.e. not cereals or sugar crops). The remainder of this section establishes the interpretation of the Annex IX definitions to be used for the purposes of this study. Section 2 investigates relevant oil crops and cropping practices, and explores the impacts of dedicating land to them. Section 3 estimates the potential production volume of feedstock and biofuel, both within and outside the EU.

1.2. Definitions

The addition of intermediate and SDL feedstocks to Annex IX may be consequential for EU biofuel policy; yet there remain ambiguities in the adopted regulatory language. Without a clear specification of which crops are considered eligible, it is impossible to make a confident assessment of potential production areas for the new Annex IX crops, evaluate the kinds of vegetable oil yields that can be expected, and estimate the biofuel volumes that might be produced. In this section we outline the working interpretation of the Annex IX criteria that we have adopted for this report, with fuller discussion in Appendix A.2.

1.2.1. Intermediate feedstocks

A key concept for EU biofuels policy is that of 'food and feed crops': these encompass oil-, starch-, and sugar- rich crops grown on agricultural land as 'main' crops, and explicitly exclude 'intermediate crops'. Intermediate crops are not directly defined in the RED: rather they are introduced only as an exception to the food and feed crop category, with 'catch' and 'cover' crops given as examples. This lack of an explicit definition makes determining what exactly counts as an intermediate crop challenging[5]. It is further stipulated that, to be eligible under Annex IX, intermediate crops should not stimulate additional demand for land (see Section 2.2), should maintain soil organic matter, and should be grown in areas "where due to a short vegetation period the production of food and feed crops is limited to one harvest".

The interpretation of the vegetation period requirement is particularly important because

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[5] We understand that the European Commission in the process of further specifying the definition of intermediate crops in an update to an Implementing Regulation (European Commission, 2022).

it determines which subsets of second crops are eligible. There are regions where double cropping is already widespread, e.g. in Brazil (Malins, 2022), and a report to the European Commission flagged the generalised use of secondary crops[6] as having potentially significant distortive effects on other markets (Haye et al., 2021). For the purpose of this report we adopt a working definition of Annex-IX-eligible intermediate feedstocks: 'Any crop grown in the off-season, on agricultural land on which a more productive main crop is grown in the same year, in a region where second cropping practices are not already normalised'.

1.2.2. SDL feedstocks

The RED stipulates that land that is subject either to excess salinity, or to both erosion and organic matter depletion, can be classed as severely degraded. These characteristics are to be assessed on a project-by-project basis, and the RED does not currently provide any explicit threshold values to enable assessment of land as severely degraded. A corollary is that no existing land-quality mapping identifies which areas count as severely degraded according to the RED definition[7].

In order to provide an indication of the areas that might be classifiable as severely degraded, this report adopts working definitions for salinated, eroded, and low-SOC land. Key considerations are discussed in Appendix A.2. The threshold values outlined in Table 1 are chosen in line with our understanding of the intent of the RED requirements, as well as for consistency with existing EU datasets (so that we are able to use them as a basis to identify land potentials).

Table 1 Working definitions for the severely degraded land types

Land type	Working definition
Significantly salinated	Severe salinity (electroconductivity >15 dS/m) or sodicity (exchangeable sodium >15%) (Elbersen, Verzandvoort, et al., 2022; Tóth, Adhikari, et al., 2008b).
Severely eroded	Topsoil loss greater than 10 t/ha/year.
Significantly low organic matter	Organic carbon in the topsoil less than 0.5% by mass.

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[6] Termed 'intermediate crops' in that report, though this diverges from the RED definition.

[7] Studies evaluating crop suitability in 'areas with natural constraints' (ANCs) – a concept used to direct support under the EU's Common Agricultural Policy (CAP) – may give useful indications in some circumstances.

2. Growing Annex IX crops

2.1. Existing land uses

2.1.1. Intermediate cropping

In the period after one main crop is harvested and before the next is established, it is not uncommon to plant cover crops that offer agricultural and ecological benefits (BIKE, 2022, 2023c; Clark, 2007). Any vegetation that provides cover to otherwise bare soil during windy and rainy seasons will reduce erosion and loss of nutrients (Fendrich et al., 2023b; Huang et al., 2025; Scavo et al., 2022). At the same time, they may enrich below-ground biomass (McClelland et al., 2021; Poeplau & Don, 2015); provide niches for soil biota (Scavo et al., 2022) and habitats and nourishment for pollinators and pest predators; and mitigate soil compaction (Dabney et al., 2001; Gentsch et al., 2024).

Leguminous cover crops can provide an organic source of nitrogen ('green manure') to reduce the need for synthetic fertiliser; this in tandem with other nitrogen cycle effects may contribute to a negative net greenhouse gas balance (Abdalla et al., 2019; Kaye & Quemada, 2017; Lugato, Bampa, et al., 2014). When crops are planted between main crops specifically to soak up excess nutrients and prevent them from infiltrating groundwater or disrupting aquatic habitats (Chambers et al., 2008), they are referred to as catch crops.

The EU's Common Agricultural Policy (CAP) makes subsidy disbursal conditional on farmers taking measures to protect a minimum proportion of their soils from erosion, with cover cropping being a primary method for achieving this[8]. EU-27 countries' reported winter planting of cover and intermediate crops rose from 5.8 Mha (million hectares) in 2010 to 7.4 Mha in 2016 (Eurostat, 2025a)[9]. But these are generally 'non-productive', in that they are not expected or intended to be left in the ground long enough to mature to the point of harvesting oilseeds or grains from them.

A transition from 'non-productive' cover cropping to 'productive' intermediates that are harvested for vegetable oil would be expected to preserve certain advantages such as establishing cover to reduce soil erosion and absorbing excess nutrients (Johnson et al., 2017); but in some cases it will be hard to maintain the full range of agricultural and ecosystem services. For example, replacing a leguminous clover with the oilseed *Brassica carinata* (see Section 2.2) would reduce nitrogen availability and most likely have to be compensated with synthetic fertiliser to avoid compromising the main crop yield.

Indeed, shifting farmers' incentives towards maximising the yield and quality of the intermediate crop would promote the use of chemical inputs and irrigation that may not

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[8] This is under the 'good agri-ecological condition' (GAEC) #6. Indeed, farmer surveys in the EU indicate that adoption of cover cropping practices is driven primarily by these policy incentives rather than soil stewardship considerations (Kathage et al., 2022; Smit et al., 2019). The European Commission has sought to weaken GAEC #6 and grant Member States further flexibility in exempting farms (European Parliament, 2024). Member States' national CAP Strategic Plans may support both productive intermediate and nonproductive cover crops.

[9] As we shall see in Section 3.2.1, there remains significant uncertainty in the actual number.

be necessary for non-productive crops (cf. Guidehouse, 2024; Von Cossel et al., 2019), while reducing the flexibility of the agricultural calendar by adding a new set of constraints on planting and harvesting dates. Rose et al. (2024) and Ziche et al. (2024) point out that in a semi-arid environment, competition for water between intermediate crops and main crops can also result in a productivity trade-off.

Finally, both non-productive cover crops and productive intermediates may require termination with herbicides at the end of the growing period (or maybe prematurely if there is a risk of them competing with the main crop for resources in a given year); though for some productive intermediates, harvesting may in theory be able to take the place of herbicides (cf. L. Yang et al., 2023), but the efficacy of this would have to be demonstrated in practice.

2.1.2. Severely degraded lands

Lands suffering from poor soil quality or salinity may currently be unable to sustain a 'normal' productive crop; but they may be rehabilitated over time through the careful introduction and rotation of crops with root systems that can stabilise and improve soil health (Magnolo et al., 2021; Valli et al., 2017), and crops with salt-remediation properties (Daba, 2025). Introducing crops on land classified as severely degraded thus gives an opportunity to improve agricultural performance while tackling renewable energy targets.

But it is important to recognise that, depending on the implementation of the policy language, in some cases land classified as 'severely degraded' may already host ongoing cultivation – i.e. profitably producing conventional crops (perhaps with lower than average yield), growing hardy crops selected to cope with the adverse conditions, or providing pasture and forage land for livestock. Turning this land over to bioenergy production would displace the prior uses, with potential knock-on effects for food prices and agricultural expansion around the world, just as in the case of displacing existing uses of higher quality land (Sandford et al., 2025; Sandford, Phillips, et al., 2024). Certain stakeholders have called for stringent thresholds to ensure that currently cultivated land is excluded by definition from the severely degraded category (e.g. EWABA, 2025).

Other severely degraded land may be unused – either having never been cultivated or having been abandoned – in which case while there is no displacement of existing production the land may support valuable semi-natural habitats and/or migration corridors free from ongoing disturbance[10]. It may play a role in supporting populations of pollinators and other wildlife (European Environment Agency, 2025; Paracchini et al., 2009; Schuster, 2025), mitigate erosion, and replenish groundwater (Blanco-Canqui, 2016; Burland & von Cossel, 2023). When left undisturbed for extended periods, soils may also build up stores of organic carbon which would destabilise and revert to atmospheric CO_2 when the soil is tilled (Lugato, Bampa, et al., 2014), although this cannot apply to land identified as degraded due to low soil carbon[11]. The RED requires land use change emissions to be accounted (using standard carbon stock factors) when there is a declared change from one land use classification to another, but this provision may not be triggered when converting unused agricultural land into productive agricultural land.

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[10] Noting that land that is not agriculturally productive may in some places still be managed to control the spread of invasive species or fire hazards (Fayet et al., 2022; Sil et al., 2019).

[11] Though of course where SDL feedstock is grown on low-SOC land, the release of soil carbon would be less of a concern.

The Horizon-EU project MAGIC estimated that 34% of the farmland that they identified as ‘marginal’ in the EU+UK was also classed as ‘high nature value’. Some fraction of this will be unused and abandoned arable that could be used for SDL feedstock production (see Section 5.4.2 of Elbersen, van Eupen, et al. (2022), for a statistical break-down). In the assessment by Allen et al. (2014) of land that could be made available for energy cropping, there is clear recognition that conversion of semi-natural habitats would result in significant biodiversity and probably carbon losses. This serves to underscore the importance of local environmental impact assessments.

2.2. Feedstock competition

OECD & FAO (2025) reports that the majority (~60%) of virgin vegetable oil produced globally is used in the food sector . About 20% goes to biofuels, and the rest to animal feed and other uses such as oleochemicals. Lipid-based biofuel demand from major markets is expected to rise by over 70% between 2023 and 2030, reaching 67 Mt (megatonnes) in 2030 (Sandford, Phillips, et al., 2024). Diversion of significant volumes of biofuel feedstock from the food and feed sector risks food price impacts, and there is considerable evidence that historical biofuel demand trends have led to systematic price increases and contributed to commodity value spikes, negatively affecting welfare (Malins, 2023).

Policy-makers aware of these issues have employed caution over the design and flexibility of biofuel mandates: the EU limited the contribution of ‘food and feed’ biofuels to renewable energy targets; the USA considers food market impacts in formulating its blending quotas; and India, China, and Malaysia provide examples of countries that have delayed or scaled back biofuel targets in response to stressed food markets (Sandford, Phillips, et al., 2024).

The oleochemicals industry uses vegetable oils to produce lubricants, soaps and detergents, adhesives, resins, bioplastics, lacquers, surfactants, plastic and rubber additives, pharmaceuticals, and a variety of platform chemicals[12]. Efforts to develop new varieties of oilseed for the oleochemicals industry have focussed on some of the crops from Table 2 (COSMOS, 2020; Landoni et al., 2023), suggesting a potential competition with the biofuels sector for these feedstocks.

The Annex IX language defining ‘intermediate feedstock’ specifically seeks to avoid the risk that biofuel feedstocks will be drawn from other markets, with the stipulation “provided their use does not trigger demand for additional land” (discussed in Appendix A.2). There is as yet no indication of precisely how this will be assessed and what kind of evidence and verification will be involved, but under a robust system, operators would have to provide assurance that (a) the intermediate crops have no existing use, and (b) growing the intermediate crop does not diminish the productivity of the main crop. The EU’s ‘low ILUC-risk’ concept, established by the RED, provides a possible blueprint for how this condition could be implemented in practice (Sandford et al., 2022; Sandford, Malins, et al., 2024)[13]; the alternative fuels industry body

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[12] Vegetable oil feedstocks may already be favoured over petroleum oil in industrial uses where leakage, toxicity, and biodegradability are important concerns (Hamnas & Unnikrishnan, 2023).

[13] The low ILUC-risk methodology applies two ‘additionality’ criteria to provide assurance that pressure is not being put on other markets and hence stimulating land demand: to supply biofuel feedstock, a project must endeavour to (i) show that improvements to agricultural productivity would not have been undertaken in the absence of EU biofuel policy, and (ii) only claim credit for feedstock generated beyond ‘business-as-usual’ yields (Sandford et al., 2023).

EWABA has championed the potential of this framework to provide a minimum sustainability guarantee (EWABA, 2025)[14]. However, since the European Commission conspicuously declined to specify low ILUC-risk certification as the way to meet the 'no additional land' condition, we would anticipate that evidence falling below this standard may ultimately be deemed acceptable. For example, as suggested above the rules may simply be interpreted to only exclude farming systems where annual double-cropping is already normalised (e.g. Brazil's soybean-maize rotation); in this case, the eligible land area would be greatly increased[15].

For SDL feedstock, there is no 'additional land' criterion: any such crops would be eligible for Annex IX status regardless of displacement effects. The potential for market distortions (and hence additional land demand) arising from the use of such feedstocks was raised as a matter of 'some concern' in a report for the European Commission (Haye et al., 2021), signalling a risk that land classified as severely degraded may already be agriculturally productive. That report endorsed the use of low ILUC-risk certification to avoid this issue. We return to the matter in Section 3.2.4, and assesses the overlap between severely degraded land and currently productive agricultural land.

2.3. Suitable oilseeds

2.3.1. Crop candidates

A number of factors determine whether a given oilseed crop will be suitable as an Annex IX feedstock in any given context. If it has to fit into an existing annual rotation schedule, a short maturation period may be key. If climatic or biotic conditions (e.g. pests) prevent growing of a secondary crop under normal conditions, then the candidate oilseed will have to be tolerant to those conditions. Similarly, if it is being grown on severely degraded land, then the oilseed will have to be viable in that poor-quality soil. Table 2 lists some candidates for the EU that have been well characterised in the literature (Elbersen, Verzandvoort, et al., 2022; Panoutsou et al., 2017, 2022)[16]. Considering their properties and minimum growing requirements, the crops listed are thought to be suitable for at least one of the EU's agri-ecological zones (cf. Von Cossel et al., 2019).

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[14] Sandford, Malins, et al. (2024), Sandford et al. (2022), and BIKE (2023a) discuss opportunities and some important potential pitfalls in its application to Annex-IX-compatible crops.

[15] An industry report (Hamelinck et al., 2025) advocates for a system where farmers are obliged to maintain a consistent allocation of land resources to the main crop: this is quantified as the product of the land area and cultivation time, with a tolerance factor to allow for natural variability. This practice-based (rather than results-based) assessment of avoiding additional land demand is simpler than the low ILUC-risk methodology, but it would fail to capture, for example, any adverse impacts on the main crop yield that may occur.

[16] Other species have been identified as promising, for instance pennycress (Luján et al., 2025; Moser, 2012; L. Yang et al., 2023; Zanetti et al., 2019); still others have been mostly dismissed from further consideration, e.g. jatropha (Kant & Wu, 2011).

Table 2 Candidate intermediate oilseed crops

Crop	Characteristics
Rapeseed (*Brassica napus*)	Widespread oilseed, often grown in rotation with cereals to prevent build-up of pests. Suitable for cultivation in temperate regions as it can germinate in low temperatures and uses available water opportunistically. Large roots stabilise the soil, but rapeseed is at high risk of fungal disease and herbivores like slugs and beetles.
Ethiopian mustard[17] (*Brassica carinata*)	Potentially high-yielding relative of rapeseed, with different varieties suited to different temperature regimes. Growing season is 105-210 days, depending on the crop variety and local conditions (Fischer et al., 2025). Carinata is suitable for integration into certain crop rotations and is tolerant of drought and salinity, but is relatively nutrient-intensive.
Crambe (*Crambe abyssinica*)	Adapted to areas with mild winters and hot dry summers; some cold-tolerant varieties have been trialled. Crambe is disease-resistant, can out-compete weeds, and has a short cropping cycle of 85-105 days (Panoutsou et al., 2017)[18]. Its oil is more resistant to oxidation than other commonly-used vegetable oils like soybean.
Camelina (*Camelina sativa*)	Camelina has a short growing season (85-100 days) and the plant is tolerant of cold, aridity, salt, and low-fertility soil (Moser, 2012; Obeng et al., 2024; Royo-Esnal & Valencia-Gredilla, 2018a; Schillaci et al., 2023), though seed yield is sensitive to high temperature (Zanetti et al., 2021). It also has low input requirements compared with conventional oil crops. Camelina is well adapted to northern temperate climates, has both winter and spring varieties (Zanetti et al., 2024), and may be planted in rotation with cereals.
Cardoon *(Cynara cardunculus)*	A thistle related to globe artichoke; cardoon is a perennial plant whose oil yield is generally lower in the first establishment year (D'Avino et al., 2020); but it may also be treated as an annual. Cardoon's deep taproot allows it to thrive in dry environments. It is moderately salt tolerant, but is damaged by cold temperatures. It has been used for phytoremediation of soils contaminated with heavy metals.
Safflower (*Carthamus tinctorius*)	Originally used as a dye feedstock, safflower grows well in semi-arid conditions due to its strong taproot. On the flip-side, it is susceptible to infection in rainy conditions, and to fast-growing weeds in the early stages of development. Harvest takes place after 110-140 days (Christou et al., 2012).
Castor (*Ricinus communis*)	Castor is well adapted to dry, hot, and saline conditions. It has a relatively long growing period (120-180 days), which can be extended to make it a semi-perennial crop (Calcagno et al., 2023). Oilseed production may be hastened by lower soil fertility. It is already widely grown as a non-food oil crop and may be treated as an annual or perennial.

A distinction should further be made between land that is severely degraded because of erosion & low soil organic carbon (SOC) versus that which is salinated, as crops which perform well in one situation may struggle in the other. For example, carinata is suited to a range of soil conditions including low SOC, but is not tolerant to salinity (Alexopoulou, 2023a), while the

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[17] For the remainder of this report, we refer to this crop as 'carinata'.

[18] Some trials have reported longer growing times (Stolarski et al., 2018).

reverse is true for rapeseed, camelina, and safflower (Matthees et al., 2018; Miyamoto et al., 2012; Nayidu et al., 2013).

Extracting vegetable oil from these oilseeds leaves a solid ‘seed cake’ or ‘meal’ rich in protein and other nutrients (e.g. Keadle et al., 2023). This co-product may be used as a livestock feed additive in place of purpose-grown feeds[19]. The treatment of the meal co-products will be relevant to the lifecycle analysis in Section 2.5, as some portion of the greenhouse gas emissions associated with biofuel feedstock production will be allocated to the meal rather than to the vegetable oil; this reduces the biofuel’s reportable lifecycle emissions.

2.3.2. Oilseed yields

Vegetable oil production is the product of oilseed yield (t_{seed}/ha/year) and extractable oil content (mass percentage)[20]. Both these factors are sensitive to crop variety, time of planting, input use, and growing conditions[21]. While yield data is available from crop trials, it can be misleading to extrapolate from research trials on small, intensively-monitored and carefully-harvested plots to larger-scale mechanised systems (cf. K. Wang et al., 2013).

