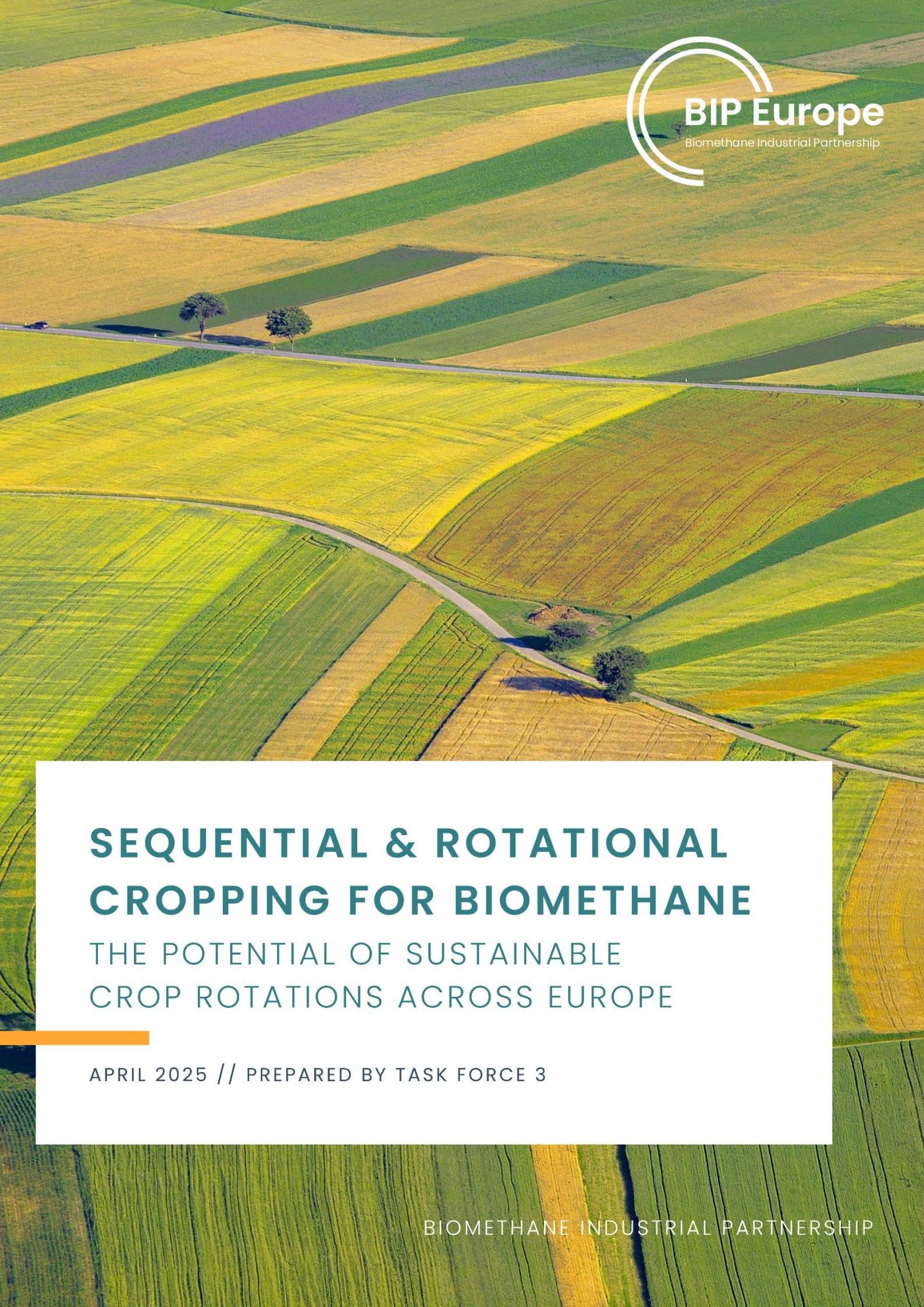

BIP Europe
Biomethane Industrial Partnership

SEQUENTIAL & ROTATIONAL CROPPING FOR BIOMETHANE

THE POTENTIAL OF SUSTAINABLE CROP ROTATIONS ACROSS EUROPE

APRIL 2025 // PREPARED BY TASK FORCE 3

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Imprint

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2025 Biomethane Industrial Partnership

ISBN
9 782960 342826

Date
April 2025

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The potential for sequential & rotational cropping for sustainable biomethane production across Europe

Executive Summary

As a sustainable alternative to fossil gas, which can be stored, distributed and used according to demand, biomethane can play a significant role towards achieving the EU's clean energy objectives. It can also be used to further diversify the EU's gas supplies, phasing out Europe's dependency on Russian fossil fuels and reducing the exposure of consumers to volatile natural gas prices.

For these reasons, there is a clear need to scale-up biomethane by 2030, as outlined in the REPowerEU Plan of 18 May 2022. As a renewable and dispatchable energy source, increasing the production and use of biomethane also helps to address the climate crisis. The EU's biomethane production, either as biogas or its upgraded version, needs to reach 35 billion cubic metres (bcm) per year by 2030 and the estimated investment need for the period amounts to €37 billion.

In order to be attributed to the national and Union's renewable energy target and benefit from the state-aid, biomethane has to be sustainable: feedstock used for biogas and biomethane production has to be sourced sustainably and create such a co-digestion mix and plant design to meet the minimum greenhouse gas emission savings, as defined in the Article 29 of the Directive (EU) 2023/2413 (also called RED II as amended or RED III). The sustainability of biogas and biomethane is defined in Article 29 of RED II as amended, with detailed methodology for GHG emissions calculations as described in Annex VI "Rules for calculating the greenhouse gas impact of biomass fuels and their fossil fuel comparators".

For the purpose of using sustainable biomass for biogas for CHP and biomethane production, specific GreenHouse Gas (GHG) emissions savings have to be achieved.

For biogas for CHP, default values of GHG emissions calculations for biogas from food and feed crops are above such GHG emissions thresholds, but there are opportunities to reduce carbon intensity by calculating actual values that may consider advanced agricultural practices enhancing soil organic carbon fraction into the cultivated soil, use of renewable energy and reducing fossil fertilisers inputs.

For the purpose of producing advanced biofuels or biogas for transport, low-ILUC risk biomass sources must be used. Such feedstocks are listed in Annex IX part A, while other non-food and

feed biomass sources are listed in Annex IX part B (and limited by a cap). Member States are encouraged to set differentiated targets for advanced biofuels and biogas produced from feedstocks listed in Part A of Annex IX and renewable fuels of non-biological origin at national level in order to fulfil the obligation set out in the first subparagraph - point (b) - Article 25 (RED II), in a way that the development of both fuels is promoted and expanded. The share of biofuels and biogas produced from the feedstock listed in Part B of Annex IX in the energy content of fuels and electricity supplied to the transport sector shall, except in Cyprus and Malta, be limited to 1.7 %.

This report discusses practices that fit under the updated Annex IX Part B (Commission Delegated Directive (EU) 2024/1405). The current definition is: "*Intermediate crops, such as catch crops and cover crops, and excluding feedstocks listed in Part A of this Annex, that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained, where not used for the production of biofuel for the aviation sector*[1].'

Given the wide range of climate adaptation practices in agriculture and uncharted territory of intermediate crops practice across the EU27, Member States may, where justified, increase the limit of 1.7%, taking into account the availability of feedstock listed in Part B of Annex IX. Any such increase is to be notified to the Commission, together with the reasons therefor, and shall be subject to approval by the Commission.

The aim of this report is to investigate and highlight how novel and innovative agro-practices based on alternating different crops in the same agro-lands, can lead to multiple benefits for the environment, soil health and biogas production, without affecting food security.

Sustainable novel crop rotations – namely rotational and sequential cropping based on innovative agricultural practices that differ from the intensive mono-cropping system – produced in line with the principles for sustainable growth (see Section 1.3) present a key opportunity across to EU-27 to offer key benefits within the non-food, and agricultural sectors, here with perspective on bioenergy:

[1] This category includes biomass from fallow land.

Energy: Generate additional biomethane

+ Improve energy security
+ Decarbonise gas sector
+ Reduced citizens' exposure to market volatility
+ Present opportunities for BECCS
+ Reduce dependence on seasonality of by-products obtained from agri-food supply chains

Agricultural: Support the transition to sustainable arable farming

+ Cut on-farm GHG emissions
+ Diversify agricultural income
+ Create jobs in the rural economy
+ Enrich biodiversity
+ Increase carbon sequestration in soils
+ Improve soil health
+ Reduce soil erosion
+ Maintain and improve food security
+ Protect natural environments
+ Increase water content in soils

FIGURE 1 KEY BENEFITS OF SUSTAINABLE NOVEL CROP ROTATIONS WITHIN ENERGY AND AGRICULTURAL SECTORS

The development of sequential and rotational crops strongly drives innovation and more generally agro-ecological practices, the basis of regenerative agriculture. This work presents a series of potential rotational and sequential cropping systems, each specific to Europe's different biogeographical regions – Atlantic, Continental, Mediterranean and Boreal (see the EEA, 2002) – and their sub-climates. By assuming the deployment of these regionally-specific crop rotations across Europe's arable land, biomass production from these systems was estimated from each country – and consequently, the theoretical *maximum potential* for biomethane production was quantified.

However, this maximum potential does not represent the real quantity of biomass that can be converted into biogas. To convert estimates into a *deliverable potential*, this report quantified the impact of various environmental and socio-economic constraints, named here as '*correction factors*'. These factors accounted for any impact on food production, different markets for crops, soil readiness and compatibility with different types of farming. This novel approach to modelling biomethane potential from novel crop rotations builds on the work of Magnolo et al. (2021), whose research established the potential of sequential cropping across Europe. The results of the work of Task Force 3.1 suggest that arable farms could sustainably generate the following amount of biogas/biomethane:

TABLE 1 POTENTIAL OF SEQUENTIAL CROPPING ACROSS EUROPE

	EU27
Deliverable potential (bcm)	**44.0 bcm**
Maximum potential (bcm)	**87.0 bcm**

However, further assessment is required to estimate the use of biomass from sequential cropping for other purposes (e.g. lipids for the aviation sector).

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1.

Integrating anearobic digestion

into sustainable arable farming

1 Integrating anaerobic digestion into sustainable arable farming

1.1 Introduction and terminology

A sustainable alternative to fossil gas, which can be stored, distributed and used according to demand, biomethane can play a significant role towards achieving the EU's clean energy objectives. It can also be used to further diversify the EU's gas supplies, phasing out Europe's dependency on Russian fossil fuels and reducing the exposure of consumers to volatile natural gas prices.

For these reasons, there is a clear need to scale-up biomethane by 2030, as outlined in the REPowerEU Plan of 18 May 2022. As a renewable and dispatchable energy source, increasing the production and use of biomethane also helps to address the climate crisis. The EU's biomethane production, either as biogas or its upgraded version, needs to reach 35 billion cubic metres (bcm) per year by 2030 and the estimated investment need for the period amounts to €37 billion. In order to increase the current capacity, new biomethane plants or reconversion of biogas for CHP plants will be considered.

The industry-driven biogas and biomethane potential assessment Gas for Climate (2022) estimates that, by 2030, purpose-grown crops could account for 21% the EU-27's biomethane potential, equating to 8 bcm production per year. The biomethane potential of all other organic feedstocks, including purpose-grown crops, food waste and animal manures, corresponds to 30 bcm; noting that this estimate fails to account for active efforts to prevent and redirect waste or improving efficiency of already existing biogas and biomethane plants, including methane leakages.

In the industry vision, over time, the relative contribution of purpose-grown crops to biomethane's potential increases significantly. By 2050, around 47% of Europe's biomethane potential is derived from crops. At this level, the anaerobic digestion (AD) industry could generate 43 bcm per year, thus displacing a third of the EU's natural gas demand, assuming absence of competition from other non-food sectors in a wider sustainable and circular bioeconomy. However, the Task Force 3.1 report focuses on the hypothesis if all purpose-grown crops would have been used for anaerobic digestion to produce biogas and biomethane (maximum potential).