Given the variability reported in the academic literature between trial plots, as well as between seasons for the same plot, any supposedly representative yield value carries a large degree of uncertainty. In practice, different yields will be achievable in different locations. With this in mind, Figure 2 presents indicative yields for the Table 2 oilseeds (these are crop oil yields, not seed yields). Conventional farming systems are at the high end; unfavourable conditions – i.e. eroded, low-organic-matter soil – are at the low end. We use these data to inform our estimate of potential biofuel production (Section 3.3).

It is evident from Figure 2 that crops grown on severely degraded land can be expected to suffer yield penalties. Newly-established crops could easily be unprofitable for the first few years as the land undergoes rehabilitation – a fact that we return to in Section 3.5.1 on certification uncertainties). Intermediate crops grown in the less favourable off-season also experience a yield penalty compared to being grown as a main crop: based on the literature review in Appendix B.1, we take viable seed yields for intermediate crops to be anything from 10% to 40% lower than the conventional benchmark. We note that the literature is well supplied with more optimistic productivity claims. For example, a report for the European Commission DG RTD & Wageningen University & Research (2024) assumes camelina seed yields of 2.0-3.3 t/ha/year in 2030 (and up to 4.0 t/ha/year in 2050). However, according to our review of the current research literature, these are a long way off from being achieved in practice.

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[19] Castor meal contains toxins and so must be treated before incorporating into animal feed. More commonly, it is returned to the field as fertiliser, and in some circumstances it is burned as a boiler fuel.

[20] Measures to increase the former may decrease the latter (e.g. Obeng et al., 2021), which has implications for farmers wishing to maximise oil production.

[21] As one example, a review of field trials found camelina oil yield falling by around 50% in overly sandy or clayey soils (Reinhardt et al., 2021).

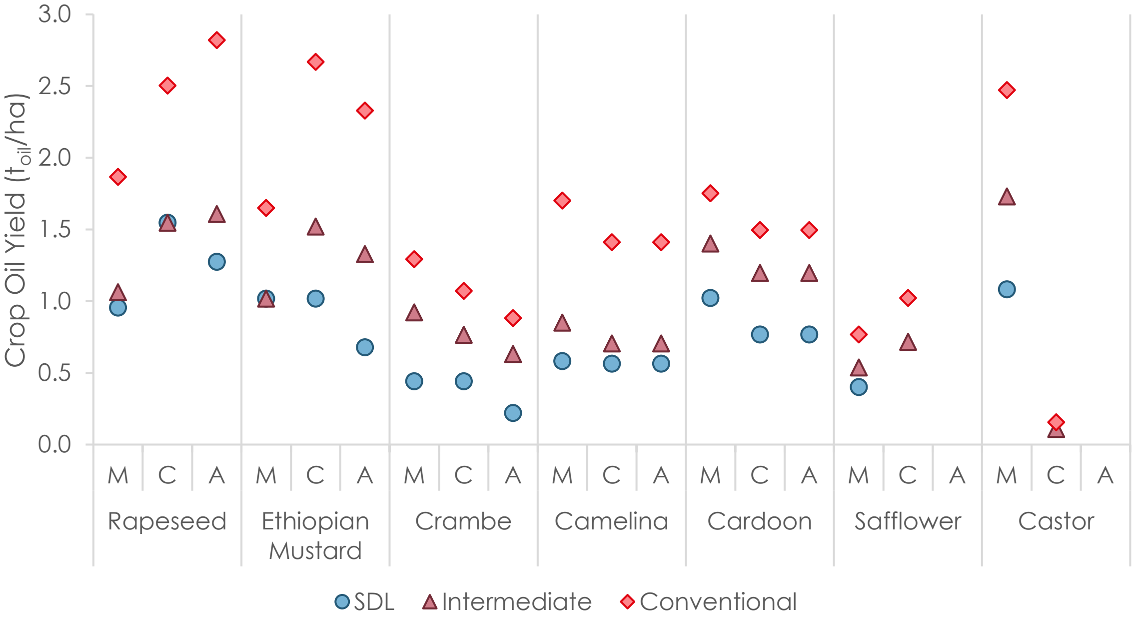

Figure 2 Indicative yield potential for crop oil in three European climatic zones (Mediterranean, Continental, Atlantic); markers indicate yields for SDL[22], intermediate, and main crops

Source: Derived from Panoutsou et al. (2022) and the sources listed in Appendix B.1.

Another important point to recognise is that intermediate crops fitting into existing rotations may not be planted every year. Cropping sequences may span several seasons before the cycle repeats, employing early- and late-sowing varieties, alternation of crop types to disrupt pest and disease proliferation, and fallow years to restore soil health. As an example, a Uruguayan project growing Brassica in rotation with soybeans and wheat took three years to complete each cycle (Ibrahim et al., 2024)[23]; various EU rotations put forward for producing cereal and grass energy crops have two- to four-year cycles (Primmer et al., 2025). A hypothetical intermediate crop which yields 3 t/ha of oilseed every three years will only yield 1 t/ha/year on average across the whole area adopting the practice.

2.4. Climate change pressures

2.4.1. Crop productivity and range

A crop's yield performance in a given location and climate is influenced by the interplay

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[22] The original source considers crops grown on 'marginal' land; for consistency with the rest of this report we have used the term 'SDL'.

[23] Note that, while this cropping system was certified as qualifying as an intermediate crop under the RED definition, it may not qualify as an Annex-IX-compliant 'intermediate feedstock' because the region can generally sustain two harvest seasons per year.

of environmental factors such as irradiance, temperature, CO_2 concentration, and water availability[24], and by the presence of pollutants like tropospheric ozone (Nowroz et al., 2024; Roberts et al., 2022) and plant pests and diseases (Yan et al., 2017). Climate change may in some contexts lead to reductions in cloud cover and more favourable temperatures; in tandem with elevated CO_2 concentrations, this can boost productivity, especially in higher-latitude regions of Canada, Russia, and northern China (Caparas et al., 2021; Hultgren et al., 2025; Rosenzweig et al., 2014). Wrapped up in these findings is a shift in the geographical limits of crop suitability. Delayed frosts and diminished snow/ice cover over winter may allow for a longer (or even an additional) growing season in some locations (Peltonen-Sainio et al., 2009): for example, van Eupen et al. (2025) concluded that the area of 'marginal' EU+UK land where growing crops is difficult would diminish by about 63 kha between 2020 and 2050[25].

Elsewhere, changing rainfall and temperature patterns will render some regions climatically inappropriate for even conventionally-cultivated crop types (Redhead et al., 2025; Rising & Devineni, 2020). The IPCC reports that changing temperature and rainfall conditions have already stimulated substantial global productivity losses for certain crops versus a stable-climate counterfactual (Mbow et al., 2019). Further such impacts are expected by mid-century both within the EU (as stated in the Hristov et al. (2020) report for the EU Joint Research Centre (JRC)), and globally (Hultgren et al., 2025; Li et al., 2025). Climate-elevated ozone concentrations are also expected to impair crop growth (Guarin et al., 2024; Lobell & Asseng, 2017); and even the positive impact of CO_2 fertilisation has been observed to follow a declining trend (S. Wang et al., 2020). Models of agricultural adaption – which include, for instance, developing drought- and pest-tolerant crop varieties – indicate that these losses could be partially mitigated (Hasegawa et al., 2022; Hultgren et al., 2025); though there is evidence that the flexibility to supply such measures might be limited in the highly optimised systems that are critical for global markets (Burke & Emerick, 2016; Hultgren et al., 2025).

Environmental conditions can affect crop growth and the prevalence of pests and diseases in abrupt, non-linear ways. Maize, soybean, barley, wheat, and cotton yields have been found to increase with average temperature up to a certain threshold before dropping steeply (Schlenker & Roberts, 2009; Schmidt & Felsche, 2024). Fluctuations and unpredictability brought on by climate change – for instance, the timing and severity of droughts, the number of days of excess rainfall, or minimum viable pollinator populations – may push crops beyond their physiological limits. Crop failures in key global export countries are projected to be far more likely in 2050 or even 2030 than they have been in the recent past (Caparas et al., 2021)[26]. A study for the European Commission considered a pessimistic scenario where average-crop

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[24] Responses to these factors depend to some extent on plant physiology. For plants with a 'C3' metabolism, e.g. wheat and rice, rising CO_2 concentrations would tend to boost productivity, while 'C4' plants like maize and sugarcane already operate close to maximum CO_2 efficiency (Jägermeyr et al., 2021; Opoku et al., 2024). On the other hand, 'C3' plants tend to exhibit higher sensitivity to drought and high temperatures.

[25] This overall effect will be very differently felt in different regions of the EU: in the same timeframe, the Mediterranean was projected to experience a 340 kha increase in marginal land. European Environment Agency (2017) map the anticipated future climate trends affecting Europe.

[26] Simultaneous or even single failures could severely disrupt global food supply (Gupta, 2023; Mbow et al., 2019), exacerbating the tension between biofuel feedstock supply and food and feed markets (cf. Malins, 2023).

yields in the Mediterranean dropped by as much as 20% by 2050, with an increase of 10% for boreal and nemoral regions (DG RTD & Wageningen University & Research, 2024)[27].

The implications for intermediate and SDL feedstock production could be bleak. Compressed and fluctuating start/end dates of cultivation windows will almost certainly reduce the scope to grow crops in the off-season. For intermediate and SDL feedstocks to comply with the regulatory criteria, they would have to be grown on land where delivery of economically viable yields of main or of second crops is already challenging; overall, climate change is set to nudge this towards impossible.

2.4.2. Land classification

As well as affecting crop productivity and viable ranges, climate change may shift the land boundaries considered eligible for Annex IX crops. For 'intermediate feedstock', the pool of land where only one food and feed crop harvest is viable could expand or contract as mentioned above, in ways that are (potentially) detached from how the Annex IX double-harvest criterion will be assessed in practice. While Brazil's annual soybean-and-safrinha-maize rotation does not produce intermediate crops in the additional RED sense (as it is already serving mainstream markets (Malins, 2022)), it is an extremely successful model of secondary cropping and provides a useful model for studying the potential climate implications on putative intermediate feedstocks. Bigolin & Talamini (2024) and da Silva Andrea et al. (2020) both point out that incremental delays to soybean harvest dates under future climate scenarios will delay sowing of the maize crop; and that after a point the latter would cease to be viable.

Changing weather patterns will also alter the pool of land qualifying as severely degraded. Droughts weaken soil structure and make it vulnerable to erosion, while more vigorous rainfall and wind can have an amplified effect on erosion rates[28]. Studies at both the global (e.g. Borrelli et al., 2020; D. Yang et al., 2003) and local (e.g. Klik & Eitzinger, 2010; Mondal et al., 2016) scales point to accelerating erosion trends in future. SOC content, while highly dependent on land use, vegetation, and agricultural practices, will also be affected by weather patterns (Lal, 2012): modelled SOC content in 2050 under different climate trajectories found significant changes strongly correlated to geography (Yigini & Panagos, 2016). Salinity of agricultural soils is also expected to increase in coastal areas through sea-level rise and salt-water inundation (Corwin, 2021; Mukhopadhyay et al., 2021; Teh & Hock, 2016), as well as in inland areas experiencing reduced precipitation and aridity (Eswar et al., 2021; Hassani et al., 2021; Okur & Örçen, 2020).

2.5. Biofuel lifecycle emissions

Under the RED III, biofuels must deliver a minimum 50%, 60%, or 65% saving in their biofuels' lifecycle greenhouse gas emissions, depending on when the relevant biorefinery became

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[27] The central scenario considered a 10% decrease in the Mediterranean and a 15% increase in boreal and nemoral regions.

[28] For instance, a 1% rainfall increase has been associated with a soil erosion rate increase of 1.7-1.8% (Nearing et al., 2004; Shrikaant Kulkarni, 2021).

operational[29]. The lifecycle analysis (LCA) for oilseed biofuels can be split into the major stages of crop cultivation, processing, and transport. Of these, the largest contribution for biofuels grown on agricultural land generally comes from crop cultivation, and these are in turn dominated by nitrogen fertiliser (which is energy-intensive to produce and generates nitrous oxide when it is spread on fields). Farmers already endeavour to optimise the financial cost of chemical inputs against the incremental yield boost, for instance by considering yield response curves (e.g. Malhi et al., 2014); growers of biofuel feedstock must in addition be attentive to the minimisation of fertiliser *emissions* per unit yield. In this section we illustrate this for low- and high-input cases of an intermediate feedstock and an SDL feedstock.

2.5.1. *Lifecycle analysis for intermediate-feedstock biofuel*

Figure 3 shows the results of an illustrative LCA for an intermediate-oilseed-feedstock-based biofuel, using the BioGrace-I spreadsheet tool[30] and with emissions allocated to the co-products by energy content (in line with RED methodology). Agricultural inputs and crop yields are drawn from a study which considered winter camelina cultivation to complement summer maize or soybean in the USA (Gregg et al., 2022). In one case, no additional nitrogen fertiliser was used for the camelina; in the other, yields were almost doubled through additional fertiliser use. We assume that the downstream stages of conversion to and transport of biofuel are common to both fuel production pathways[31]. Numerical parameters are tabulated in Appendix B.2; inputs not listed use the default BioGrace configuration.

The ‘zero nitrogen’ case in Figure 3 satisfies the RED threshold, while the ‘with nitrogen’ case, drawn from the same study does not. This resonates with the conclusion in Berti et al. (2025) that biofuels made from intermediate crops like camelina may fail to offer the greenhouse gas reductions that are often assumed in the wider policy and industry literature. Some cropping systems and locations will of course be more successful than others: for instance Pari et al. (2024) report similar yields to our ‘with nitrogen’ case, but with only two-thirds of the nitrogen use and minimal other inputs. This delivers a boosted 49% saving compared to the fossil comparator: almost enough to achieve RED compliance if supplying a biofuel facility that was operational by 2015.

The ‘zero nitrogen’ case reflects camelina seed yields of 0.7-0.8 t/ha/year (Gregg et al., 2022): likely too low to be profitable for farmers[32] (cf. Sessa et al., 2025). Taken together, it becomes clear that farmers will have to strike a careful balance in their selection of crop varieties and development of agricultural practices: capitalising on available nitrogen to produce an economically-viable yield (cf. Veeramani et al., 2023), while minimising their cultivation emissions. There may be many locations in which it is not possible to deliver an economically viable yield while meeting the RED emission threshold. RED compliance may also depend on

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[29] The threshold is 50% for biorefineries starting operation before October 2015, 60% between October 2015 and the end of 2020, and 65% from 2021 onwards. We would expect that all else being equal, if a given feedstock is likely to push the finished biofuel close to one of the thresholds, it will be preferentially used in an older biorefinery in order to ensure compliance.

[30] Version 4d (Institut für Energie- und Umweltforschung, 2015). We updated relevant standard parameters following to align to RED II/III following Padella et al. (2019).

[31] This may not be totally realistic, as production systems that achieve greater spatial density would generally imply lesser transport emissions, and the chemical portfolio of different crop oils will influence the conversion technology steps. But it is a perfectly sound first approximation.

[32] Though of course this depends on the market value signal for Annex IX biofuels.

the ability of downstream biofuel producers to minimise process emissions, for instance by using renewable electricity and heating, or by investing in higher-efficiency technologies.

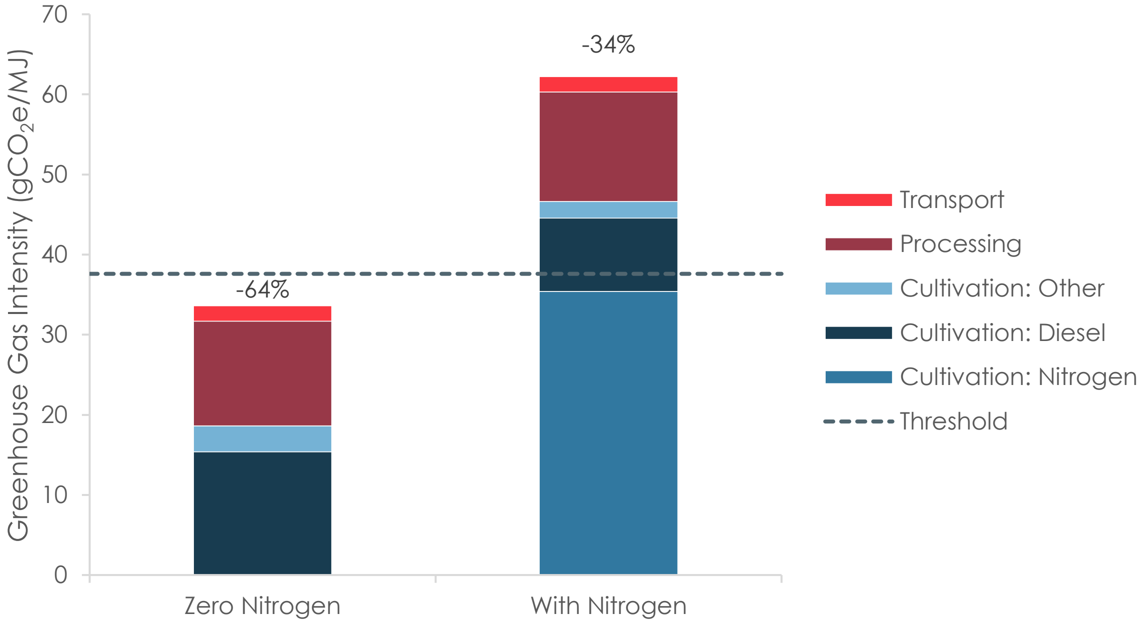

Figure 3 Illustrative LCA results for HEFA made from a camelina intermediate feedstock, considering a lower-input and a higher-input case, and indicating the percentage emissions reduction compared to the fossil fuel comparator

Note: The threshold shown is a 60% reduction against the fossil comparator (94 gCO_2e/MJ). ILUC is not considered.

A final observation that emerges from this illustration is that a moderate rate of nitrogen application could improve yields (and hence economics) above those of the ‘zero nitrogen’ case while preserving the feedstock’s ability to meet the regulatory thresholds. It is likely that the absolute emissions reductions achievable per area of land would also improve, even if the lifecycle emissions intensity (i.e. emissions per unit of finished fuel) was slightly worse.

2.5.2. Indirect land-use change

Any LCA methodology comes with omissions and assumptions (Malins & Sandford, 2023). A key issue for crop-based feedstocks is indirect land-use change (ILUC): in the present context, introducing a new productive intermediate crop into an existing rotation may harm the yields of the main crops (EWABA, 2025), so that expansion and/or intensification of agricultural activity around the world may be needed to maintain the feedstock supply to other users (Section 2.2). However, the additional emissions thus incurred are difficult to confidently quantify.

A judicious choice of intermediate crop that complements rather than competes with the main crop's growing cycle can vastly reduce ILUC risk[33]; but as farmer experience and the development of fast-growing oilseed varieties are both nascent, the opportunity of a bullish feedstock market may incentivise farmers to make trade-offs with main crop yields. Some early research and commercial trials have reported main-crop yield impacts: for example in studies of camelina as an intermediate crop, Patel et al. (2021) found a 13-42% reduction in main-crop soybean yield; Gesch & Archer (2013) similarly reported respectively 18% and 28% drop in soybean and sunflower yields, and Pari et al. (2024) quote a 28% sunflower seed yield drop along with a 13% drop in sunflower oil content; Potter et al. (2023) assumed that camelina would reduce a following pea crop by 25% compared to a fallow base case; and reductions in main wheat yields have been put at 13-15% (Chen et al., 2015; Obeng et al., 2024).

The study used in the Figure 3 analysis did not report impacts on the main crop. However, considering for illustrative purposes the case of a rotation of camelina that caused just a 5% reduction on the yield of the main crop, factors from GLOBIOM ILUC modelling (Biggs et al., 2016) imply that this would lead to an additional 9.1, 5.9, and 10.4 gCO_2e/MJ emission for HEFA when the main crop is spring wheat[34], maize, or soybean respectively.

2.5.3. *Lifecycle analysis for SDL-feedstock biofuel*

The lifecycle analysis of crops grown on severely degraded land that is not currently under agricultural production (e.g. grassland or scrubland) includes all the lifecycle stages mentioned above; it may also be required to include a direct land-use change (DLUC) term, arising from the clearance of vegetation and from ploughing up soil[35]. The magnitude of these emissions means that any biofuel feedstock produced on converted non-agricultural land will struggle to meet the emissions threshold (Guidehouse, 2024). The RED LCA methodology provides a partial counter-balance to this in the form of a 'bonus' of 29 gCO_2e/MJ for crops grown on severely degraded land[36]. This bonus term is only available "provided that a steady increase in carbon stocks as well as a sizable reduction in erosion phenomena … are ensured", but it is unclear how this conditionality is to be assessed, and in which cases the real benefits from SOC increase would justify the size of the bonus. Historically the biofuel volumes employing this provision have been negligible (Eurostat, 2025b), but this could change with the Annex IX additions.

Calcagno et al. (2023) investigated the response of single-crop castor bean to different irrigation and fertilisation regimes in the semi-arid Mediterranean. These results are the basis of the illustrative LCA shown in Figure 4[37]. As in Section 2.5.1, we find that feedstock that complies

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[33] E.g. Moore et al. (2020) found no reduction in main crop maize yields after introduction of a camelina intermediate.

[34] Wheat is the principal crop grown in Europe and would be agriculturally sensible to rotate with an oilseed (Heller et al., 2024; Royo-Esnal & Valencia-Gredilla, 2018a).

[35] For intermediate crops, the land is already agricultural and so there is no DLUC.

[36] To be eligible for the bonus, land must not only be classed as severely degraded, but also demonstrate that it was not in use for agriculture in January 2008. This criterion may originally have been intended to exclude agriculturally productive land, but its fitness for this purpose in 2025 is debatable (Guidehouse, 2024).

[37] Note that though castor meal is typically used as fertiliser rather than animal feed, the RED LCA methodology still requires emissions allocation by energy content.

with the Annex IX conditions may nevertheless struggle to meet the RED emissions threshold: in this case, the production model with nitrogen fertilisation would just barely deliver a 50% reportable emission reduction, if no DLUC emissions were included.

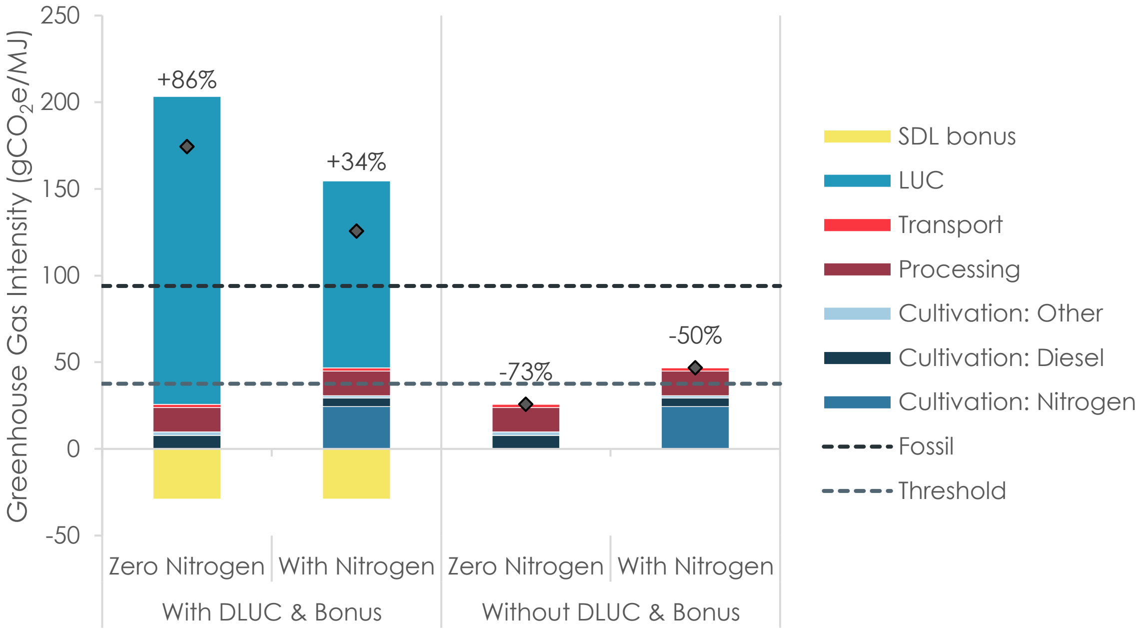

Figure 4 Illustrative LCA results for HEFA made from castor grown on severely degraded land, considering a lower-input and a higher-input case, with and without land-use change, and indicating the percentage net emissions reduction compared to the fossil fuel comparator

Note: The threshold shown is a 60% reduction against the fossil comparator (94 gCO$_2$e/MJ). ILUC is not considered.

The left-hand side of Figure 4 provides a hypothetical illustration of the land-use change emissions that would have to be added to the LCA if the land were converted from ‘scrubland’ status. Following the RED rules and default factors (European Commission, 2010), clearing and ploughing this land causes the biofuels’ emissions to far surpass those of the fossil fuels they seek to replace – even with the RED bonus[38]. Note that, since land-conversion emissions are to be spread over 20 years’ worth of crop production, we see that the higher-yielding system that uses more fertiliser reports a lower DLUC impact per MJ of biofuel. The severely degraded land bonus on the other hand has a fixed value per MJ of biofuel production.

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[38] Direct LUC emissions are calculated as the vegetation and soil carbon stock for the final land use minus those for the original land use, amortised over 20 years. The calculation uses standard factors. For instance, for warm and dry temperate areas, high-activity soils set to 38 tC/ha. Above-ground vegetation for subtropical European scrubland is 37 tC/ha, whereas for agricultural land it is set to 0 tC/ha.

3. Potential production volume

3.1. Feedstock demand

Meeting the ReFuelEU Aviation and FuelEU Maritime regulatory targets will require the supply of rapidly increasing volumes of alternative fuel. The ReFuelEU Aviation quotas are readily translatable into vegetable oil demand – Table 3 shows these as percentages and as absolute fuel volumes, and calculates the equivalent vegetable oil required to meet the entirety of the implied biojet demand with HEFA[39]. In 2030, nearly 3 Mt of vegetable oil would be needed; by 2050 the figure is 19 Mt.

Table 3 ReFuelEU Aviation targets and fuel demand

Quantity	Unit	2025	2030	2035	2040	2045	2050
Alternative fuel target	%	2%	6%	20%	34%	42%	70%
RFNBO target[40]	%	0.0%	0.7%	5.0%	10.0%	15.0%	35.0%
Alternative fuel demand	ktoe	914	2,755	9,193	15,752	19,641	31,936
RFNBO demand	ktoe	0	321	2,298	4,633	7,015	15,968
Biojet demand	ktoe	914	2,434	6,895	11,119	12,626	15,968
Equivalent as vegetable oil	**Mt**	**1.1**	**2.9**	**8.2**	**13.2**	**15.0**	**19.0**

Note: Using the aviation fuel demand from scenario A2 of the ReFuelEU Aviation impact analysis (Giannelos et al., 2021). Assumes that all non-RFNBO alternative fuel demand will be met with HEFA.

For shipping, FuelEU Maritime is an emissions intensity standard rather than an alternative fuel quota: this means deriving vegetable oil demand is more complicated. Satisfying the target depends on the emissions intensity of the mix of maritime fuels used, as well as the deployment of wind-propulsion systems[41]. Four technology adoption scenarios were considered in Phillips et al. (2024), taking into account fuel properties, engine efficiencies, industrial scale-up timelines, and the availability of feedstocks such as biomass crops and used cooking oil. The study concluded that there will be considerable demand for Annex-IX-compliant oilseeds – indeed that it would stretch credulity to satisfy FuelEU Maritime targets without a mammoth

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[39] Any volumes of cellulosic, recycled carbon, and other non-food-and-feed biojet would alleviate this pressure on vegetable oil. For instance, Sandford & Malins (2025b) argued that up to 400 ktoe of aviation fuel could plausibly be derived from cellulosic biomass in 2030, subject to rapid capacity deployment.

[40] RFNBO stands for ‘renewable fuel of non-biological origin’: in this context meaning electro-jet fuel. For 2030, we have assumed the minimum RFNBO contribution permitted under ReFuelEU Aviation; the average contribution over the 2030-31 period must be at least 1.2%.

[41] These would reduce the demand for fuel in general, and FuelEU Maritime also includes reward factors that reduce the emissions intensity target for ships with wind propulsion installed.

shift in agriculture towards the production of these crops. In 2050, demand for Annex IX crop oil reaches 11.3-21.6 Mt/year depending on the scenario, requiring 15-20 Mha of land[42].

Putting these numbers in perspective, DG RTD et al. (2024) estimated that in a feedstock-constrained future, production of lipid-based Annex IX Part B biofuels could rise from 3.1 Mtoe/year (megatonnes of oil-equivalent per year) in 2023 to reach 5.9 Mtoe/year in 2030 and 11.0 Mtoe/year in 2050; this would represent, at best, a third of expected aviation and maritime demand. The DG RTD et al., figures include the contribution of residual lipids (used cooking oil and low-grade animal fat); but since these feedstocks are already highly utilised (IEA, 2022), the modelled expansion would have to be driven by Annex-IX-compliant crops.

3.2. Land area mapping for the EU

While the suitability of each candidate oilseed in different agri-environmental zones can be assessed by extrapolating the results of smaller-scale field trials, quantifying – even approximately – the area of land which could or would realistically be made available for these crops is difficult. In the following analysis we produce such an estimate, using existing maps and data in combination with our interpretations of the Annex IX eligibility criteria.

We begin by considering the potential for growing Annex IX intermediate crops (Section 3.2.1), and then consider each component of severely degraded land (Sections 3.2.2-3.2.3, recognising that in practice severely degraded status must be assessed by certification bodies on a project-by-project basis), and the composite total (Section 3.2.4). The eligibility of severely degraded land that is currently under arable cultivation is addressed (Section 3.2.5).

3.2.1. Intermediate crops

As a starting point to investigate the viability of intermediate cropping, we can look to which areas in Europe already sustain a cover crop. EU legislation (Commission Implementing Regulation 2018/1874, 2018; Regulation (EU) 2018/1091, 2021) requires Member States to gather and submit data on the agricultural holdings within their territories to the Farm Structure Survey (Eurostat, 2024). Farmers and land-owners are periodically surveyed on land cover over the winter season (soil erosion peaks in the rainy winter in much of Europe, hence the focus on this season). The land area identified as hosting cover crops over winter came to 7.1 Mha (Eurostat, 2025a). Combining these NUTS-2 data[43] with satellite images and statistical modelling at the higher spatial resolution of 1 ha (Fendrich et al., 2023b), the total cover-cropped area rises to 13.1 Mha[44].

The data on current cover cropping indicates an area where growing an off-season (albeit unproductive) crop is biophysically viable and is a practice that has been accepted and adopted by farmers. Moreover, soil cover over winter is one of the criteria for availing CAP subsidies and cover crops are anyway associated with agricultural benefits; hence, farmers

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[42] The land figure is based on previous estimate by the authors (Phillips et al., 2024), assuming a preponderance of 'intermediate feedstock' with on average a two-year cropping cycle.

[43] NUTS is the EU's Nomenclature of Territorial Units for Statistics; NUTS-2 indicates a sub-national region.

[44] The discrepancy between this dataset and Eurostat is acknowledged by the authors (see Appendix C.2); for this study we proceed using the second higher-resolution dataset, with the caveat that both datasets are subject to uncertainties.

who can't grow a winter crop have an incentive to grow a cover crop, unless seasonal conditions (e.g. snow) prevent it, or it is acceptable to leave main crop residues on their fields rather than gathering them for straw etc.

There is still a chance that the current cover crop dataset fails to identify areas where winter intermediate cropping could be practised in future. And in the hotter and drier parts of the EU, the off-season will be summer rather than winter and these areas will not be reflected in the dataset. Conversely, there will be areas where a non-productive cover crop is currently grown but where a productive intermediate crop would not be viable. The results of this sub-section should therefore be thought of as establishing an indication of the potential growing area rather than a technical potential as such.

In order to be relevant for intermediate oilseeds, the area identified should be screened for water availability, sufficient growing period, and appropriate off-season temperatures for crop maturation. A number of research efforts have been directed at mapping areas where conditions are favourable for off-season crops (e.g. MAGIC, 2023; van Eupen et al., 2025). Modelling by Heller et al. (2024) found that 54% of arable land in Europe could sustain productive intermediate crops; in the present study, we count only those areas of existing cover cropping that overlap with areas categorised as 'suitable'. The result is that about 7.1 Mha of EU land could potentially be used for intermediate feedstock production (see Appendix C.5 for the country break-down). Other biophysical and socioeconomic constraints will further diminish the plausible potential area; these will be reflected in the feedstock production estimation in Section 3.3.

It will inevitably take some time for new practices to be adopted. Since summer crop varieties already exist for hotter climates, Hamelinck et al. (2025) argues that faster adoption may be foreseen in southern Europe, while in northern Europe suitable varieties may take longer to develop. This constrains the degree to which Annex IX feedstocks could contribute to near-term renewable fuel targets.

3.2.2. Severely degraded land – erosion and organic carbon depletion

Recalling that the erosion and organic carbon depletion conditions must both be satisfied for land to be considered severely degraded, this subsection treats them in turn. Appendix C.5 presents the total eroded + SOC-depleted land areas by EU country. Several studies have examined the availability of 'marginal' land within the EU, for example reporting 38 to 54 Mha in the EU+UK (Gerwin et al., 2018; Von Cossel et al., 2020). The MAGIC project (MAGIC, 2023), which aimed to help farmers decide which industrial crops are suitable for different respective marginal locations, found that 29% of the agricultural land in the EU+UK could be considered marginal.

3.2.2.1. Eroded soil

Erosion is challenging to measure at scale. The Revised Universal Soil Loss Equation (RUSLE) is an empirical model that predicts soil erosion rates (in tonnes of soil lost per hectare per year) based on estimates of local and regional soil erodibility, rainfall erosivity, topography, land cover, and conservation practices (JRC, 2022). Commonly used thresholds are 5 t/ha/year for moderate erosion and 10 t/ha/year for severe erosion[45]. Panagos et al. (2015) estimated that 5.2% of the EU's cropland suffers from severe erosion, with around 1.5% experiencing soil loss of over 20 t/ha/year. The Netherlands and Denmark experienced the lowest rates on average (0.54 and 0.61 t/ha/year respectively), while Malta and Italy experienced the highest (15.93 and 8.38 t/ha/year). Panagos et al. (2018) revised the EU's severely eroding area to 7.2% (just over 12 Mha) and connected this to lost crop productivity in each region, with Slovenia and Italy experiencing the greatest such losses (3.28% and 2.64% of yield respectively).

Along similar lines, Borrelli et al. (2023b) produced a RUSLE-based map of European arable land at 1 ha resolution. Applying the threshold of 10 t/ha/year to their data leaves an area of around 13.8 Mha that is undergoing severe erosion. Because this dataset only covers arable land, it will miss other agricultural and non-agricultural areas that could be converted to crop production. This can therefore be regarded as a conservative estimate.

3.2.2.2. Depleted organic carbon

Modelling of SOC pools in the top 20-30 cm of agricultural soils in the EU has estimated a stock of 9.3-17.6 GtC (De Rosa et al., 2024; Lugato, Panagos, et al., 2014). A range of mechanisms has tended to deplete this over time: one estimate puts the rate at 0.75% over the period 2009-18 (De Rosa et al., 2024), with greatest loss rates observed in Austria and Slovenia. Topsoil erosion is a primary channel for such depletion (Yoon et al., 2025); others include tillage (which disrupts soil aggregates and leads to carbon oxidation) and lack of replenishment of organic material through over-grazing and removal of crop residues.

Determining when an agricultural soil should be considered 'low' in SOC is non-trivial and subjective, as it depends on soil type and climate, as well as what the farmer is trying to grow. Three low-SOC indicators, constructed at large spatial scale and incorporating contextual information, are discussed in Appendix C.3. A simpler option, albeit one that fails to capture this complexity (cf. Feeney et al., 2024a), is to consider a single uniform threshold for soil SOC content: this has been advocated by some stakeholders, and it is certainly possible that the European Commission and certification schemes will take this approach. Setting an appropriate level for the threshold then becomes a delicate issue; Elbersen, Verzandvoort, et al. (2022) and Guidehouse (2024), among others, consider a uniform threshold of 0.5% organic carbon (by mass) across EU topsoil (note that this may be less appropriate for soils in other regions like the tropics).

For this study, we used a European soil database developed for the European Commission Joint Research Centre at 1 km^2 resolution (Hiederer, 2013) alongside the 0.5% threshold. The dataset includes swaths of non-agricultural land (roads, urban areas, mountains, forests), which we excluded using a GIS layer derived from the CORINE Land Cover (CLC) survey (European Environment Agency, 2020)[46]. The final low-SOC area comes to 7.0 Mha.

Performing the same analysis with a 1.0% threshold, the total land area rises an order of magnitude to 88.4 Mha, implying considerable sensitivity to the threshold. The comparison by EU country is shown in Figure 5.

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[45] OECD uses a threshold of 11 t/ha/year (cf. Ballabio et al., 2017).

[46] The CLC has 100 m resolution; the comparative coarseness of the SOC dataset introduces uncertainty into the final result, but is fine for an indicative estimate.

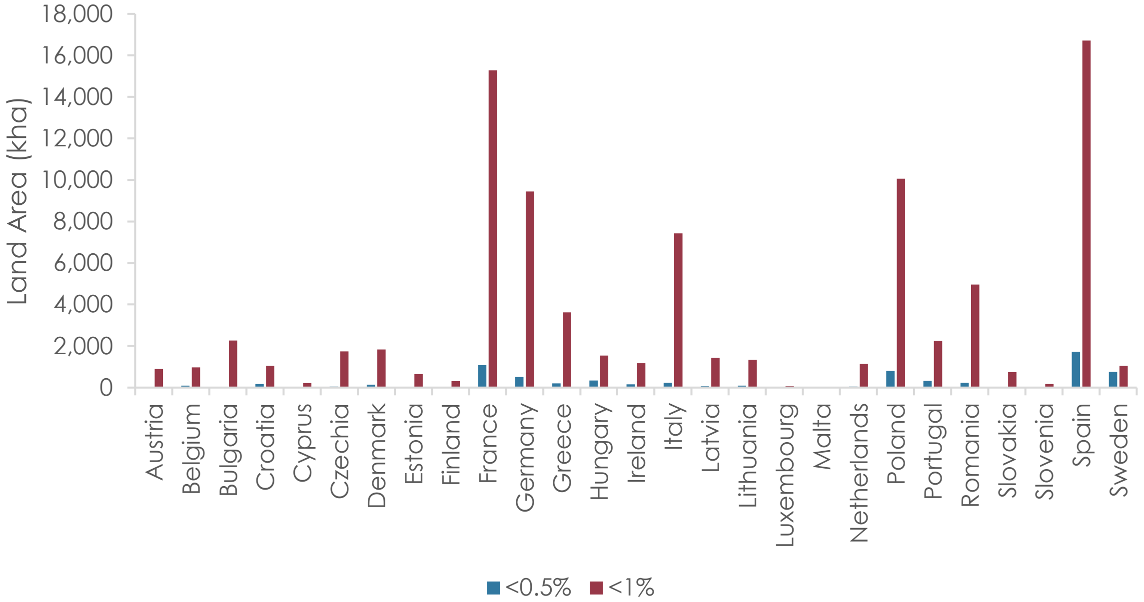

Figure 5 **EU land area classified as 'low SOC' under a 0.5% and a 1.0% threshold**

3.2.2.3. Intersection of eroded and depleted organic carbon soils

While the estimated area of eroded soils is 13.8 Mha and the estimated area of depleted organic carbon soils is 7.0 Mha, only the intersection of these areas would be eligible to produce SDL feedstocks under the RED rules. This intersection is a much smaller area – only 430 kha. It is possible that in cross-referencing the data products used to estimate the eroded and depletedorganiccarbon areas, some information has been lost due to the different spatial resolutions – the erosion data is at hectare resolution, whereas the organic carbon data is at km^2 resolution. Any correlations within those km^2 areas between eroding and low-SOC areas would be lost from our aggregate estimate. Equally, for a km^2 pixel with average soil carbon close to a threshold value, part of that km^2 area might be above the threshold and therefore not qualify for SDL feedstock production if directly assessed. These results must therefore be understood as providing an indication of the likely scale of the opportunity, but not as an exact or final assessment.