Crucially, these crops for biogas *must* be grown sustainably – i.e. farming practices may continue indefinitely without resulting in environmental degradation.

Groundbreaking work by the *BiogasDoneRight™* team, led by Prof. Bruce Dale and the Consorzio Italiano Biogas (CIB) (BiogasDoneRight, 2017), demonstrates that crops grown for biogas production can be integrated within arable crop rotations in Italy to deliver a range of benefits to the farm, environment and communities. Their approach enables farmers to generate biogas with minimal impact on food production, while also improving soil health, enhancing agricultural resilience, and increasing farms' economic viability.

The Task Force 3.1 report has been corroborated by numerous biogas-specific studies across Europe (see Magnolo et al. 2021; Guidehouse, 2023), and more broadly worldwide (see Zegada-Lizarazu et al. 2022; Yang et al. 2024).

This win-win approach to arable farming could offer substantial benefits across Europe's energy and agricultural sectors. However, being developed in Italy's Po Valley, the *BiogasDoneRight™* model must be adapted for Europe's varying biogeographical regions, in order to maintain productivity.

The Task Force 3.1 report explores how the principles first introduced by BiogasDoneRight™ could be adapted across Europe to greatly improve the sustainability of arable farming.

The resultant biogas/biomethane can be used to decarbonise heat and transport and used as source of valuable biogenic carbon in the production of non-energy products (chemicals, biomaterials etc). However, the estimates provided by the Task Force 3.1 report consider a scenario where all intermediate crops from the selected arable lands are dedicated to biomethane production, therefore not considering the competition with other biofuels (maximum potential). The authors suggest applying further corrective factors for a thorough assessment of the deliverable potential.

Defining key terms

The agricultural sector uses numerous specialist terms – many of which are not well-defined within EU nor national regulations. For clarity, the following defines a selection of key cropping terms, each relevant to the deployment of novel crop rotations across Europe:

1.1.1 Monocropping

Monocropping involves planting the same crop year after year on the same piece of land. While this can be efficient in terms of equipment and labour, it can lead to problems with soil health, increased pest and disease pressures, and reduced biodiversity.

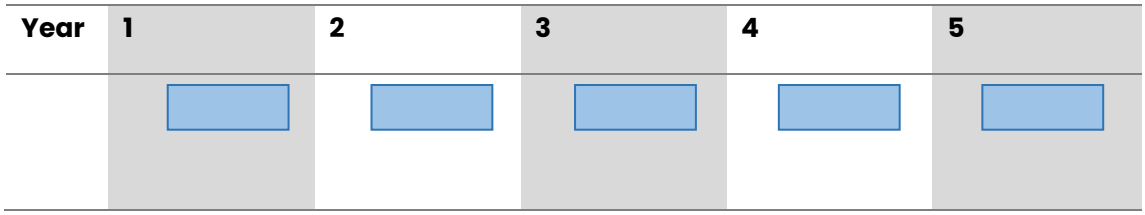


FIGURE 2 MONOCROPPING

1.1.2 Rotational cropping

Rotational cropping involves alternating crops grown on a specific field (or fields) in a planned pattern or sequence in successive crop years so that the same species are not grown without interruption on the same piece of land.

Usually, crops are rotated annually, but rotations can also be multi-annual (Eurostat, 2020) whereby more than one crop is grown per year on average – for example, a field may harvested seven times within a 5-year period.

Although there is no limit to the number of crops used in a rotation, nor in the amount of time it takes to complete, it is commonly accepted to use a threshold of 5 years. For example, a farmer might rotate between wheat, oilseed rape, maize and beans across three different fields in the same year or on the same field in three years.

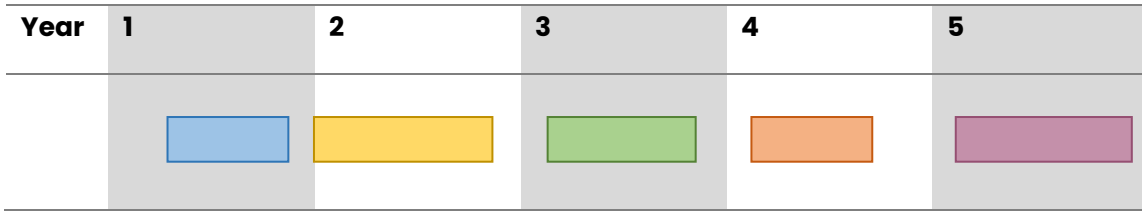


FIGURE 3 ROTATIONAL CROPPING (ONE POSSIBLE COMBINATION)

A long, diverse crop rotation can support the delivery of multiple environmental and agronomic benefits (see Yang et al. 2024) – in many cases:

- **Improve soil fertility**. Growing legumes (e.g., beans) within a rotation increase fertility by fixing nitrogen, a key plant nutrient, within the soil structure. The following crop(s) will consequently benefit from an increased nutrient availability, supporting growth and reducing the demand for additional fertiliser spreading (see Notz et al. 2023). Moreover, by rotating crops, nutrient levels remain stable – no single nutrient is consistently depleted and there is time for other key nutrients to replenish.
- **Increase soil carbon**. The remains of root structures from different crops promote in-soil biodiversity and development of soil humus – with the latter benefitting water retention, crop fertilisation, and carbon sequestration. Higher soil carbon can protect crops against adverse weather conditions, thus building farms' resilience of climate change (see Droste et al. 2020). Furthermore, by incorporating biogas into farm systems, the production and use of digestate can further replenish soils with organic carbon.
- **Enhance crop yields**. Crop rotation can increase yields by up to 25% (Marini et al, 2020). It allows farms to select crops which are best suited to the season and soil at the given time, thus promoting optimal growth.
- **Protect topsoil**. This outermost layer of soil has the highest concentration of nutrients, organic matter and microorganisms – all critical to productivity. When left bare, this layer is vulnerable to erosion, from wind and rain. Crop rotations can maximise the time in which this topsoil is protected by crops.
- **Control pests and disease**. By rotating crops, the ability of pests and diseases to become established is limited. Consequently, fewer carbon-intensive pesticides are required and the crops' vulnerability to disease is reduced (see Huss et al. 2022).