3.2.3. Severely degraded land – saline soil

Salination from human activities is thought to affect 3.8 Mha in the EU, and is identified among the major threats to soil health (albeit some way down the priority list) (European Commission, 2021a). Salination is particularly problematic in agricultural areas using heavy irrigation, where roads are de-iced using salt, where soils are inadequately drained for extended periods, and in dry climates where salt compounds are not flushed out by rainwater. The impacts differ by crop type, and in some cases may only be evident in drier years; but generally, salinity leads to water stress, slower growth, lower yields, and vulnerability to pests and diseases.

Depending on the portfolio of salts it harbours, a soil may be classed as saline or sodic;

these may have different levels of impact on a given crop (Tóth, Montanarella, et al., 2008). Measurement of salinity and sodicity requires different measurement protocols: salinity arises from water-soluble salts and can be measured using fairly straightforward electroconductivity tests, while sodic compounds tend to exist in solid-phase complexes where they flood the soil cation reservoir with sodium ions.

Using the dataset compiled described in a report for the JRC (Tóth, 2008; Tóth, Adhikari, et al., 2008b), in conjunction with the CLC agricultural land layer, we produced a rough map of saline and sodic agricultural land in the EU. As discussed in Appendix C.4, the resolution of the underlying data is low, and it is necessary to introduce arbitrary factors to arrive at a useable result: thus this analysis should be treated as having high uncertainty. Our estimate for the salt-affected area in the EU is 2.5 Mha; some countries have smaller more localised areas of more concentrated salinity, while others (such as Spain) have expanses of more distributed salinity; see Appendix C.4.

3.2.4. *Total severely degraded land*

Figure 6 unites the contribution of severe erosion + low SOC (assuming a 0.5% threshold) with the contribution of salinity to derive an estimated 2.9 Mha of severely degraded in the EU. According to the definitions used in this study, the majority of land identified as severely degraded is in the saline category[47].

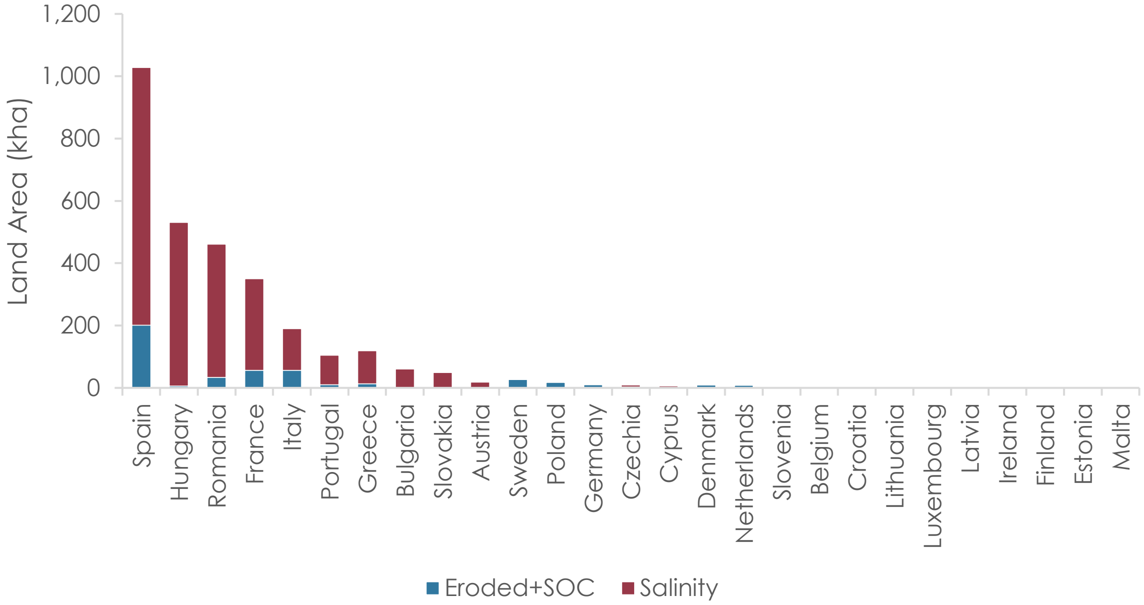

Figure 6 Severely degraded land area in EU Member States

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[47] For comparison, an analysis for the European Commission estimated that a degraded land area of 1.5-6.4 Mha could be made available for production (DG RTD & Wageningen University & Research, 2024). The definition of 'degraded' in that study was based on the Sustainable Development Goal (SDG) framework, which considers soil carbon levels in combination with productivity and land cover indicators and may not be confined to agricultural land (Trends.Earth, 2025; Von Cossel et al., 2019).

The composite map of Europe is shown in Figure 7, visualising the severely degraded land distribution alongside the areas identified as candidates for intermediate feedstock production in Section 3.2.1.

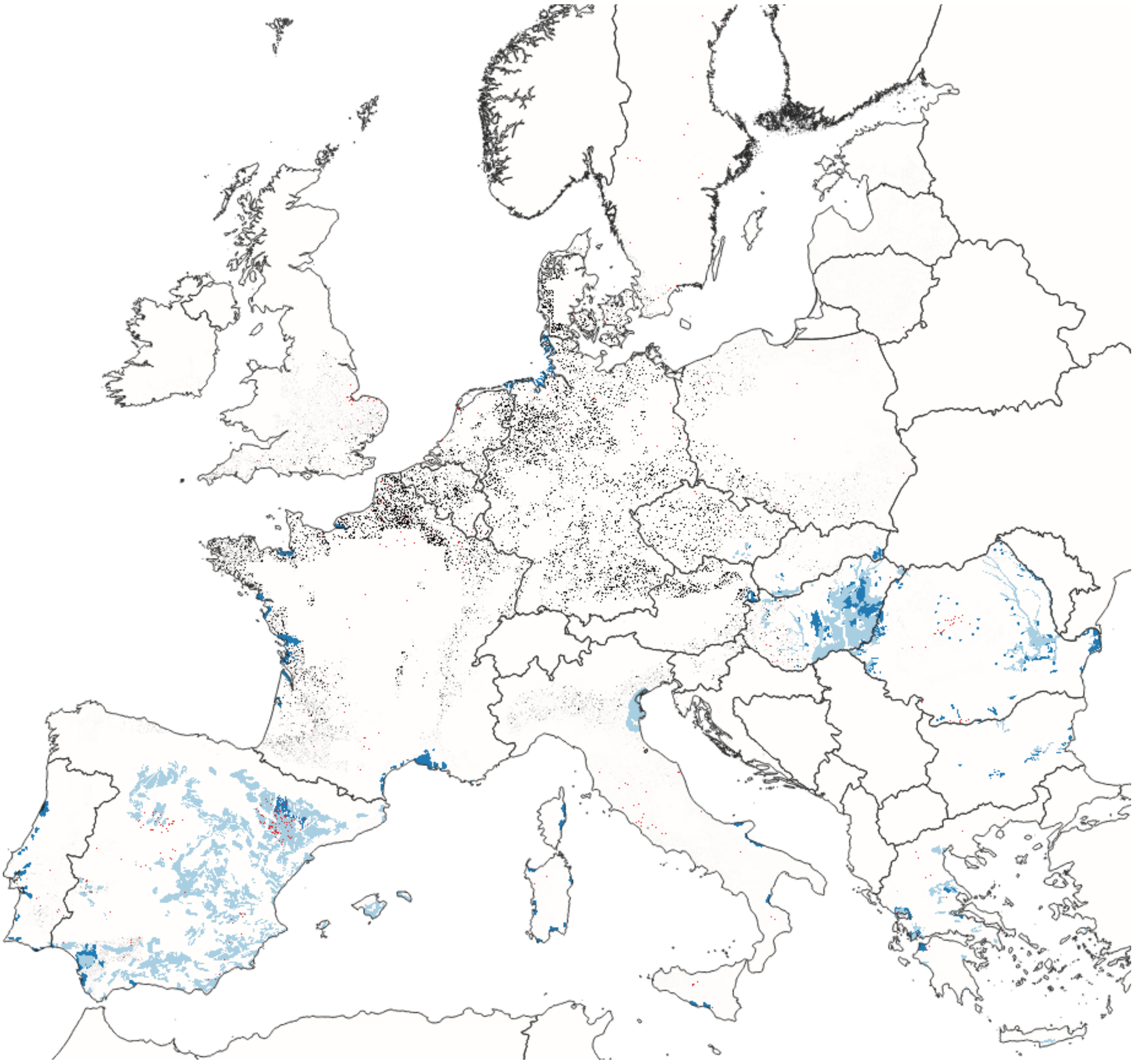

Figure 7 Map of Europe at 100 m resolution, showing cover cropping intensity in areas potentially viable for productive intermediate crops (shades of black), eroded + low SOC (red), low salinity intensity (light blue), and high salinity intensity (blue)

Note: Low and high salinity intensity refer to the proportion of land in each grid pixel that is salinated; see Appendix C.4.

3.2.5. Severely degraded yet productive land

Though the land in Figure 6 has been identified as 'severely degraded' according to our adopted definitions, some of it may nevertheless be agriculturally productive under current economic conditions (i.e. without the extra incentive of biofuels policy). In this case, material sourced from those areas would be diverted from existing markets and lead to indirect emissions such as ILUC (Section 2.2).

Elbersen, Verzandvoort, et al. (2022) quotes the result that 29% of EU agricultural land (according to the CLC classification) is designated as ANC; and though the primary constraints identified by Elbersen, Verzandvoort, et al. (2022) (viz. poor rooting conditions, adverse climate, excessive soil moisture) are not the same as the severely degraded land conditions, it is noteworthy that crops continue to be grown in these adverse conditions. For example, the productivity loss from soil erosion may be limited in the short term (Panagos et al., 2018); indeed, though we have adopted a 10 t/ha/year threshold for severe erosion (following the JRC), the United States Department of Agriculture has long considered levels below 12 t/ha/year as acceptable for maintaining crop productivity (Montgomery, 2007).

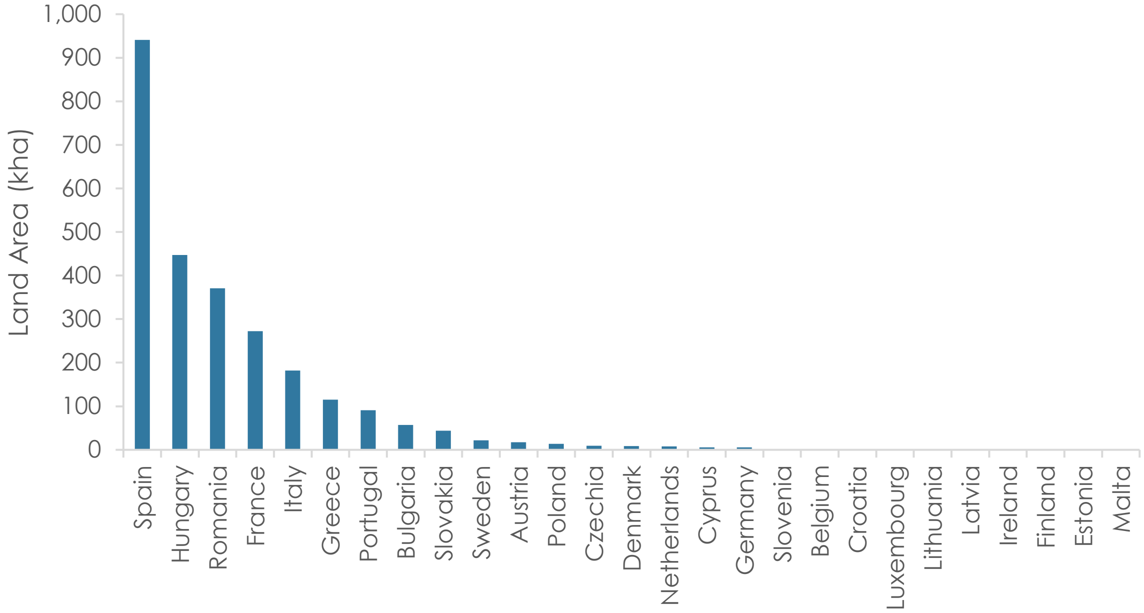

Figure 8 Cropland area identified as severely degraded land in this study, by EU Member State

From Figure 8 we see that, all told, 2.6 Mha of the land we identify as severely degraded (i.e. 90%) is classified as some form of cropland by the CLC[48]. It is debatable whether incentivising the diversion of whatever production this currently sustains to the biofuels industry is consistent with the European Commission's intention in adding feedstock from severely degraded land to Part A of Annex IX. At the same time, it is likely that some of the CLC's cropland category is minimally productive or not productive at all (e.g. long-term fallow): here, the introduction of cultivation systems that promise to improve soil quality and enable genuinely additional (and ecologically sustainable) feedstock production could be encouraged. Absent any guidance from the European Commission, certification bodies and their auditors may decide

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[48] This may be an overestimate, owing to the finite resolution of the CLC mapping and the coarseness of the land classes.

to establish their own protocols for deciding whether a given plot of severely degraded land is ‘too productive’ to be considered for Annex IX. The table in Appendix C.5 presents total land areas with and without the cropland overlap.

3.3. Feedstock production

Combining the land area estimates with the oilseed crop yields from Section 2.3, we present a ‘plausible potential’ for Annex IX oil production in the EU. We re-emphasise that the land availability estimates of Section 3.2 are highly uncertain, as are the crop yields that might be expected from commercial farms using available varieties. A suite of unaccounted biophysical factors will limit the suitability of Annex IX oilseeds for given farm areas. Even in areas where crops can be grown in principle, economic factors will limit farmer adoption – biofuel policy value won’t necessarily make low-yielding oilseeds on unconventional land profitable. There are also practical issues of availability of seeds and expertise in the farmer’s locale, and the availability of machinery that is capable of harvesting novel crops. As a final caveat, it is uncertain whether measures will be introduced to proscribe severely degraded productive land (Section 3.2.5) from Annex IX status[49].

We consider two scenarios: a ‘pessimistic’ scenario where crop yields are towards the lower end and uptake by farmers is confined to 5% of the identified land area, and an ‘optimistic’ scenario where crop yields are higher and adoption is 20%. These values are informed by the modelling of DG RTD & Wageningen University & Research (2024), where the deployment of oil crops on severely degraded land in 2050 reaches 3-21% of the technical potential after economic and ecologic constraints are taken into consideration[50]. They are also contextualised by the Brazilian experience with ‘safrinha’ maize, whose planted area grew from 2.4 Mha in 2000/01 to a projected 18.1 Mha in 2025/26 – a 17 percentage point increase from 19% to 36% of the total soybean area over 25 years[51] (CONAB, 2025a, 2025b). Rapid uptake was enabled by the crops’ complementarity in annual rotation and competitive yield, among other factors, and it seems unlikely that intermediate cropping in the EU would be able to exceed or even match this rate of adoption. For both our pessimistic and optimistic scenarios, we assume an average two-year cropping cycle for intermediate feedstocks (meaning that only half the land area identified in Section 3.2.1 will be available in any given year).

The results are shown in Figure 9: the pessimistic scenario employs 0.32 Mha of land annually to produce 0.20 Mt/year of Annex-IX-compliant vegetable oil, while in the optimistic scenario, 1.28 Mha is used annually to produce 1.66 Mt/year[52]. We assume that these crops can be

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[49] In the calculations that follow, we assume that all identified severely degraded land is allowed to contribute to biofuel production. Even though this might trigger additional land demand, there is no language in the RED or Annex IX that safeguards against this in the case of SDL feedstocks.

[50] For intermediate crops, the range is closer to 1-10% of the technical potential. Our land area determination already includes an element of farmer uptake via our inclusion of current cover cropping practice, making it is less comparable with the technical potential as calculated by DG RTD & Wageningen University & Research (2024).

[51] Percentages are based on three-year averages to moderate annual variations.

[52] As a comparison, DG RTD & Wageningen University & Research (2024) used an entirely different approach to estimate that 2050 vegetable oil production could reach 0.2-1.2 Mt/year from ‘degraded’ (i.e. not ‘severely degraded’) land, and 0.2-3.2 Mt/year from intermediate crops. Note that

produced in a way that satisfies the RED III threshold for greenhouse gas savings; as discussed in Section 2.5 this is not a given, and if varieties and agricultural techniques struggle to bring down cultivation emissions, our proffered values will be over-estimates.

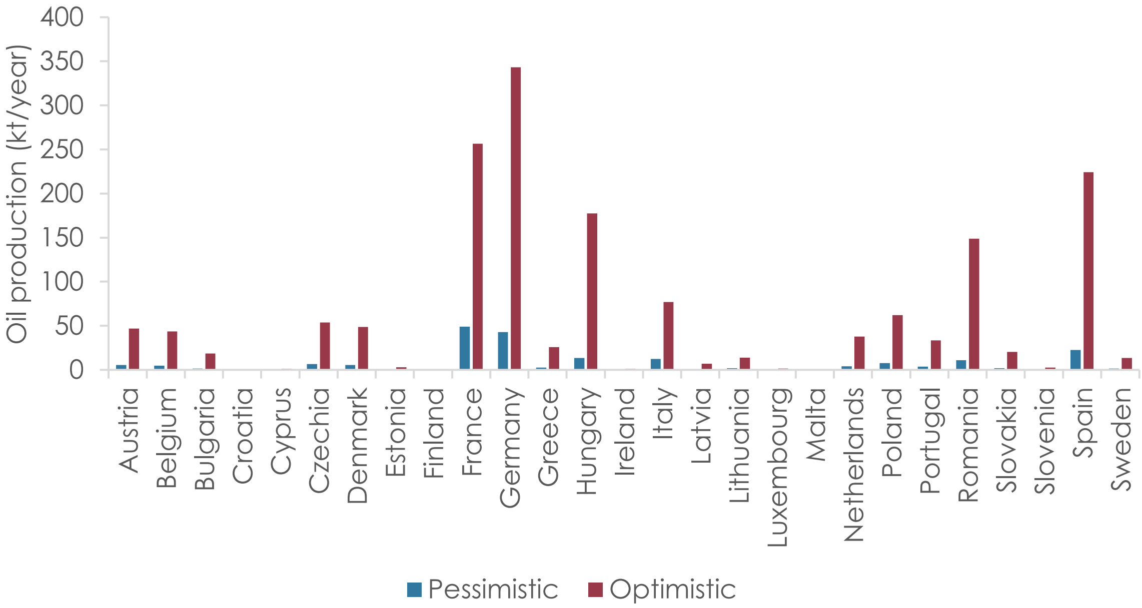

Figure 9 Annex IX vegetable oil production in European countries under two scenarios of crop yield and uptake

If delivered by 2030, a roll-out on this scale this could make a considerable dent in the ReFuelEU Aviation and FuelEU Maritime demand (see Section 3.1). However, the uncertain value proposition and the absence of successful commercial-scale demonstrations, among other factors, will inevitably slow uptake, with even positive projections anticipating that significant ramp-up is unlikely until well into the 2040s (Hamelinck et al., 2025). Set this against the projected energy demand in aviation and shipping in 2050[53], and we see that even in our optimistic scenario the contribution of Annex IX crops represents only around 1.5% (for the pessimistic scenario this dwindles to 0.2%). This strongly suggests EU-grown Annex IX crops can make at most a modest contribution to long-term transport decarbonisation.

3.3.1. Competition with cellulosic biofuels

Development of suitable crop varieties for intermediate and SDL feedstock production, and

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Hamelinck et al. (2025) quotes a much larger production of intermediate crops (27 Mt/year in 2030) based on DG RTD & Wageningen University & Research (2024). However, this value is the technical potential ignoring economic and ecologic limits; it is not appropriate to use such a technical potential as an indicator of the actual likely rate of vegetable oil production.

[53] The impact assessments accompanying ReFuelEU Aviation and FuelEU Maritime projected 2050 energy demand of 45.6 Mtoe for aviation (Giannelos et al., 2021) and 65.5 Mtoe for shipping (European Commission, 2021b).

integration into existing multi-year rotations, will take time and involve financial risk on the part of farmers and agri-business stakeholders. High demand for Annex-IX-compliant crop oils to meet policy targets could be expected to drive up feedstock prices: this builds the business case, but at the same time generates political risk if a narrative emerges of sustained high costs passed through to fuel users.

The dynamics of this policy-led market will of course depend on the rate of deployment of other compliance alternatives. Adding intermediate and SDL feedstocks to Part A of Annex IX establishes a competition between them and the other biofuel feedstocks on that list including cellulosic feedstocks. There is no formal guarantee in EU policy of market space for cellulosic fuels either in 2030 or out to 2050, though expected limitations on the supply of Annex IX crop oils mean that cellulosic biofuels should still be considered critical for satisfying RED III's advanced biofuel sub-target in 2030, and that it may be impossible to satisfy the 2050 ReFuelEU Aviation quota without them. Fulfilling FuelEU Maritime's emissions intensity targets will be increasingly dependent on the use of fuels with very low lifecycle emissions scores – in particular, far lower than the example calculations for intermediate and SDL feedstocks in Section 2.5. Thus, the contribution of intermediate and SDL feedstocks to maritime targets may be innately constrained (cf. Sandford & Malins, 2025a).

It is tempting to think that adding compliance options to EU policy ought to make targets easier to achieve. But in fact, adding compliance options compounds uncertainty: the rate of deployment and cost structure of the slate of competitors can stymie investment across the board, at least temporarily. Following the recent adjustments to the EU's fuel policy, it will be important to foster a period of stability to allow investment confidence to develop.

3.4. Potential beyond the EU

3.4.1. Intermediate feedstocks

The special treatment of intermediate crops in EU fuels policy makes the EU the world's most promising market for intermediate oilseeds. But some of the largest crop trials for intermediate oilseeds are taking place outside the EU – notably camelina, carinata, and rapeseed in the USA and South America (e.g. Keadle et al., 2023).

Seepaul et al. (2023) promotes carinata as well-suited to rotations with corn, peanut, cotton, or soybean on 5 Mha of the southeast USA, with the potential for planting every three years. The Association of Argentine Cooperatives is reported as targeting 1 Mha of the same (Alsop, 2024). In the case of Brazil, Malins (2022) pointed to limited interest in intermediate oilseeds beyond research trials (owing to the spread of the well-demonstrated annual soybean-and-safrinha-maize rotation, as well as the absence of strong markets); but this may change in due course, especially since the safrinha system still leaves a gap during the dry season (roughly August to November) where a drought-tolerant and fast-maturing intermediate could be considered[54].

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[54] Brazil is a large and climatically diverse country, so the agricultural calendar varies between regions. In those parts of Brazil that already produce two crops per year, soybeans may be planted between November and January and harvested in February-April; 'safrinha' maize would be planted directly afterwards for harvest in May-July. Cover crops may be grown in the period between the maize harvest and the next soybean sowing.

A report from IIASA and WWF examined gaps in annual cropping schedules in South America (Fischer et al., 2024), where the land is left bare or a non-productive cover crop is planted during the dry season. The report identified 22 Mha of land suitable for incorporating camelina into the annual rotation (87% of which is in Argentina), and 28 Mha suitable for carinata (with 51% in Brazil). Together, this was quoted as producing a potential 759 PJ/year (18.1 Mtoe/year) of biofuel[55]. However, it should be remembered that in regions where the land already supports two harvests (i.e. where there is interest in growing a productive intermediate as a third crop in the dry season between the two main cropping periods), it may not be eligible under the intermediate feedstock rules (Appendix A.2).

3.4.2. SDL feedstocks

Worldwide, large areas of land have been labelled as degraded or marginal; some of these will qualify for the EU's severely degraded definition, though at present the information needed to quantify the potential for Annex IX feedstocks scant. At a high level, the UN has classed 1,220 Mha as degraded (16% of the land area analysed – this includes agricultural and non-agricultural land) (UNCCD, 2020). Other estimates say that a third of soils globally are degraded (Heinrich-Böll-Stiftung & TMG Research, 2024), including, for instance, 132 Mha of degraded cropland in Africa (Mansourian & Berrahmouni, 2021), and 98 Mha of degraded land in Inda (Government of India, 2023). McCormick et al. (2014) concluded that 2,000 Mha of global degraded land could be restored in part through innovative agricultural practices: this would include growing energy crops that are chosen to be tolerant of local stresses.

Lands that satisfy the specific definition of severe degradation under the RED – i.e. lands that are salinated, or are eroded and SOC-depleted – will comprise a subset of these. The FAO reports that 20% of cultivated land worldwide is affected by salinity (Badraoui et al., 2015): a number that is expected to rise (Eswar et al., 2021). Daba (2025) equates this to 1,030 Mha of land, and quotes an estimate that three hectares of arable land are lost every minute to salination. MarginUp! (2023) describes a large-scale trial (15 kha) of winter rapeseed, carinata, and camelina on salinated soils in Argentina.

At the same time, though improved agricultural practices have stemmed the decline of SOC in soils around the world (e.g. Ogle et al., 2023), Prăvălie et al. (2021) estimate that 190 Mha of global cropland is suffering net SOC loss today; and vast amounts of carbon has already been and will continue to be lost from soils due to climate change (Poeplau & Dechow, 2023; M. Wang et al., 2022). In Brazil, for example, Fischer et al. (2024) used high-resolution mapping of pasture and grassland to characterise 33 Mha of soils as suffering severe degradation[56] (including erosion and low SOC).

Putting this all together with Section 3.4.1 above, a picture emerges of potentially millions of hectares around the world that could satisfy the RED definition of 'severely degraded land'; a consensus will have to emerge over the appropriate interpretation in each global agri-environmental zone before the areas of interest can be pinned down more precisely. And only a subset of those areas thus identified will be biophysically capable of producing oilseed crops in a way that meets the RED's stringent greenhouse gas threshold. And even in

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[55] Consistent with harvesting the intermediate crop roughly every other year.

[56] This term, used by the authors, differs from the RED definition. A fraction of the identified land area falls under ecological protection and should be excluded from biofuel development.

climatically promising areas, there remain significant impediments to uptake in lower-income countries whose agricultural sectors are less industrialised: access to seeds, harvesting machinery, and technical knowledge for cultivating novel varieties, as well as access to the EU market. In short, practical challenges along with the uncertain value proposition for low-yielding crops – grown with difficulty in adverse conditions – will hinder uptake in the near term.

3.5. Certification

3.5.1. Uncertainties

From the project developer's perspective, there are a number of uncertainties that will slow the development of Annex IX oilseed cultivation. One major one is the stringency with which certification schemes will assess the Annex IX criteria: one example noted above is whether stakeholders' aforementioned calls for severely-degraded-but-currently-productive land to be excluded will be heeded in the European Commission's rules for implementation, and/or the methodologies developed by certification bodies.

Another issue is what evidence will be needed to verify that cultivation of intermediate crops does not stimulate demand for additional land. If this boils down in practice to an exclusion of certain regions where double-cropping is already common, as posited above, the targeted areas will have to be determined. But since adverse impacts on main crop yields cannot be ruled out when introducing a new productive crop into a rotation (Sandford et al., 2023), the European Commission may yet decide to adopt a more robust interpretation of the language, for example by incorporating elements of the low ILUC-risk methodology (see the discussion in Section 2.2).

Another potential source of uncertainty arises from the designation of land as severely degraded. EU biofuel policy seeks to incentivise measures to improve land condition, but farmers of SDL feedstocks risk becoming victims of their own success and losing their 'severely degraded' status if SOC improves, but still struggling to deliver yields that are economically competitive with better-quality cropland[57]. If the introduction of biofuel crops on severely degraded land is being used to rehabilitate and improve it, then the early years of such projects will likely be lower-yield and perhaps loss-making. Farmers may be wary of a 'Catch-22' where farming is unprofitable at first due to low yields despite the policy support, and then the policy support is removed before yields become high enough to be profitable without it. Biofuel producers entering into medium-term offtake agreements with farmers (needed to get projects off the ground) will also be hesitant to commit to paying an Annex IX premium if the feedstock may not be considered Annex-IX-compliant after a few years.

The European Commission's response to these issues may be clarified in a forthcoming update to its Implementing Regulation for voluntary schemes (European Commission, 2022).

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[57] In the best-case scenario for the farmer, the land will lose its severely degraded status only after it has recovered to a degree that makes it competitive with 'normal' food-and-feed crop production; but this is not guaranteed.

3.5.2. Fraud risk

The potential demand for Annex-IX-compliant vegetable oil is immense. Whether or not the extra value afforded by EU fuel policy will be sufficient to motivate supply through widespread development and adoption of new agricultural practices, it certainly creates an incentive for simple mis-labelling fraud. This issue is already familiar for biofuels made from the original Annex IX Part B feedstocks – used cooking oil and low-grade animal fat – where there have been examples of virgin vegetable oil being mis-labelled as residual oil (Suzan, 2023). In the case of Annex IX crop oils, mislabelling fraud may be even harder to detect, as there is no chemical signature that distinguishes, for example, rapeseed oil grown as an intermediate feedstock from rapeseed oil grown as a main crop, and because after seed crushing the oils can enter the same agricultural commodity supply chains.

For this reason, a report for the European Commission classified both intermediate crop feedstocks and feedstocks originating from severely degraded land as high fraud-risk (Haye et al., 2021). Verifying feedstock volumes at every point in the supply chain – from the certified field where they are produced, through common transport links to the biorefinery and ultimately to the last supply point – will be challenging for certification bodies and entails cumbersome record-keeping and reporting for producers. The more complex the supply chain, the more opportunity there is to introduce incorrect origin information[58], the Union Database for Biofuels may enable though better information tracking.

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[58] Chemical tracers that don't degrade the quality of the oil and/or biofuel, and which remain detectable even after rounds of blending, may offer a possible solution (e.g. Thepithar et al., 2025), at least for the value-chain stages before mass-balance accounting is used. However there is no evidence that the EU is considering mandating such an approach.

4. Conclusion

Based on current targets, and on optimistic rates of electrofuel scale-up, we have estimated that ReFuelEU Aviation will generate demand for up to 2.9 Mt of lipid feedstock in 2030. For 2050, depending on the scale-up of cellulosic biofuels, lipid demand from the aviation and maritime segments will be in the tens of millions of tonnes. Oilseed crops that qualify under Part A of Annex IX of the RED are the most potentially scalable source for these lipids.

There are two types of oilseed crops that fit within Annex IX: intermediate crops that are grown between the cultivation periods of main crops, and crops grown on severely degraded land. Promising candidates include rapeseed, carinata, crambe, camelina, cardoon, safflower, and castor – these are tolerant to growing conditions that would not support many conventional main crops, and some of them mature quickly enough to fit between crop seasons.

There remain some major definitional ambiguities for the European Commission and/or certification bodies to clarify. These include how intermediate crops' impact on additional land demand will be assessed; what thresholds apply to the designation of land as 'severely degraded'; and whether crops grown on 'severely degraded land' are to be treated as *de facto* outside the technical category of 'food and feed crops' as defined in the RED. Answers to these questions will have critical implications for the volume of Annex-IX-compliant oilseed that can be produced. Regulatory clarification will play a large part in determining whether these feedstock categories will remain a footnote to the global biofuel industry, or will play a large role in delivering EU targets.

Supporting these types of crops is not without risk. Agricultural expansion (in the case of severely degraded land) and intensification (in the case of intermediate crops) entail ecological risks that are not directly addressed by the RED's general sustainability criteria. For instance, severely degraded land may currently offer habitats and hydrological regulation that would be lost if ploughed up and put into production. Annex-IX-compliant intermediate crops that displace existing cover crops may also displace some of their agri-ecological benefits (e.g. nitrogen fixation, leading to greater need for chemical fertiliser). The RED establishes threshold greenhouse gas savings that biofuels must satisfy in order to be eligible. We have shown that there is likely to be a need to minimise nitrogen use for intermediate crops that do not have default agricultural emissions values available; there is a risk that this also implies an incentive to compensate with additional fertiliser during the main cropping season, which can be masked by the use of main crop default values. This would have concerning climate and ecological implications.

The introduction of an additional compliance option in Annex IX Part A also threatens the investment case for other less mature alternative fuel technologies, notably cellulosic fuel production technologies, for which RED III had briefly offered a relatively clear value signal. It is at present doubtful that production of the Annex IX crops will be able to scale on the time-frame required to make much of a dent in RED III's 2030 target; nevertheless, the spectre of (and hype around) the new compliance options re-introduces the kind of uncertainty that has historically stymied investment in advanced cellulosic biofuels. In the longer term, we deem it unlikely that Annex IX crop oils will be enough on their own to meet projected ReFuelEU Aviation biofuel demand or to meet the stringent emissions intensity standards under FuelEU Maritime: from this perspective, cellulosic biofuels could still have an important medium- to long-term role in meeting EU targets.

There is language in Annex IX that asserts that demand for additional land should be avoided, which would minimise ILUC impacts from the use of intermediate crops; but the robustness of the implementation will determine whether this is actually realised. For example, it is unclear whether reductions in main crop yields will be monitored by the assessment methodology. The European Commission chose not to tie the intermediate crop category to the existing and relatively stringent low ILUC-risk certification. It will be informative to compare protocols developed for the certification of Annex IX crops with the low ILUC-risk framework.

The area of land that could be dedicated to production of Annex IX crops in the EU has yet to be convincingly established, in part due to the lack of definitional clarity. Nevertheless, it has been subject to optimistic assessments in the past. It is important that results quoted from the literature are properly contextualised – for instance, distinguishing between 'technical' land availability and feedstock production potentials, and analyses that attempt to include realistic constraints in order to develop more plausible results. In this report, land suitable for intermediate cropping was identified based on existing cover cropping practices in combination with a filter on where off-season crops are thought to be biophysically (though not necessarily socio-economically) viable[59]. The severely degraded land area was estimated using a combination of four geographical data layers: erosion rate, SOC level, salinity statistics, and land-type classification. Recognising that: (i) Annex IX crop yields will be lower than would be expected under conventional growing conditions; (ii) not all intermediate cropping areas will be able to produce a crop every year; and (iii) farmers uncertain of the economic prospects of the new crops and unfamiliar with their cultivation will be slow to adopt them, we presented two scenarios of EU feedstock potential that would deliver between 0.20 and 1.66 Mt of vegetable oil feedstock year.

The potential for Annex IX crop production outside the EU is likely to be much greater. While it was beyond the scope of the report to perform a systematic review of extra-EU production potential, the potential global land resource is easily in the millions of hectares. Camelina and carinata as intermediate crops have been trialled in South America and the USA, as has oilseed cropping on degraded land in South America and Africa. However, there is not yet a definitive indication of sustained appetite for commercial-scale production. Given that our estimated of EU production potential is well below the estimated demand from EU fuel regulations, there is a clear market draw to import these feedstocks.

At this juncture the contribution that Annex IX oil crops will make to EU energy targets remains uncertain. We still lack commercially viable agricultural models that demonstrably and reliably meet the RED's greenhouse gas thresholds and sustainability specifications. Should these emerge, farmer adoption on the time-frame and at the scale that we need is far from guaranteed. Thus, though farmers who are willing to pursue the stringent certification requirements have the prospect of availing support for rehabilitating their land and increasing its productivity, it is doubtful that the EU's implied demand for these novel vegetable oils can be met. This strongly suggests that that measures that reduce total aviation and shipping energy demand (including measures to manage demand growth) will be needed if the EU is to meet its climate commitments.

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[59] This may in theory miss some areas where cover cropping is not currently practised but could be. The Common Agricultural Policy (CAP) rules make winter ground cover a condition for receiving subsidies, and so those farmers that don't use cover presumably have a good reason not to.

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Annex A Policy definitions

A.1. Eligible feedstocks

A.1.1. ReFuelEU Aviation

Biofuels, renewable fuels of non-biological origin (RFNBOs, also known as electrofuels or PtL hydrocarbons), and recycled carbon fuels (RCFs) can all contribute to ReFuelEU Aviation (European Union, 2023a), provided they meet the eligibility criteria. Here we focus on the rules for biofuel feedstocks.

Alongside RED III's greenhouse gas saving thresholds (see Section 2.5 of the main text), sustainability criteria for biofuel feedstock include prohibition of material derived from forests, wetlands, and highly biodiverse areas. Certain feedstocks are excluded altogether owing to their sustainability risks: most consequentially 'food and feed' crops (according to the RED definition), but also soap stock and palm- and soy-derived feedstocks not falling within Annex IX[60]. Intermediate crops must satisfy the Annex IX criteria to be eligible; and the contribution of any other feedstocks not listed in Annex IX is limited to a maximum of 3% of fuel from any fuel supplier[61]. Unlike in RED III, there is no nominal cap on Annex IX Part B feedstocks, meaning they can contribute without limit (though beyond the cap they may not receive the extra RED value[62]).

A.1.2. FuelEU Maritime

FuelEU Maritime (European Union, 2023c) places an obligation on ship operators to reduce the average greenhouse gas intensity of the fuels they use. The standard that must be met tightens over time (Table 4), and can be met with the alternative fuels noted in the previous section along with natural-gas-based fuels like liquefied natural gas (LNG) and methanol. Food-and-feed-crop biofuels are not permitted, but other feedstocks are – i.e. there is no restriction to the Annex IX list. There are also provisions to promote wind-assisted propulsion and the consumption of on-shore power while ships are at berth.