- **Diversify agricultural income**. Each farm can become less financially dependent on single product. Their economic viability is less exposed to market volatility and poor yields of a particular crop (e.g., due to poor weather or disease).

Crop rotation can be considered one of the key factors on the path towards sustainable agriculture (Zani et al. 2022). With adequate soil management practices, crop rotation can improve the soil's physical, chemical, and biological conditions and, consequently, the longevity of the agricultural systems, their fertility, water availability to plants, and crop yields, reduce the costs related to synthetic inputs (including fertilizers, pesticides, and other agrochemicals), and reduce erosion by wind and water, boost biodiversity, and improves the resilience of the agricultural systems against weather (as a general risk), climate change, as well as economic risks (Ibid).

Within this report, ***rotational crops*** are defined as those grown within a long (5+ year) crop rotation, which aligns with the sustainable growth principles[2].

1.1.3 Sequential cropping

Sequential cropping specifically relates to a rotation in which two crops can be grown and harvested within the same year. Note, the term *second crops* is used in certain European countries (e.g. Italy) and may be used interchangeably with the term *sequential crops*.

This practice can greatly increase lands' productivity, by maximising growing time throughout the seasons and minimising time in which soils are left uncovered thus reducing soil erosion and nutrient leaching.

Sequential cropping, however, requires a climate highly favourable to arable farming. The growing season must be long enough to reliably produce two crops per year. This typically means long, warm summers, and an adequate supply of water – either from rainfall, or nearby water systems or aquifers for irrigation. In Europe, these conditions are typically associated with mediterranean regions, although sequential cropping is possible – albeit with lower yields – across much of Europe. Developed in the highly fertile Po Valley, Italy, the *BiogasDoneRight™* model pioneered the use sequential cropping for AD. Two crops could be grown each year – one for food and one for energy – thus mitigating any impact on food production.

Sequential cropping also delivers, and arguably optimises, the environmental and agronomic benefits outlined in Rotational Cropping (Section 1.1.2). It promotes climate resilience through higher plant resource efficiency (space, nutrients, and water) and the natural suppression of insect pests, pathogens, and weeds (Huss et al., 2022). In particular, sequential systems based on legumes increase nitrogen (which is an essential nutrient for plant growth) in the soil. This is the

[2] In crop rotations which harvest grass cuttings over multiple years, the duration of a rotation may be shorter (e.g., 2+ years).

case because nitrogen competition from legumes is lower than in other plants (Rashid et al., 2022).

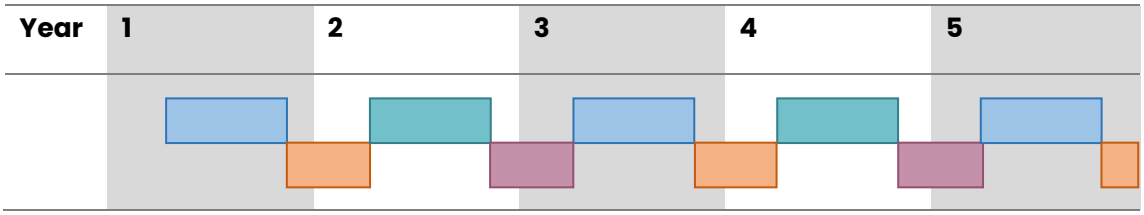


FIGURE 4 SEQUENTIAL CROPPING

Sequential cropping methods have the benefit of creating a ***net increase in total product harvested from a land unit*** in a one or two-crop-year timeframe, compared to a previous cropping system with monocrops in the same timeframe (CIB). Under the right circumstances, sequential and intermediate cropping can ***enhance profitability for farmers***. The sale of biomass crop production is often under contract before planting, so it is a guarantee of income for the farmer.

1.1.4 Intermediate cropping

Much like sequential cropping, intermediate cropping refers to the cultivation of two (or more) crops on a piece of land within a single growing season. However, its definition is typically used more broadly than sequential cropping.

Intermediate crops may be inter-sown with another crop, such that two crop types are growing simultaneously across the same field, or sequentially, such that one crop is grown after another. Regarding the latter, using the term intermediate, rather than sequential, may emphasise the value of one crop over another. An intermediate crop is simply grown between two primary crops – it is likely considered less valuable and less important than the main crop.

Considering intermediate cropping's generalised definition, the report focuses on *sequential cropping*, emphasising the approach's ability to produce two economically valuable and environmentally beneficial crops within a season growing season.

Legislative definition

In the Renewable Energy Directive (RED II) **intermediate crops** are part of the definition on *'food and feed crops'*:

> **"Starch-rich crops, sugar crops or oil crops produced on agricultural land as a main crop excluding residues, waste or ligno-cellulosic material and intermediate crops, such as catch crops and cover crops, provided that the use of such intermediate crops does not trigger demand for additional land"**

Recently, the updated Annex IX, Part B introduced a specific definition:

> **"Intermediate crops, such as catch crops and cover crops, and excluding feedstocks listed in Part A of this Annex, that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained, where not used for the production of biofuel for the aviation sector"**

In a sequential cropping system, land that would otherwise be fallow between the main crop growth cycles is now used to grow a second crop. This second crop can then be used for anaerobic digestion to produce biogas and biomethane if does not trigger additional land demand for food production.

The benefit of sequential cropping is that, as long as the yield of the main crop is not affected, no additional land is needed to grow crops for energy production. At the same time, no land is taken from the main crop as the crop intensification is only in the time dimension.

Sequential and intermediate cropping are influenced by various climatic and geographical factors. For instance, sequential cropping is suitable in areas with a long growing season and high rainfall as it allows for continuous land use (García-Lara et al., 2015). Sequential cropping is therefore less suitable for areas with a short growing season, such as northern European regions. Whereas intermediate cropping can be implemented in high- and low-rainfall areas.