Calculating the emissions intensity of a given fuel batch follows the RED III methodology for well-to-tank (WtT); FuelEU Maritime provides its own methodology for additional tank-to-wake (TtW) emissions. The full well-to-wake (WtW) emissions intensity must satisfy the RED III minimum emissions savings threshold, and determines the compliance value of the fuel.

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[60] An exception is made for oil recovered from palm oil mill effluent (POME), and for empty palm fruit bunches.

[61] This could be consequential in the near term as the ReFuelEU Aviation quota is only 6% in 2030.

[62] Member States do have some discretion under the RED to increase the Annex IX Part B threshold.

Table 4 FuelEU Maritime greenhouse gas intensity standard

Emissions Intensity	Unit	2025	2030	2035	2040	2045	2050
Reduction	%	2%	6%	14.5%	31%	62%	80%
Target	gCO_2e/MJ	89	86	78	63	35	18

Note: Percentage reductions are with reference to a 91.16 gCO_2e/MJ benchmark.

A.2. Annex IX crops

A.2.1. Specifications

Here we provide more detail on the crop feedstocks that were added by a 2024 amendment to Annex IX of the RED (European Commission, 2024). We focus on the following two feedstock categories:

> *Intermediate crops, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land, and provided the soil organic matter content is maintained;*

and

> *Crops grown on severely degraded land, except food and feed crops.*

Where biofuels from crops meeting these criteria are supplied to the aviation transport segment, they may be counted as Annex IX Part A feedstocks (Items (t) and (u) respectively); otherwise they are counted as Annex IX Part B feedstocks (Items (f) and (e) respectively).

We shall discuss these crop types in the following sub-sections. First, it is important to note that crops grown for cellulosic biomass are already covered by Annex IX Part A under Items (p) and (q)[63]. This would include perennial grasses (e.g. Miscanthus and switchgrass), annual grasses (e.g. biomass sorghum), and potentially other plants that may be economical to harvest for their cellulose content. Therefore the Annex IXcompliant feedstocks that were introduced in the quotes above are implicitly crops grown for their oil, starch, and/or sugar content.

A.2.2. Annex IX intermediate crops

There are two major models for intermediate cropping: sequential crops and intercrops. Sequential crops are introduced as part of a rotation in the period between harvesting one crop and preparing the land to sow the next, while intercrops are grown at the same time

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[63] These are “Other non-food cellulosic material” and “Other ligno-cellulosic material except saw logs and veneer logs” respectively..

as a main crop, for instance in alternating rows on the same field (Howard, 2016). These intermediate crops must satisfy four overlapping criteria: it must be (i) an intermediate crop that (ii) does not trigger additional demand for land, that is (iii) grown in an area where production of food and feed crops is limited to one harvest, and that is (iv) grown in a way that doesn't degrade soil organic matter. To understand what kinds of crops may qualify, we must address each criterion.

Intermediate crops are implicitly defined in contrast to 'food and feed' crops in the RED, Article 2. Food and feed crops are oil-, starch-, and sugar-rich crops grown on agricultural land as 'main' crops. There is no detailed definition of what counts as a main crop[64], and as the RED uses the indefinite article ("a main crop" rather than "the main crop") there is no explicit limitation to one main crop per year. Consequently in some rotations there may be ambiguity as to what qualifies as an intermediate crop.

Criterion (iii), that production of food and feed crops is limited to one harvest, is likely to exclude second crops grown in already well-established double-cropping systems, such as Brazilian safrinha maize grown in annual rotation with soybeans. Using such crops would also seem to violate the restriction in criterion (ii) on triggering additional land demand, as diverting such crops to the biofuel market would represent a displacement from existing food and feed markets[65], causing a supply shortage and an incentive for agricultural expansion (Malins, 2022). Further discussion of the nuances of intermediate crop definition is given in a report for the European Commission (Guidehouse, 2024, Appendix C.2).

Criterion (ii) could be interpreted as also mandating that a new sequential crop or intercrop must produce 'additional' feedstock in order to qualify. This may not be the case if it replaces an existing sequential crop or intercrop, or if introduction of the new crop adversely affects the yield of the main crop, but it is unclear whether this sort of additionality will be rigorously assessed.

Finally, criterion (iv) is the requirement that soil organic matter is maintained. This is largely a function of farm management practices, and can be evaluated through soil sampling. However, variability within and between fields, weather-related fluctuations, and the difficulty of baselining, all make this a complex and (if done rigorously) costly activity (BIKE, 2023d); but It remains to be seen what level of monitoring will be required to satisfy this condition in reality. It is possible that a 'practice-based' assessment (as opposed to a 'results-based' assessment) will be deemed acceptable: this would presume the preservation of soil organic matter to be achieved if the farmer adopts specified conducive practices like conservation tillage, mulching, and limiting the removal of crop residues. In any case, it isn't possible to determine ex *ante* which land areas would maintain their organic matter under intermediate cropping without prior knowledge of land management activities and/or assessment on the ground for each project, and so this condition is not considered in our analysis of potential land areas.

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[64] Informally, we may consider the crops with the highest financial value, which occupy the field for the longest time or which simply have a history of being grown by that farmer or in that area. Annex C.2 of Guidehouse (2024) discusses how main crops may be distinguished from intermediate crops in greater depth.

[65] Safrinha corn represents around 70% of Brazil's corn production, or 10% of global production. Eliminating this from the world's food and feed markets would clearly have a profound impact on maize prices and hence land demand.

A.2.3. Severely degraded land

The designation of ‘severely degraded land’ was introduced in the original RED in 2009, where biofuel feedstocks grown on severely degraded land were to be awarded a bonus term in their LCA of 29 gCO_2e/MJ. Thus, a crop-based biofuel which would ordinarily be unable to meet the emissions intensity threshold to qualify under RED II[66] may have been able to qualify with the help of the bonus term. RED Annex V Part C Paragraph 8 gave the following definition:

> *‘Severely degraded land’ means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded.*

Only Sweden is recorded in official EU statistics as making use of this provision, declaring about 8.8 ktoe of biofuel between 2011-2018 (Eurostat, 2025b). The ‘severely degraded land’ status acquired an additional role through the development of the low ILUC-risk framework, as crop feedstocks grown on severely degraded land were to be exempt from any additionality test. This meant that it was not necessary to show that the feedstock had not been diverted from other markets.

There are several points that need to be clarified in order to consistently operationalise the severely degraded land definition. Firstly, for want of a comma, it is unclear whether the ‘severe erosion’ condition must be (a) satisfied both in the case of severe salination and in the case of low organic matter, or (b) just in the case of low organic matter. In this report we follow ISCC (2024)and treat option (b) as the correct interpretation (cf. Figure 4 in that document).

The terms ‘significantly salinated’, ‘significantly low organic matter’, and ‘severely eroded’ also need further specification – e.g. no thresholds are given in the legislation. A subsequent Implementing Regulation (European Commission, 2022, Article 26) provided further guidance on how these conditions were to be assessed by stipulating the following test conditions[67]:

> *(a) in the case of salinisation, the results of testing by a qualified agronomist of the electroconductivity of the soil using the saturated paste method;*
>
> *(b) in the case of low soil organic matter, results from an appropriate number of samples of soil from the delineated plot, determined by a qualified agronomist, using the dry combustion method;*
>
> *(c) in the case of severe erosion, at least 25% of the delineated plot shall have been eroded as determined by a qualified agronomist, supported by photographs.*

While these clarify what evidence is required, they do not set objective thresholds, and do not fully determine the basis on which an expert judgement should be made, making it difficult to place definitive limits on which lands count as severely degraded and which do not. In their discussion (and recommendation) of more precise thresholds Guidehouse (2024) caution that selecting a single standard threshold would fail to represent the diversity of climates and land

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[66] E.g. a fuel that was unable to meet a required 60% emissions reduction compared to the fossil fuel comparator.

[67] We assume this Implementing Regulation will apply in the context of RED Annex IX entries, though this may need to be confirmed.

types, and note the variability of soils and sampling results within fields and over time. Adoption of multiple differentiated thresholds, on the other hand, could become complex and cumbersome, and so the Implementing Regulation's deferral to the judgement of a qualified agronomist on a case-by-case basis is understandable. But it does make it challenging to confidently determine which land areas may be suitable for growing Annex IX compliant crops; Guidehouse (2024) suggest that territorial surveys by Member States to identify severely degraded land could provide certainty to farmers and other market operators (provided, of course, that the mapping results are approved by the European Commission).

A.2.4. "Crops grown on severely degraded land, except food and feed crops"

The definition of SDL feedstocks explicitly excludes "food and feed crops", but it is debatable what this exclusion of food and feed crops signifies. The basic definition of food and feed crops is "starch-rich crops, sugar crops or oil crops produced on agricultural land as a main crop, excluding intermediate crops". If degraded land is to be counted as agricultural land, this suggests that starchy/sugary/oily crops grown as main crops would be excluded from the definition. This interpretation, however, would be extremely restrictive as only (i) other vegetable or fruit crops, or (ii) intermediate crops that are grown on severely degraded land would qualify (cellulosic crops are already covered in Annex IX Part A).

Option (i) seems improbable from a technology and economic standpoint (it would require purposefully targeting crops that are the least appropriate for biofuel production). Option (ii) would overlap with the category for intermediate crop feedstocks and therefore be almost entirely redundant: the only advantage offered by growing crops on severely degraded land would be to obviate the requirements on the vegetation period and soil organic matter (cf. Appendix A.2.2). In any case, assuming there is a high bar for a plot to count as severely degraded, agronomically viable opportunities for growing a second crop on severely degraded land are likely to be rather scarce.

Thus we turn to an alternative interpretation of the language: if identification of land as 'severely degraded' determines that it is non-agricultural, then any crops produced thereon would fall outside the definition of 'food or feed crops'. We note though that this interpretation would make the phrase "except food and feed crops" in the Annex IX language entirely redundant. Some redundancy of language is not unheard of in EU legal documents, however. This interpretation also carries the implication that 'severely degraded land' would be considered non-agricultural even if currently being used successfully for the production of crops, and that those crops would count as not being food and feed crops even if they are being supplied to people and animals to be eaten! Such linguistic gymnastics are not unprecedented – for example recall that the term 'food and feed crops' is not actually predicated on edibility. On balance, we believe that the interpretation that any crop grown on severely degraded land qualifies for Annex IX and is not subject to the food-and-feed-crop cap most plausibly aligns with what we take to be the intentions of the European Commission, and it is what we have adopted in this report.

Annex B Lifecycle analysis parameters

B.1. Feedstock production

Representative main crop yields for the oilseeds under consideration for the three EU agri-ecological zones are provided in Panoutsou et al. (2022). The oil content of different seeds and the yield response to fertiliser application are key parameters for the calculation of lifecycle emissions; another is the difference in yields between trials where oilseeds are grown as a main crop versus trials where it is grown in the off-season in rotation with other crops. The studies consulted for intermediate feedstocks are listed in Table 5.

Table 5 Literature consulted for characterising yields of intermediate feedstock

Reference	Description
Panoutsou et al. (2022)	Representative yields for the oilseeds considered in this study when grown as conventional / main crops.
Alexopoulou, 2023b (2023a)	Carinata yields and inputs for case studies in Uruguay and Greece.
Potter et al. (2023)	USA trials of camelina.
Avola et al. (2021)	Comparative camelina yields in the semi-arid Mediterranean, with lower and higher levels of fertilisation.
Gregg et al. (2022)	Camelina in the northern USA under two fertilisation regimes.
Berti et al. (2025)	Winter camelina yields in the USA under a range of nitrogen applications.
Patel et al. (2021)	Intercropping of pennycress and camelina with maize and soybean in the USA.
Sessa et al. (2025)	Carinata yields when grown as a summer intermediate crop in northern Italy.
Moore et al. (2020)	Response of maize-pennycress rotation yields to a range of nitrogen application levels.
Zanetti et al. (2021)	Review of camelina trials and achieved yields in Europe.
Tiwari et al. (2021)	Carinata in the southeastern USA as a winter cover crop, in rotation with main crops and with fallow period.
Iboyi et al. (2023)	Carinata in rotation with main crops in the southeastern USA.
Ren et al. (2015)	Rapeseed rotations yield response to fertilisation regime in China.
Samarappuli et al. (2020)	Review of reported crambe yields.
Berzuini et al. (2021)	European trials of crambe seed varieties spanning agri-ecological zones.

Royo-Esnal & Valencia-Gredilla (2018b)	Camelina rotations in the semi-arid Mediterranean, trials under different cultivation conditions.
Chen et al. (2015)	Impacts of an experimental replacement of an unproductive season with camelina in wheat rotations in the USA.
Chiaramonti & Barsali (2023)	Yield modelling of camelina and soil carbon in the Mediterranean EU.
Obeng et al. (2024)	Yield impacts of a wheat-camelina versus a wheat-only rotation in the USA.
Aiken et al. (2015)	Exploration of how planting and cultivation practices influence the yields of oilseeds cultivated in the off-season in the USA.
DG RTD & Wageningen University & Research (2024)	Intermediate camelina crop and oil yields in different EU agri-ecological zones.
Rose et al. (2024)	Study of a summer rapeseed intermediate crop in semi-arid Australia, including yield impact on the main winter wheat crop.
Alexopoulou (2024)	Presents intermediate camelina trials in the Mediterranean.
Pari et al. (2024); Stefanoni, Latterini, Ruiz, Bergonzoli, Attolico, et al. (2020); Stefanoni, Latterini, Ruiz, Bergonzoli, Palmieri, et al. (2020)	Sequence of trials on cultivation and harvesting of camelina as an intermediate crop in France and Spain.

Similar issues pertain to SDL feedstocks, though here the nature and degree of the land's degradation influences what crops may be suitable and what yields could be expected. Relevant literature is listed in Table 6.

Table 6 Literature consulted for characterising yields of SDL feedstock

Reference	Description
Panoutsou et al. (2022)	Representative yields for the oilseeds considered in this study when grown on eroded and low-SOC land.
Traverso et al. (2023)	Marginal land castor bean cultivation inputs in Kenya.
Calcagno et al. (2023)	Mediterranean castor bean trials with different input levels.
Haberzettl et al. (2021)	Complex constraints on plant growth for lignocellulosic crops on marginal land.
Cafaro et al. (2025)	Castor yield ranges in Mediterranean trials.
DG RTD & Wageningen University & Research (2024)	Yield ranges for oilseeds under different crop development scenarios.
Reinhardt et al. (2021)	Reports yield penalties for camelina and cardoon in unfavourable growing conditions.
Zanetti et al. (2024)	Camelina on marginal land in Europe, with restricted fertiliser application.
Carrino et al. (2020)	Review of castor trials.
Schillaci et al. (2023)	Rotations of camelina with barley in depleted soil.

Matthees et al. (2018)	Tolerance of camelina and other oilseed germination to salinity.
Francois (1994)	Rapeseed yield impact from saline growing conditions.
Glenn et al. (1999, 2013)	Oilseed yields in saline growing conditions.
Nayidu et al. (2013)	Dependence on salinity for oilseed crops.

It should be noted that, aside from the heterogeneity of growing conditions between any two projects, the results of research trials may not be representative of commercial-scale systems. Small plots are more subject to edge effects, where plants growing on the plot borders get a yield boost owing to diminished competition for light and nutrients. Research trials at the plot and field level also benefit from more diligent monitoring and a concentration of specialist attention that would not apply in commercial settings.

B.2. Input parameters

To perform the greenhouse gas lifecycle analysis, we followed the low- and high-input cases considered by Gregg et al. (2022) for intermediate camelina and by Calcagno et al. (2023) for SDL castor. The input values are summarised in Table 7; otherwise we used the RED defaults as discussed in Section 2.5.

Preventing soil erosion has a direct carbon benefit (Lugato et al., 2016), and so it is possible that an operator growing an SDL crop could be able to report soil carbon sequestration under the RED LCA e_{sca} term. Similarly, some intermediate crops are thought to build soil fertility. However, the complexity of monitoring and demonstrating soil carbon increases (BIKE, 2023d, 2023b) mean that this may be viable for only a small subset of projects, and we have opted to neglect that calculation.

Allocation of emissions between co-products was done on the basis of energy content. The BioGrace results for HVO were applied translated to HEFA assuming a relative feedstock-to-fuel yield penalty of 93% by mass (O'Malley et al., 2021; M. Wang et al., 2024). Additional hydrogen usage – as jet-specification fuel requires extra isomerisation and hydrocracking – was assumed to add 0.94 gCO_2e/MJ to the emissions score (Prussi et al., 2020; Rosales Calderon et al., 2024).

Table 7 Input parameters for the BioGrace lifecycle analysis

Parameter	Unit	Intermediate camelina		SDL castor	
		Low Input	High Input	Low Input	High Input
CROP					
Crop yield	kg/ha	745	1,325	1,575	2,597
Moisture content	%	10%	10%	10%	10%
Oil mass share	Mass %	27%	34%	40%	41%
Oil energy share	Energy %	41%	50%	56%	57%
FUEL USE					
In-field diesel	MJ/ha/year	2,568	2,720	2,768	2,910
Seed transport	km	50	50	50	50
Crop oil transport	km	150	150	150	150
FIELD INPUTS					
Nitrogen	kg-N/ha/year	0	89	0	120
Manure	kg-N/ha/year	0	0	0	0
Lime	kg-CaO/ha/year	0	12	0	0
Phosphorous	kg-P_2O_5/ha/year	14	14	70	70
Potassium	kg-K_2O/ha/year	27	27	0	0
Pesticide	kg/ha/year	1.2	1.2	1.2	1.2
Seeds	kg/ha/year	6.0	6.0	6.0	6.0
N_2O EMISSIONS					
Field N2O emissions	kg-N_2O/ha/year	0.00	2.01	0.00	2.71

Note: Gregg et al. (2022) data averaged across 2019 and 2020 sequential results for maize and soybean cases for nitrogen-fertilised, and across 2017 results for maize and soybean for nonnitrogen-fertilised.

Annex C EU land area data

C.1. CORINE Land Cover Survey

The CORINE Land Cover Survey (CLC) takes place every six years and categorises each hectare of the EU and neighbouring countries into five land types (artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands, and water bodies). Within these are two layers of sub-categories: for example, agricultural areas are split into arable land, permanent crops, pastures, and heterogeneous areas; then arable land is split into non-irrigated, irrigated, and rice fields. A full description of the categorisation system is given in Kosztra et al. (2018). The most recent full CLC data publication was for 2018.