While climatic and geographical aspects play a role in farmers' decision to adopt sequential or intermediate cropping, the choice is not only related to climatic factors.

Indeed, even in areas with a favourable climate, the second crop is often not cultivated because of the lack of economic incentives to overcome production costs, which are not always covered

by revenues. Growing energy crops alongside food and/or feed crops helps shield farmers from fluctuating commodity prices, and diversifying the crop markets mitigates market fluctuations and creates additional and stable income for farmers.

In this way, food, feed, and sustainable fuel are not opposing forces but rather complementary products.

Defining terms

Within a long and diverse crop rotation, it can be difficult to distinguish the intermediate crop, based on its broad definition. While the 'main' crop is often considered to be the more-profitable food crops (e.g., wheat for milling), all crops within a sustainable rotational may be considered fundamental.

FRENCH DECREE

Any crop fulfilling at least one of the following conditions is considered to be the main crop:

1. Single crop harvested on a plot during a calendar year.
2. Crop declared as the main crop in an application for aid under a support scheme under the CAP.
3. Crop harvested on a plot for which no application for aid under a support scheme under the CAP has been made for the harvest year.
4. Crop present on the plot on June 1, or, where applicable, on another date between June 1 and June 15, defined by the representative of the State in the department, with regard to the specific climatic conditions and the cultural practices.
5. Perennial crop mentioned in article R. 411-9-11-1 of the rural and maritime fishing code or crop grown on a plot on which a perennial crop is planted.

Sequential crops are crops grown in the territory of the European Union which are not main crops, and which are sown and harvested on a plot between two main crops harvested in one calendar year or two consecutive calendar years.

1.1.5 Regenerative agriculture

Regenerative agriculture (RA) is a collective term for outcome-based farming systems that nurture and restore soil health, which can protect the climate and water resources and biodiversity and can enhance a farm's *long-term* productivity and profitability.

It comprises a range of techniques, supported by innovative technologies, which can improve soil health, while also reducing GHG emissions and protecting the land's ecosystem. These outcomes mitigate farming's contribution to climate change and builds its resilience to environmental impacts.

1.2 Overview of crop types

Anaerobic digestion (AD) can convert any organic material into biogas – this includes all arable crops.

However, certain crops are typically favoured for digestion according to their biomass yield (t/ha), biogas yield (m^3/t), digestion time (days), and their biochemical composition. Lignified material, such as woody biomass, requires pre-treatment prior to decomposition within a digestion tank. For this reason, typical AD feedstocks tend towards crops that are high in starch and sugars, with lower lignin content, and may be grown sustainably within the local geography. Plants may opt to accept a variety of different crop types to improve digestion processes and derisk supply.

The following explores some of the key crops used across Europe to produce biogas:

- **Maize** [spring/summer crop]
  Responsible for the greatest amount of crop-derived biogas, maize is one of the best-suited crops for AD. Nevertheless, maize is also grown for food and fodder across Europe. Varieties can deliver very high biomass and biogas yields, maximising energy production per hectare. Maize generally prefers warmer conditions, making it generally less suitable for Boreal regions.

- **Rye** [spring/summer or winter crop]
  Commonly grown for food, feed, and energy across Europe – particularly in the *Rye Belt*, an area covering north-eastern Europe (from Germany to the Baltic States). It is tolerant of cold and dry conditions, making it a strong winter cereal.

- **Barley** [spring/summer or winter crop]
  Most commonly grown as animal fodder and as a source of malt for beer (and other foods), barley is also suitable for biogas production. As one of the earliest cultivated grains, there are numerous variants, each adapted to different climatic conditions and end-uses.

- **Wheat** [spring/summer or winter crop]
  The most widely grown cereal worldwide. It is highly versatile with a broad range of uses but is most commonly used to produce food for humans and as an animal feed. In Europe, it is primarily located in lowland regions, with a temperate climate and moderate levels of rain; the most productive wheat regions are found in northern France, Germany, and Czechia. Much like barley, its ancient cultivation has resulted in countless varieties, each suited to different conditions.

- **Triticale** [spring/summer or winter crop]
  Triticale is a hybrid of wheat and rye, it can also be used for food, feed, and energy; for the latter, it is suitable for both biogas and bioethanol production. Due to hybrid vigour, triticale is a hardy crop, more resistant to extreme weather and various pests and disease.

- **Oats** [spring/summer or winter crop]
  Typically grown for food and feed, oats may also be used as a feedstock for biogas. Due to frost risk, summer varieties are the most commonly grown in Central and Eastern Europe.

Winter oats have a higher yield potential and are therefore more frequently planted in Western Europe.

- **Sorghum** [summer crop]
  While it is most commonly grown for food or feed, it is increasingly being used in Europe to produce biogas. Sorghum has a high biomass and biogas yield and represents a potential alternative to maize exhibiting a higher drought resistance due to the extensive root system that allows to an efficient use of water from deep soil layers and minor fertilisation.

- **Grass** [Temporary or permanent crop; or annual crop]
  Grass cultivation can be integrated within various types of farms. It can be grown over several years to provide feed for animals and, increasingly, feedstock for biogas. In northern regions grasses are more competitive plants and have higher yield capacity than, for example, cereal crops. Grass production is very diverse, ranging from protection zones and natural pastures to intensive silage production. Grasses are hardy, tolerant of very wet conditions and may be grown on marginal agricultural land.

- **Legumes** [spring/summer or winter crop]
  Primarily grown for human consumption and fodder, legumes cover a broad range of crops - including beans, soybeans, chickpeas, peanuts, lentils, grass peas, Italian sainfoin (*Hedysarum coronarium L.*) and clover – whose root systems are able to fix nitrogen into the soil. This ability significantly increases soil fertility within a crop rotation, while reducing its demand for artificial fertilisers. At present, just 3% of arable land in Europe is used to grow legumes, despite their ability to holistically improve the sustainability of agriculture.

- **Sugar beet** [spring/summer or winter crop]
  Despite being the world's largest producer of sugar beet, the EU only produces around 20% of the world's sugar (the majority of which is derived from sugar cane). Most of the EU's sugar beet is grown in the northern Europe, including France, Germany, the Netherlands, Poland and Belgium. While most of the sugar beet is grown for food markets, sustainable biogas represents a key alternative market for farmers.

These crops, when grown within a long and diverse rotation, can help build farms' resilience – diversifying income, mitigating climate risk, and embedding sustainable agricultural principles.

1.3 Principles for sustainable growth

Crop rotations are fundamental to sustainable arable agriculture (see Tanveer et al. 2019), within which, crops may be grown to produce biogas via AD. This approach must be accompanied by complementary agricultural practices and technologies, which can ensure the long-term sustainability of our environment and communities.

Having evolved over millennia, agriculture across Europe is highly diverse. Within each region, it has responded and adapted to countless socio-economic and environmental drivers. Consequently, it is not possible to prescribe a set of practices which are universally sustainable

across Europe. Therefore, the following outlines a set of principles, under which novel approaches to arable farming should align with – noting these are not specific to sequential or rotational cropping systems.

1. **GHG emissions**

Agriculture is responsible for around 11% of the EU's annual GHG emissions (EEA, 2022), of which 38% may be derived from the management of soils and fertilisation application, generally associated with the cultivation of arable crops (Mielcarek-Bochenska and Rzeznik, 2021). To deliver the EU's Net Zero by 2050 target, arable farming must significantly cut its GHG emissions. Crucially, markets will increasingly demand low-carbon production from farms, forcing them to decarbonise their processes. Actions *can* include:

i. Reduce the use of conventional, synthetic fertilisers, which are highly carbon-intensive to manufacture, through the application of low GHG emission organic biofertilisers (e.g., digestate) and cultivation of nitrogen-fixing cover crops.
ii. Reduce the use of chemical inputs, such as pesticides and herbicides, which are derived from fossil resources.
iii. Replace fossil-fuelled vehicles and machinery within those powered by renewable energy (e.g., biogas).
iv. Minimise tillage to protect organic carbon in soils, maximising soils' ability to sequester carbon.
v. Enhance nature-based carbon sequestration of farmed land.

2. **Soil health**

Soils are fundamental to all agricultural productivity and therefore to food security. Healthy soils are more productive and more resilient to stress. However, over 60% of European soils are now considered unhealthy as they continue to be subject to severe degradation processes, such as erosion, compaction, organic matter decline, pollution, loss of biodiversity, salinisation and sealing. This damage is the result of unsustainable land use and management, overexploitation and emissions of pollutants (EC, 2023). It is critical that farming practices do not continue degrading soil health, and instead, act to improve it. Actions to restore and improve soil health *can* include:

i. Monitor soil health and implement a plan to restore soil health.
ii. Use rotational or sequential cropping systems to maintain fertility, prevent nutrient depletion, enhance soil structure, control weeds, and suppress diseases and pests.
iii. Minimise tillage to inhibit soil erosion.
iv. Use cover crops to protect the soil from erosion between harvests, improve soil structure, improve water retention, and reduce nitrate leaching.
v. Better target fertilisers and use of biofertilisers (organic fertilisers and soil improvers) to enhance organic content of the soil.

3. **Carbon sequestration**

Soils within the EU27 currently store an estimated 75 gigatons of carbon within its top 30cm (European Parliament, 2022) – the equivalent to 25-years-worth of GHG emissions from these same countries. Over time, intensive agricultural practices have degraded soil carbon in soils, thus shifting carbon into the atmosphere. Sustainable agricultural practices can reverse this trend, increasing its ability to sequester carbon. Actions to increase carbon sequestration in soils *can* include:

i. Measure and monitor soil carbon over time to better understand trends and the impact of agricultural practices.
ii. Increase the crop diversity within a rotation.
iii. Minimise tillage to inhibit soil erosion.
iv. Use of rotational or sequential cropping systems to increase root structures present at different horizons through the soil.
v. Use of cover crops to protect the soil from erosion between harvests, improve soil structure, improve water retention, and reduce nitrate leaching.
vi. Apply organic fertilisers (e.g., digestate) to the soil to replenish organic carbon.

4. **Biodiversity**

Biodiversity is essential for the health of all environments, contributing to ecosystem stability, resilience, and the provision of vital resources and services. On farm, biodiversity can mitigate pests and disease and increase productivity, thus reducing the demand for costly and non-renewable chemical inputs. It is estimated that every €1 spent on conserving biodiversity delivers wider benefits valued at €100 (EC, 2020) – yet biodiversity across Europe is in decline. Actions to conserve/improve biodiversity *can* include:

i. Increase diversity within a crop rotation.
ii. Use long and diverse crop rotations.
iii. Use cover crops between harvests to protect the soil, improve its structure, and provide habitat and food for beneficial insects.
iv. Minimise tillage to inhibit soil erosion to improve soil structure and microbial diversity, reducing disturbance to soil-dwelling organisms.
v. Sow wildflower strips along field margins or within fields to attract pollinators, insects, and birds, enhancing biodiversity.
vi. Develop hedgerows, wetlands and ponds, and forested areas to create new habitats for wildlife.

5. **Agricultural resilience**

Building agricultural resilience reduces farms' vulnerability to impacts of climate change and political/economic variability. Economic and financial resilience are essential to a sustainable agricultural sector across Europe. Farms must be commercially viable and capable of adapting to new external drivers. Actions to enhance agricultural resilience can include:

i. Use diverse crop rotations to reduce the dependence on individual crop varieties.

ii. Grow crops for different markets, such as food and energy, to diversify income.
iii. Improve soil health (see point 2).
iv. Improve biodiversity (see point 4).

6. **Production**

Farms are fundamental to food (and energy) security. Therefore, the agricultural sector's transition to more-sustainable practices must ensure that food, fodder, and sustainable energy production is maintained. Sustainable farming balances production with positive environmental outcomes.

i. Maintain reasonable yields from land.
ii. Select crop types which suit local/regional demand.