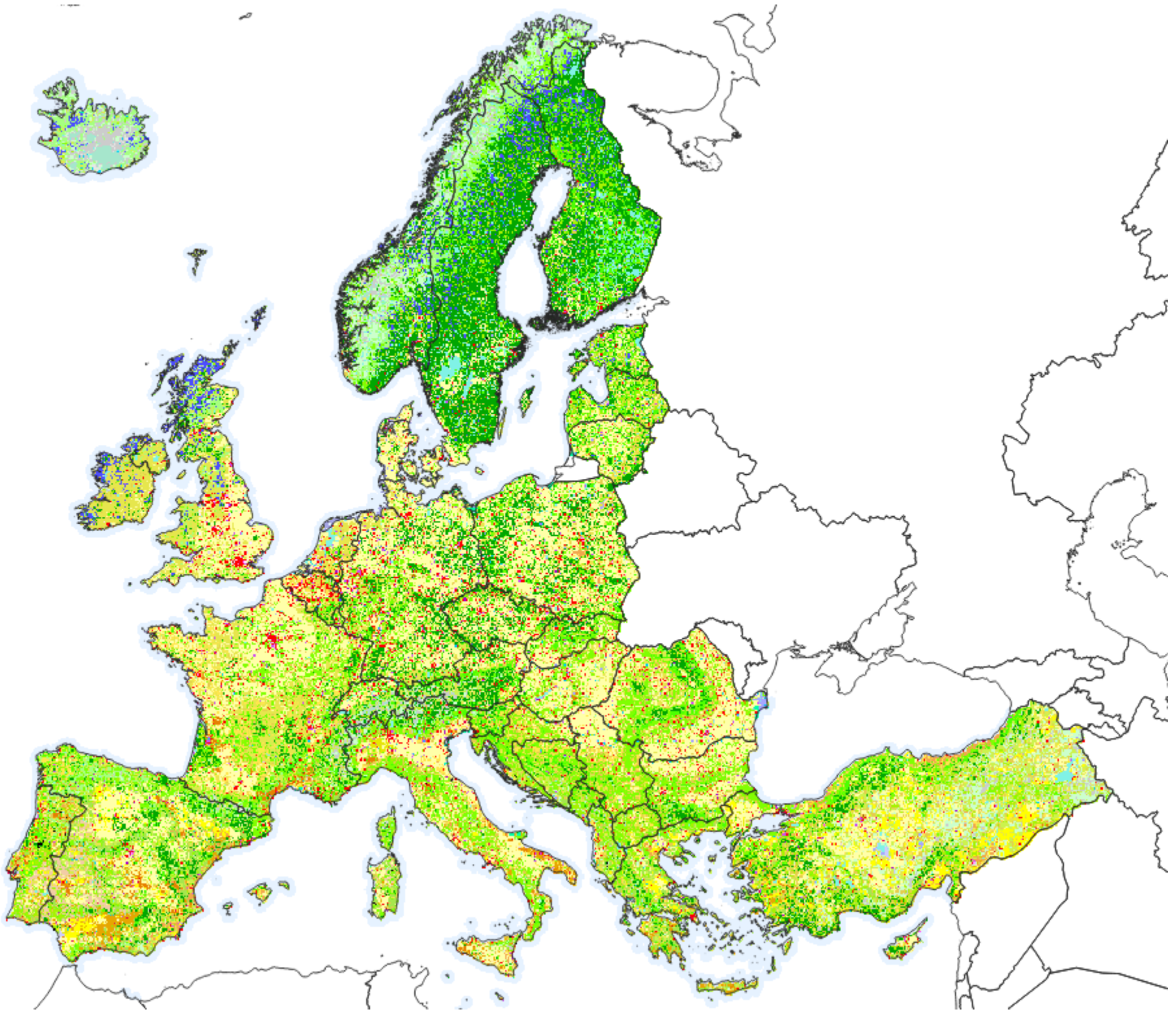

Figure 10 The CLC-2018 map layer, clipped to Continental Europe; red colours indicate artificial surfaces like urban areas, yellow agricultural areas, green forest and shrubland areas, blue wetlands and inland waterways

Figure 10 shows the CLC dataset (excluding outlying regions), with the colour code given in the legend. Each colour category is divided into a number of sub-categories; see European Environment Agency (2020) for the full mapping. Figure 11 illustrates the CLC dataset at higher resolution for a recognisable region of the map, while Figure 12 indicates cropland (including complex crop-pasture rotations).

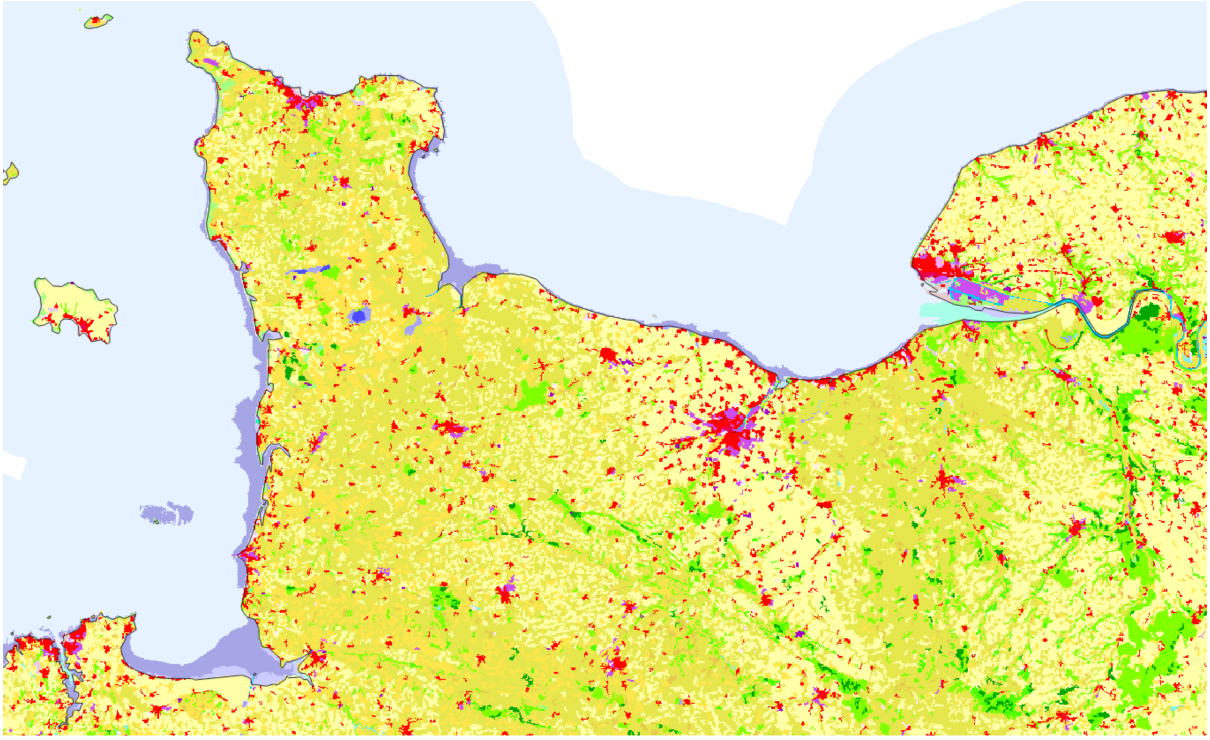

Figure 11 Detail of the Normandy peninsula, showing the CLC categories (same colours as Figure 10)

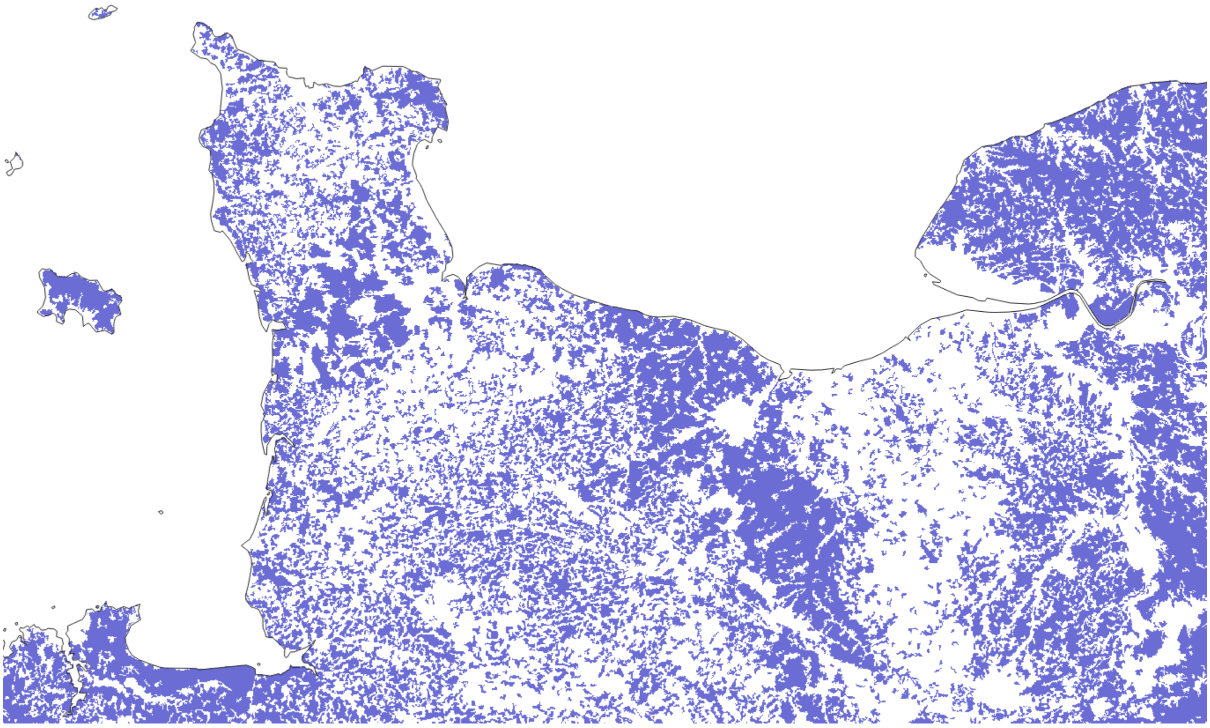

Figure 12 Detail of the Normandy peninsula (see Figure 11), indicating cropland

C.2. Cover cropping

The distribution of winter season land cover across EU Member States according to Eurostat is shown in Figure 13 (Eurostat, 2025a); this data is from 2016. For our purposes, 'normal winter crop' and 'multi-annual plants' mean that the land is occupied and there is little scope for introducing an intermediate crop without stimulating additional land demand[68]. Land covered in 'plant residues' or left as 'bare soil' could in some cases be used to grow a new winter cover crop; however, given the existing EU incentives to grow cover crops, it is likely that biophysical factors would prevent a productive winter crop from being grown, so we also exclude this land from consideration. That leaves the 'cover crop' category, which, according to this dataset, spans an area of 7.1 Mha in the EU. A productive intermediate crop could be substituted in place of the cover crop in those cases where there is sufficient water availability, growing period, etc. for the oilseed to mature.

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[68] This may not be quite true in the case of intercrops grown between rows of e.g. maize, in which cases excluding those two categories would tend to underestimate intermediate cropping potential.

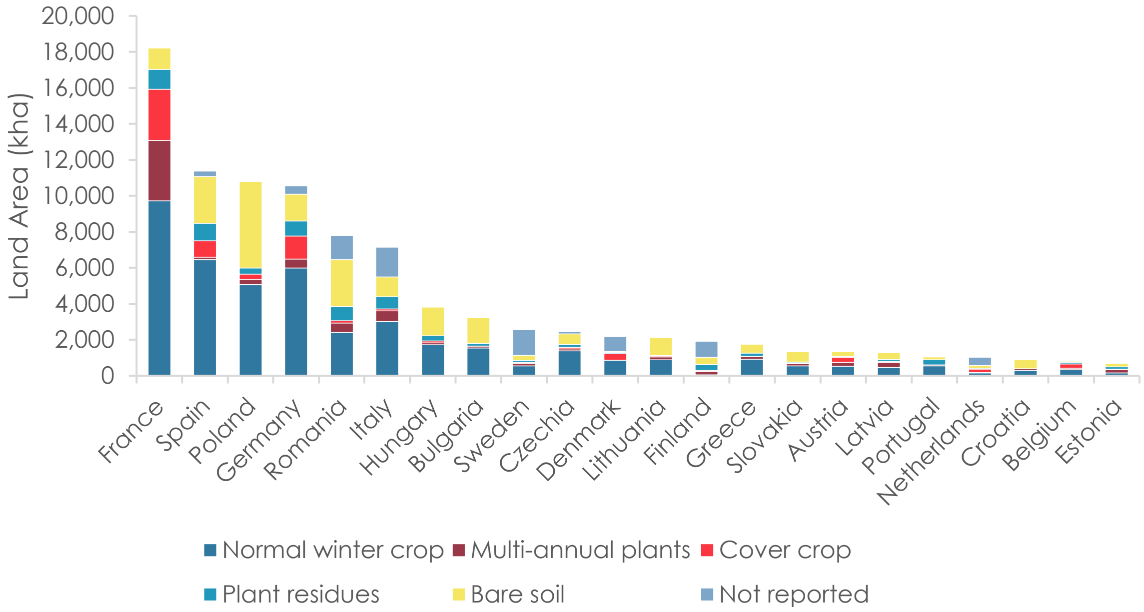

Figure 13 Winter management of European countries' cropland areas

Source: Eurostat (2025a)

The data for Figure 13 are available at the NUTS-2 level. In pursuit of higher spatial resolution, Fendrich et al. (2023b) combined these with satellite images and statistical modelling to derive a map of cover cropping in the EU+UK at a 1 ha resolution. A detail from their dataset is shown in Figure 14. Each pixel has a value in the range [0%,100%] corresponding to the density/probability of cover cropping in that pixel.

As noted in Section 3.2.1, there are significant discrepancies between the Fendrich et al. (2023a) results and the Eurostat data they are based on in terms of total land areas at the country level and at the EU level. The authors identify two contributing factors. First, there is a disagreement between the areas identified as agricultural by the Farm Structure Survey (the basis of the Eurostat dataset) and by the CLC which the authors use in their statistical pipeline, requiring a re-scaling step. These disagreements can make a material difference for some countries. Second, the authors point to higher uncertainty at lower cover cropping densities – owing, for example, to the difficulty of detecting small, scattered areas using satellite data in cloudy winter months, and to the trade-off between smoothing assumptions and fidelity to the raw data. They note that 'pragmatically' setting all values below 10% to zero eliminates a large area of low-confidence signal, and brings the results of the two datasets in line.

Figure 14 Cover cropping practice in Germany; pixel colours span the range [0%,100%], with darker colour indicating a higher density of cover cropping

Source: Fendrich et al. (2023a)

C.3. Erosion and soil organic carbon depletion

C.3.1. Erosion

Figure 15, based on Eurostat (2019) shows that 15.8 Mha of the EU's 198 Mha of agricultural land is categorised as severely eroded (using the threshold of 10 t/ha/year of topsoil loss[69]).

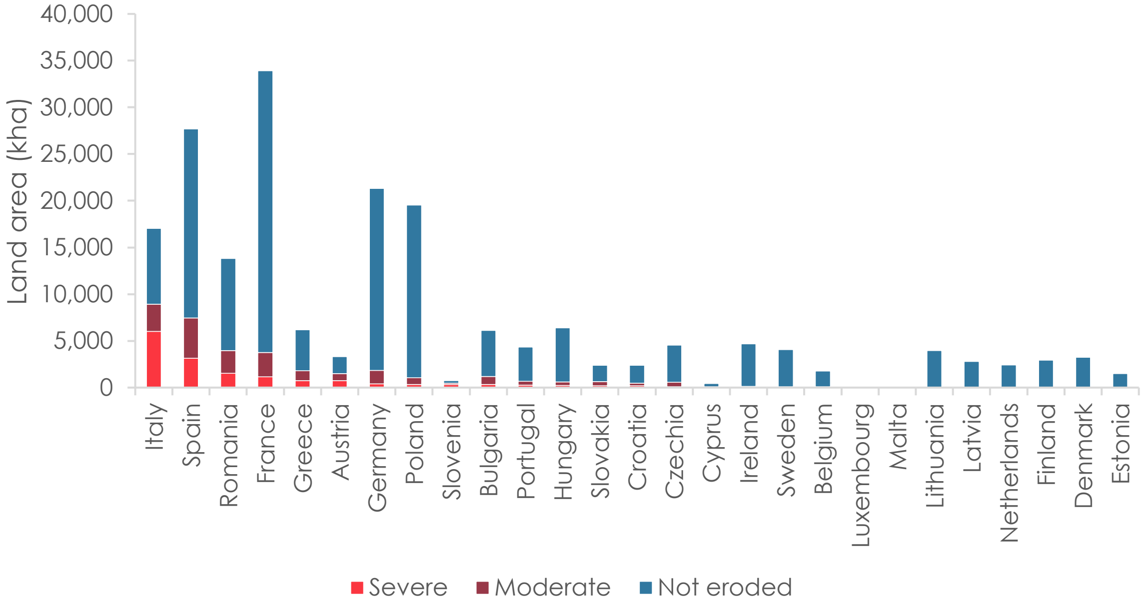

Figure 15 Land area in three soil erosion categories for European countries, ranked by the area of severe erosion
Source: Eurostat (2019)

In order to more accurately intersect eroded and low-SOC areas, we require a dataset with greater spatial resolution. Borrelli et al. (2023b) used a RUSLE-based model to construct a map of EU soil erosion at the 1 ha level. We take a 10 t/ha/year threshold and find the area of severely eroding land in each EU country; a comparison is shown in Figure 16. The two datasets have slightly different scopes: the former is agricultural land (~200 Mha) and the latter is just arable land (~110 Mha): This explains why for some countries the Eurostat value exceeds the Borrelli et al. value. In countries like France and Germany, the situation is reversed, potentially due to the updated parameter values used in the latter study.

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[69] The OECD uses a threshold of 11 t/ha/year (Parris, 1999).

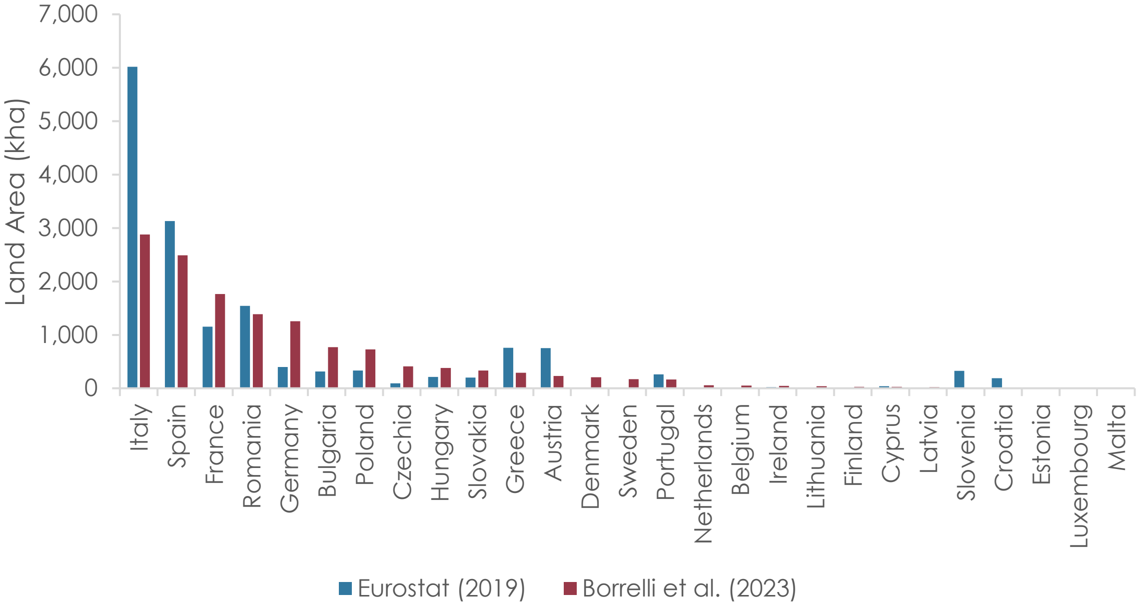

Figure 16 European land areas undergoing severe erosion according to two datasets
Source: Borrelli et al. (2023a); Eurostat (2019)

Figure 17 shows severely eroding areas in Italy according to the Borrelli et al. (2023b) dataset as an illustration.