7. **Pollution and contamination**

Certain agricultural practices risk damaging the environment beyond the farm-gate, namely via air and water pollution. For example, fertilisers (both artificial and organic) can release ammonia into the air, harmful to human health, and leach excessive nutrients into waterways, resulting in eutrophication of freshwater. Sustainable farming farm takes measures to mitigate these risks wherever possible. Possible actions to reduce/minimise pollution can be:

i. Develop a nutrient management plan to assess the crop and/or soil nutrient demand.
ii. Do not apply excessive levels of chemical inputs.
iii. Avoid spreading chemical inputs if the weather increases contamination risk.
iv. Spread organic fertilisers using low emission techniques, such as injection, to minimise the volatilisation of ammonia.
v. Improve manure management.

The principles of sustainable agriculture should also align with the UN's 17 Sustainable Development Goals (SDGs):



FIGURE 5 UN SUSTAINABLE DEVELOPMENT GOALS

1.4 Sustainably producing food and biogas

In line with the principles for sustainable growth, arable farms can sustainably grow food *and* non-food crops. Long-term food security can only be assured with the use of sustainable agricultural practices. The benefits of crop rotations are well-established and broad ranging (see Section 1.1.2). They are essential for sustainable crop farming.

Within a long (5+ years) and diverse crop rotation, crops grown for biogas production can be cultivated intermittently between a variety of food crops. Representing rotational or sequential crops within the rotation, these crops for biomethane production can deliver multiple agronomic advantages, supporting a farms' transition to sustainable practices.

As highlighted by *BiogasDoneRight™*, the integration of sustainable crops within a crop rotation can build farms' resilience to both environmental and economic change – essential for a sustainable agricultural sector. Such an approach supports the diversification of revenue, reduced exposure to volatile markets for chemical inputs, and restoration of soil health.

Land is a critical and finite resource, capable of addressing multiple issues facing Europe:

- Food security
- Energy security
- Biodiversity
- GHG emissions
- Environmental health

Therefore, lands' management must seek to address multiple of these key issues simultaneously. Sequential and rotational cropping systems, integrated with biogas production, can support the delivery of positive outcome across all these pressing issues faced across Europe.

Sequential and rotational crop rotations allow sustainable crops to be integrated with biomethane production to be grown alongside food crops, thus improving both food and energy security simultaneously.

Detailed approach:

Sequential crops are introduced, as an additional crop into an existing crop rotation, during periods where the land is usually bare (not productive) between two main crops. Any crop which is grown as 'sequential crop', being it a starch/sugar/oil rich crop, own clear advantages:

1. Enhanced photosynthesis activity: CO_2 concentrations in the atmosphere are reduced, by producing more carbon for the soil and energy.
2. Additionality: the biomass produced is additional to the output provided by the existing cropping systems (main crop). They do not displace food and feed.
3. Positive effects on the environment and soil carbon balance: prolonged soil coverage gives positive effects on biodiversity increasing; enhancing of soil fertility; reduction of losses due to nitrate leaching into groundwater and run-off of superficial soil particles; increasing of nutrient recycling related to growing crops in winter; less impact of weeds and diseases and consequently less use of pesticides.

For the same reasons, it is not a coincidence that the maintenance of cover crops is a practice adopted in organic farming and regenerative agriculture and is part of the agro-environmental measures of current and presumably future Rural Development Programs (RDP).

For example:

Grass in the context of the rotational cropping system.

It should be noted that grasses have not been considered within past assessments of biogas potential – except for Germany (permanent grassland).

To adapt sustainable agricultural practices into northern regions, where sequential cropping is infeasible, grasslands play an important role in it. To understand the characteristics of northern growing season, catch crops/cover crops are good case in point: Due to short growing season, the catch crop yield of the grain farming is relatively low while biomass is profitable to reincorporate into the soil as green manure instead of collecting the biomass for AD.

In many countries, the grass used for fodder production and the grass reserve for food production (not in active agricultural use in that crop year, but still quickly usable for food production) can represent a large arable area. For example, in Finland, grassland (cultivated grassland in the CAP; permanent grassland was 1% of the grassland in 2022) accounts for 50% of the arable land, corresponding to approximately 1 million hectares. It would be possible to use part of this grass in the production of biogas without affecting food production and in addition, it would bring many agro-economic benefits as mentioned in the "BiogasDoneRight" concept. Note that in many countries, the amount of animal production is decreasing, which frees up the arable land needed for fodder production. In this work, it is therefore important to also take into account the development direction of agricultural production.

The actual availability of grass that can be allocated for biogas production will depend on the local conditions, management practices as well as the future trends and developments of the ruminant population. Unfortunately, the current share of grass already used for biogas in the EU has not been extensively identified.

Perennial grasses have multiple advantages on sustainable farming:

1. By diversifying and increasing crop rotations including deep-rooted grasses on all farms, soil structure and water holding capacity can be improved. When also added to the rotation nitrogen-fixing plants, the use of artificial fertilisers can be decreased.
2. Positive effects on the environment and soil carbon balance: soil coverage with deep-rooted grasses and legumes gives positive effects on biodiversity; enhancement of soil fertility; reduction of losses due to nitrate leaching into groundwater and run-off of superficial soil particles; increasing of nutrient recycling related to growing crops in winter; less impact of weeds and diseases and consequently less use of herbicides and other pesticides.
3. Deep-rooted grasses are efficient in capturing and storing atmospheric carbon dioxide.
4. Soil productivity and fertility can be enhanced in cereal farming practices by adding grasses into crop rotation. This will in the long run enhance the yield potential of cash crops.
5. Grasses in ruminant farming systems include considerably unexploited potential to increase yields, without displacing feed production. This surplus part could be used for AD.



2.