C.3.2. Soil organic carbon depletion

Soil organic carbon (SOC) refers to the quantity of elemental carbon in organic matter in soil (and therefore excludes inorganic carbon, for example carbon in carbonates). Soil organic carbon is part of soil organic matter (SOM), which includes the quantity of other elements in organic material. SOC and SOM may be used interchangeably in many contexts, as the carbon content of organic matter only varies within a narrow range (50-60%). Thus a soil that is low in SOC (compared to some reference or baseline) will also be low in SOM. A number of SOC and SOM maps exist for the EU, as this is in important indicator of soil health and fertility, as well as representing a considerable (though labile) carbon reservoir. For field measurements it is often more convenient to focus on SOC as this can be determined faster and more cheaply.

In the RED LCA methodology, individual projects may claim emissions credit for increasing SOC, following a sampling and quantification protocol specified in a Commission Implementing Regulation (European Commission, 2022). For more information about this protocol and potential issues with it, see BIKE (2023d). It is unclear whether a 'severely degraded land' designation will require a similar protocol, or whether some other evidence base will be used; but for this report, where we seek to estimate the total potential area of severely degraded land, we consider the results of larger-scale soil carbon surveys rather than the outcomes of individual project measurements.

Figure 17 Severely eroding areas in Italy (100 m resolution dataset)
Source: Borrelli et al. (2023a)

Figure 18 below highlights three approaches that have highlighted the location and extent of SOC-depleted areas in the EU. First, Feeney et al. (2024b) calculated a 'SOC index', calculated as the quotient of an area's observed and typical SOC and applied it to survey measurements in Europe. This classified grid point values into statistical quartiles, characterised as 'Low', 'Intermediate', 'High', or 'Very High' SOC (the published dataset does not allow for a more granular analysis (Feeney et al., 2024c)). 'Low' points would be candidates to narrow the search for severely degraded land; on the other hand, designating a whole quartile as potentially severely degraded would be unduly permissive.

A second approach estimates the maximum SOC that a given soil in a given environment would have under natural conditions (based on calibrated soil models), and calculates the level of degradation compared to this benchmark. In the dataset created by Panagos et al. (2024), based on De Rosa et al. (2024), areas with a SOC content less than 40% of this maximum are flagged as 'unhealthy'. A mapped snapshot is shown in Figure 19. Again, while this could be used to direct the search, it would have to be considered a low bar for the 'severely degraded' classification.

The third approach can be thought of as combining elements of the first two. Breure et al. (2025) developed a classification system that combines SOC loss and the degree to which 'mineral-associated organic carbon' content is depleted compared with its modelled maximum potential value. These two quantities are mapped onto an IPCC-inspired 'hazard-risk' framing, where SOC loss is the hazard, and low mineral associated organic carbon content is the risk.

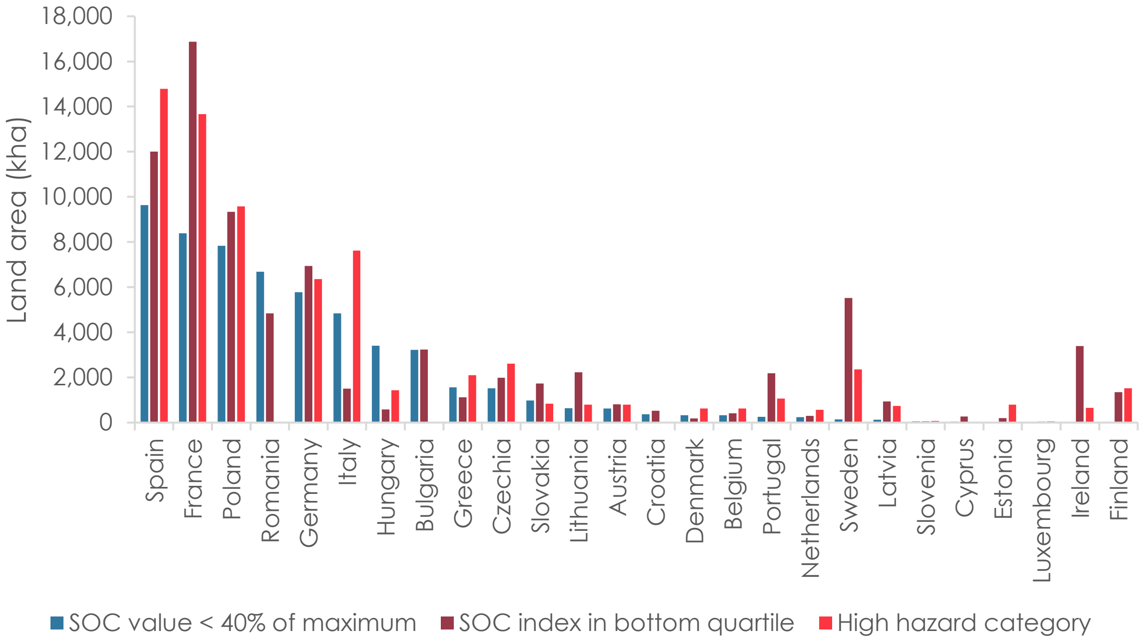

Figure 18 Land area with low SOC according to three quantification approaches, by European country

As mentioned in Section 3.2.2, a single fixed threshold provides a blunt but regulatorily / computationally tractable solution to determining low-SOC areas. The Horizon 2020 project MAGIC assumed a threshold SOC content of less than 0.5% in the topsoil (Elbersen, Verzandvoort, et al., 2022), and reported on this basis that 2.9% of EU agricultural areas (7 Mha) had low SOC, with concentrations in Mediterranean, boreal, and forested areas. We re-emphasise that none of the indicators presented in this sub-section, truly reveal the extent to which low SOC thus determined impairs farmland's ability to grow crops (which we believe to be the spirit of the 'severely degraded land' designation) – that would have to be assessed on a case-by-case basis.

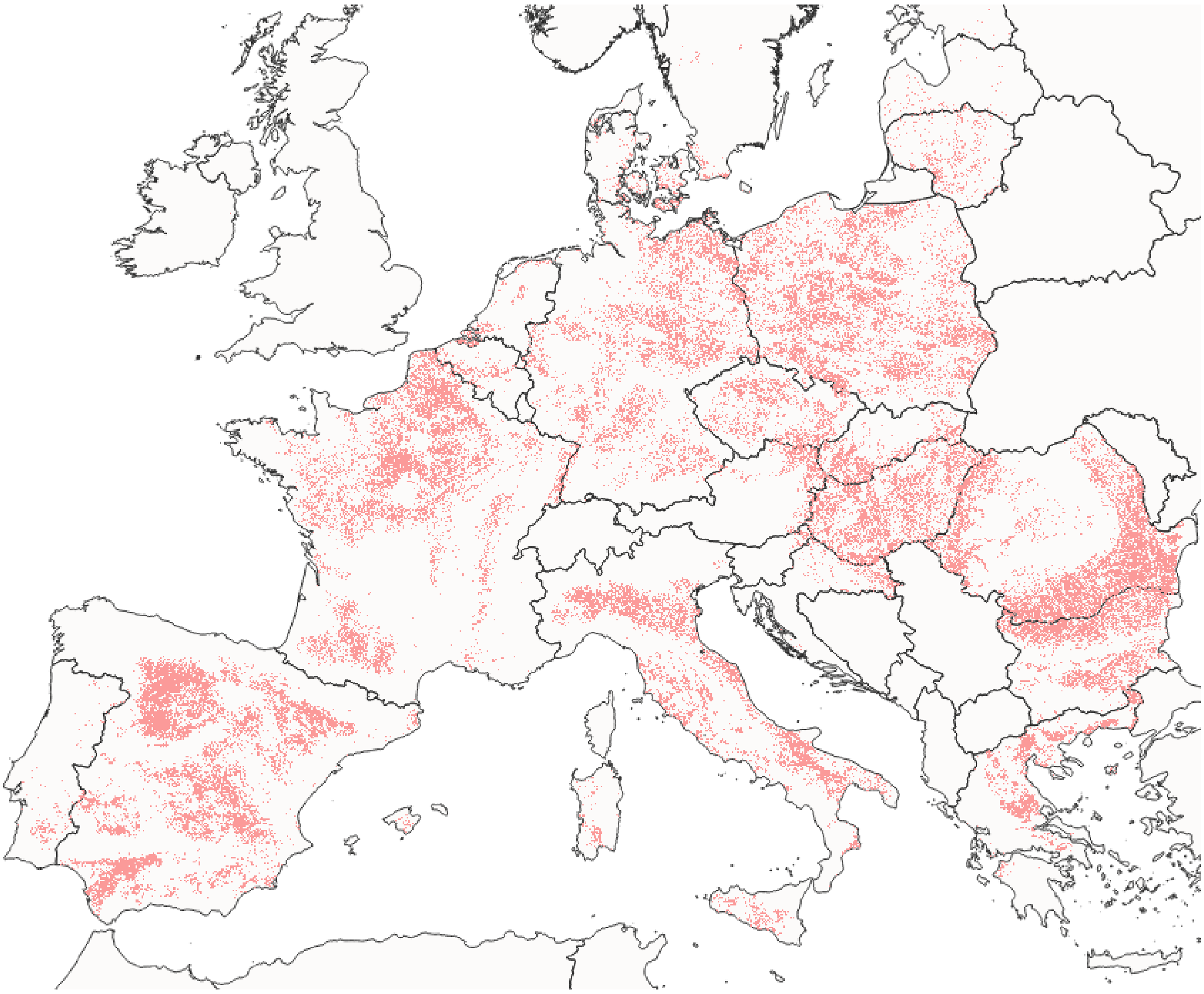

Figure 19 Areas identified as having low SOC (<40% of the maximum value) indicated as red points

Source: Panagos et al. (2024), Indicator 14

C.4. Salinity

Salinity in the EU has been mapped by the European Soil Data Centre (ESDAC), an arm of the European Commission's Joint Research Centre (JRC). The GIS dataset (Tóth, Adhikari, et al., 2008a) classifies areas into six categories: 'saline > 50% of the area', 'sodic > 50% of the area', 'saline < 50% of the area', 'sodic < 50% of the area', 'potentially salt affected', and 'no risk of salt accumulation'. See Figure 20.

The distinction between saline and sodic soil is discussed in Section 1.2.2. Typically classification of soils as saline or sodic relies on a measurement of electroconductivity; however, the literature hosts multiple definitions and thresholds for of varying complexity – depending for instance on soil depth, composition, and pH. In the context of the ESDAC dataset, the authors present a mapping between these layered definitions and a simple ‘low/medium/high’ indicator for salinity and sodicity (Tóth, Adhikari, et al., 2008b). We assume that soils deemed to be sodic but not necessarily saline still count as ‘severely degraded’.

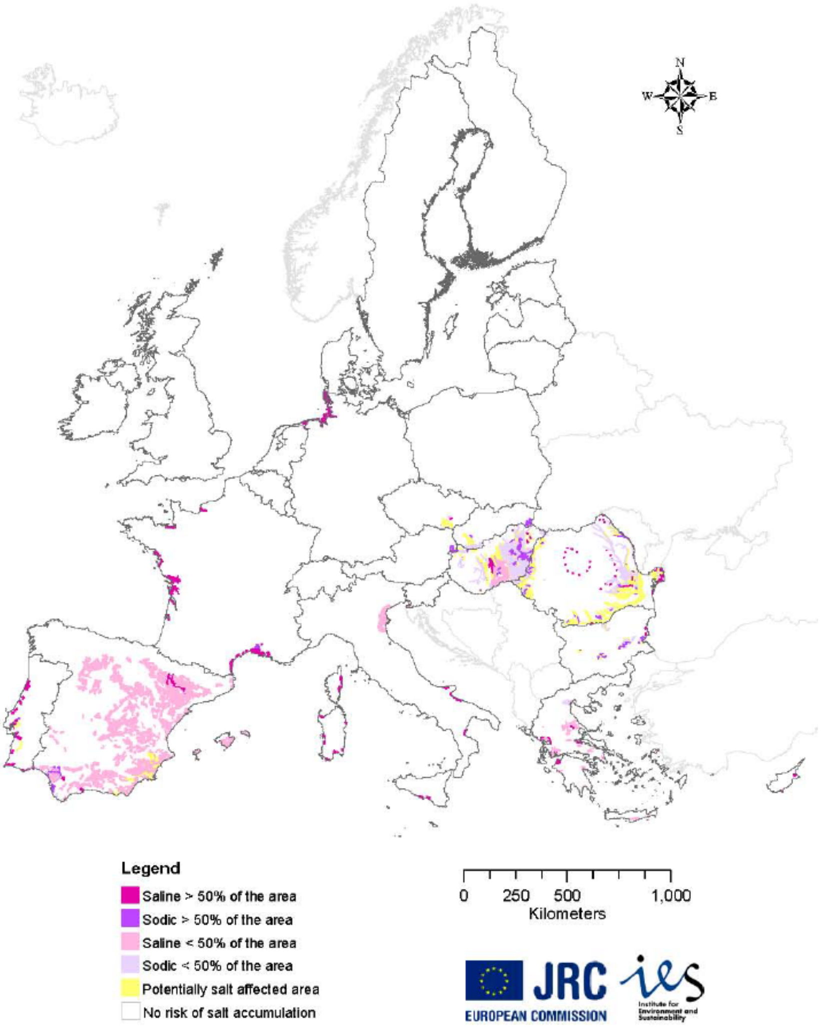

Figure 20 Map of salt-affected areas in the EU

Source: Tóth, Adhikari, et al. (2008b)

The categories introduced above indicate the percentage of the land area that is salt-affected, coarsely distinguishing ‘more than half the indicated area is salt-affected’ versus ‘less than half’. The authors state the accuracy of their input data only allowed for this high-level statistical treatment; this means that any country-wise area estimate derived from the ESDAC dataset will only be indicative at best.

Section 3.2.3 presents such an area estimate based on the ESDAC dataset’s statistical categories. We emphasise that these results should not be taken literally, but they give an indication of which countries are more affected by salt, and of the contribution of sodicity in each country. To arrive at the results in Section 3.2.3, we assumed that 65% of the land area in the '>50%' categories were salt-affected, 10% in the '<50%' categories, and 0% in the 'potentially affected' category.

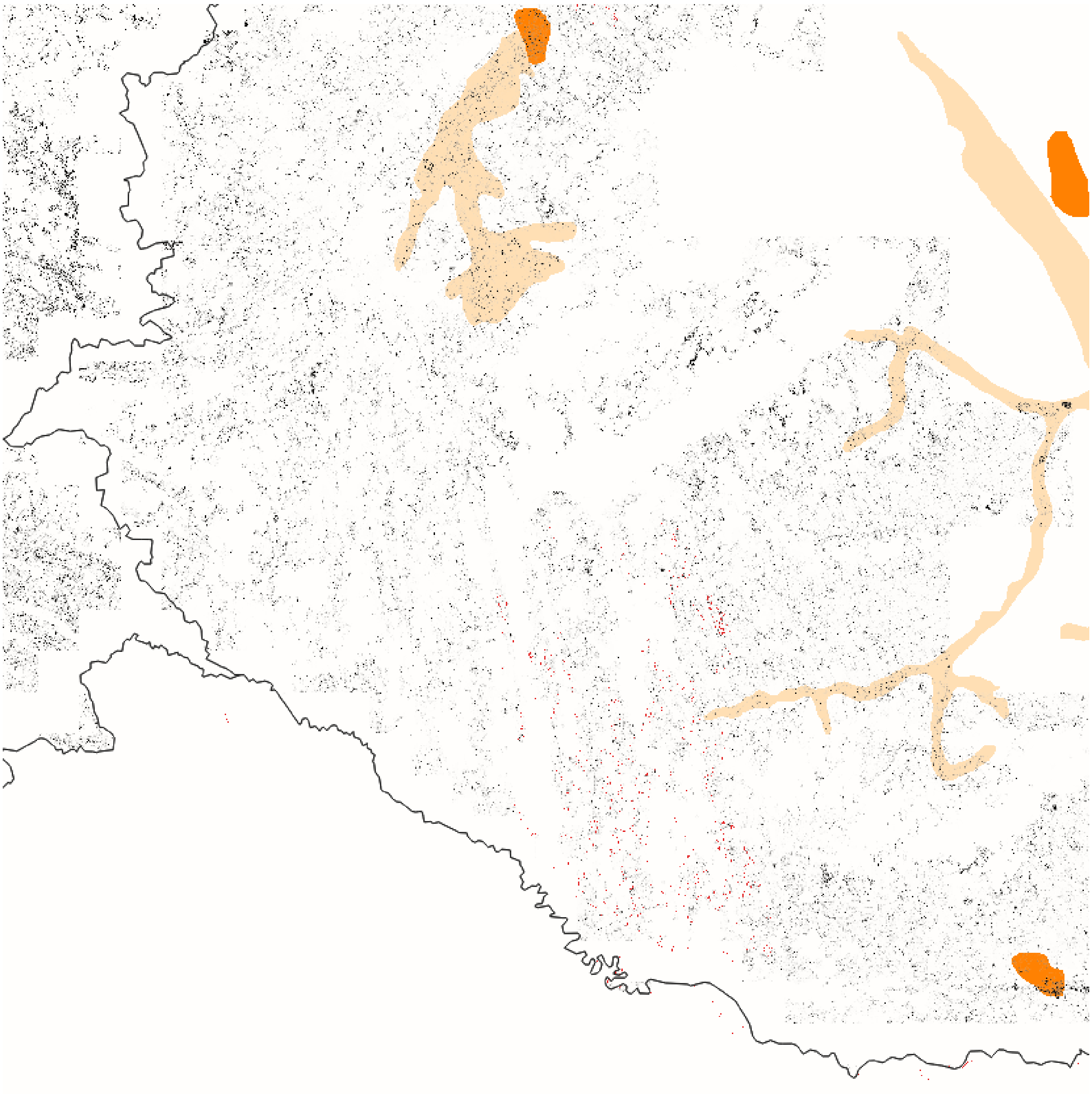

Figure 21 Detail of south-western Hungary (with Slovenia and Austria to the west and Croatia to the south) at 100 m resolution, showing cover cropping intensity not inimical to productive intermediate crops (shades of black), eroded + low SOC (red), low salinity intensity (light orange), and high salinity intensity (orange)

C.5. Land area by country

Table 8 presents the identified land areas of intermediate crops and severely degraded land by EU country. The last two columns show severely degraded land totals with and without the cropland overlap (see Section 3.2.5).

Table 8 **EU land area (in kha) identified as suitable for growing Annex-IX-compliant crops**

Country	Intermediate crops	Severely degraded land			
		Eroded + low SOC	Salinated	Total (including cropland)	Total (excluding cropland)
Austria	274	0	18	18	1
Belgium	269	2	0	2	0
Bulgaria	0	0	60	60	3
Croatia	4	1	0	1	0
Cyprus	0	0	6	6	0
Czechia	335	3	7	9	0
Denmark	291	9	0	9	0
Estonia	19	0	0	0	0
Finland	1	0	0	0	0
France	2,017	56	294	343	71
Germany	2,242	10	1	7	2
Greece	10	13	105	116	1
Hungary	100	6	524	529	81
Ireland	8	0	0	0	0
Italy	415	56	134	184	2
Latvia	45	0	0	0	0
Lithuania	90	1	0	1	0
Luxembourg	9	1	0	1	0
Malta	0	0	0	0	0
Netherlands	223	8	0	8	0
Poland	381	17	0	16	2
Portugal	46	10	95	103	13
Romania	56	34	427	455	85
Slovakia	37	0	48	49	5
Slovenia	26	0	1	1	0
Spain	194	201	826	975	34
Sweden	45	27	0	27	5
Total	7,139	457	2,548	2,922	308

Note: The total severely degraded land is not exactly equal the sum of the salinated and eroded + low SOC component columns owing to slightly overlapping land areas.