Biogas crop potential

across Europe

2 Biogas crop potential across Europe

To assess the potential of biogas from novel crop rotations, the research subdivided Europe into the biogeographic regions defined by the European Environmental Agency (2017):

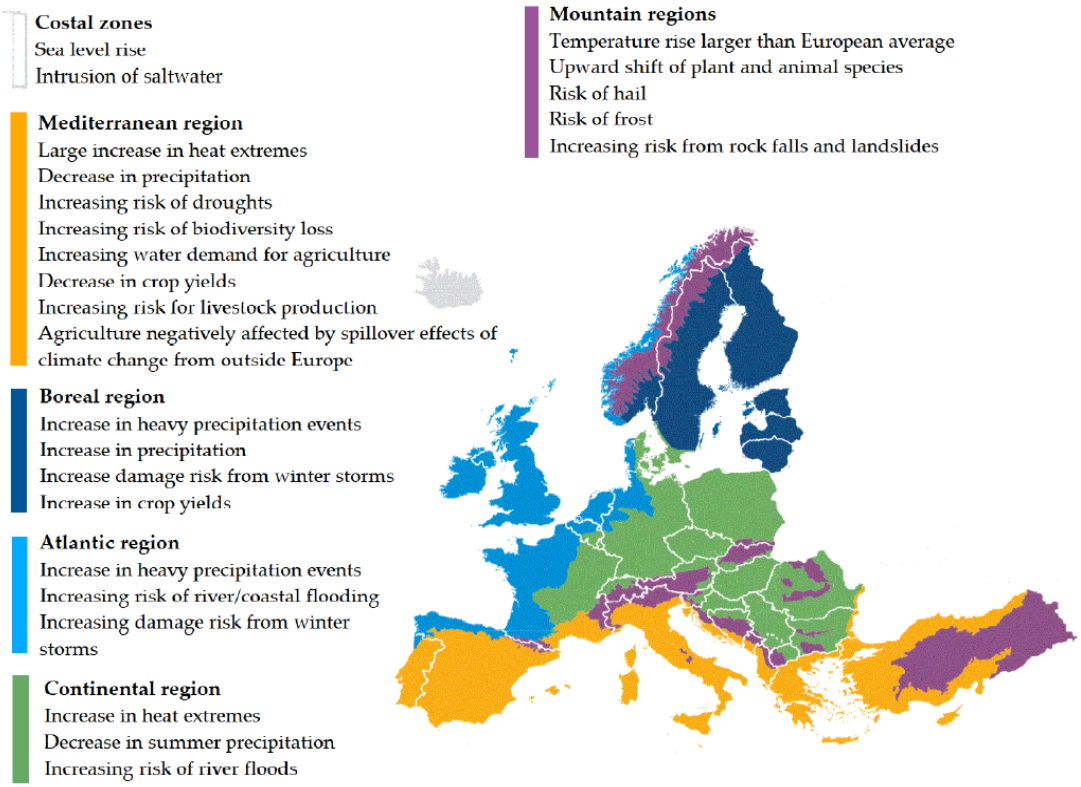


FIGURE 6 BIOGEOGRAPHIC REGIONS IN EUROPE

Methodology for assessing the maximum biomethane potential

For each region and sub-regions across Europe, exemplary crop rotations were designed, each incorporating sustainable biogas crops into the rotation. Average crop- and biogas-yields expected within each region were further ascribed to each crop rotation. This approach enables the estimation of biomethane potential according to the deployment of these rotations (in hectares).

The **maximum biomethane potential** is subsequently assessed by applying exemplary crop rotations to 100% of arable land within each country (data from Eurostat, 2021), where sequential/rotational cropping system could be implemented. For countries which include multiple biogeographical regions, the total arable land is proportioned according to each regions' coverage (see table below). In reality, arable land will not necessarily be distributed across a country, and thus in the same proportion as biogeographical regional coverage; nevertheless, without more detailed data, this approach permits a reasonable assessment of countries' suitability to different crop rotations.

In boreal regions, where sequential or intermediate cropping systems are not practicable for AD due to short growing season, maximum biogas potential of rotational grasses must be recognised individually, in such a way that food or feed production do not be imperilled.

The **deliverable biomethane potential** is then assessed through the application of various correction factors, accounting for various drivers which may impact the deployment of sequential and rotational approaches (*see chapter 3).*

The following table estimates the proportion of land within each biogeographical region for each country:

	%				
	Mediterranean	**Continental**	**Atlantic**	**Boreal**	**Mountain**
Austria		20			80
Belgium		50	50		
Bulgaria		90			10
Croatia	40	50			10
Cyprus	100				
Czechia		100			
Denmark		70	30		
Estonia				100	
Finland				100	
France	20	30	50		
Germany		80	20		
Greece	100				
Hungary		100			
Ireland			100		
Italy	90				10
Latvia				100	
Lithuania		20		80	
Luxembourg		100			
Malta	100				
The Netherlands			100		
Poland		100			
Portugal	100				
Romania		80			20
Slovakia		10			90
Slovenia		80			20
Spain	90		10		
Sweden				80	20

2.1 Mediterranean

TABLE 2 OVERVIEW MEDITERRANEAN (ADAPTED FROM EUROPEAN ENVIRONMENT AGENCY, 2017)



CLIMATE

- Hot summers and mild winters
- Prevailing aridity and desert conditions
- Climate change forecast to intensify aridification

SOIL

- Mineral rich
- Generally low organic content and vulnerable to erosion
- Intensive irrigation often deployed at arable farms

GEOMORPHOLOGY

- Highly variable,
- Characterised by hilly mountainous landscapes and rocky coastlines.

Area	1,200,000 km²
EU27 countries	Spain, Italy, Greece, Portugal, France, Cyprus, Croatia, Malta
Primary habitat types	Agriculture (36%) Heathlands and scrubs (29%) Forest / other woodland (25%)

There are a range of crops that could be included within a sustainable crop rotation, including:

- Cereals: triticale, wheat, sorghum, barley, oats and rye.
- Fodder crops: grasses and legumes.
- Other cellulosic crops: silphium, sorghum-Sudan grass, thistle, Arundo Donax.

The following provides a few examples of potential rotations, suitable for different conditions within the Mediterranean biogeographical region.

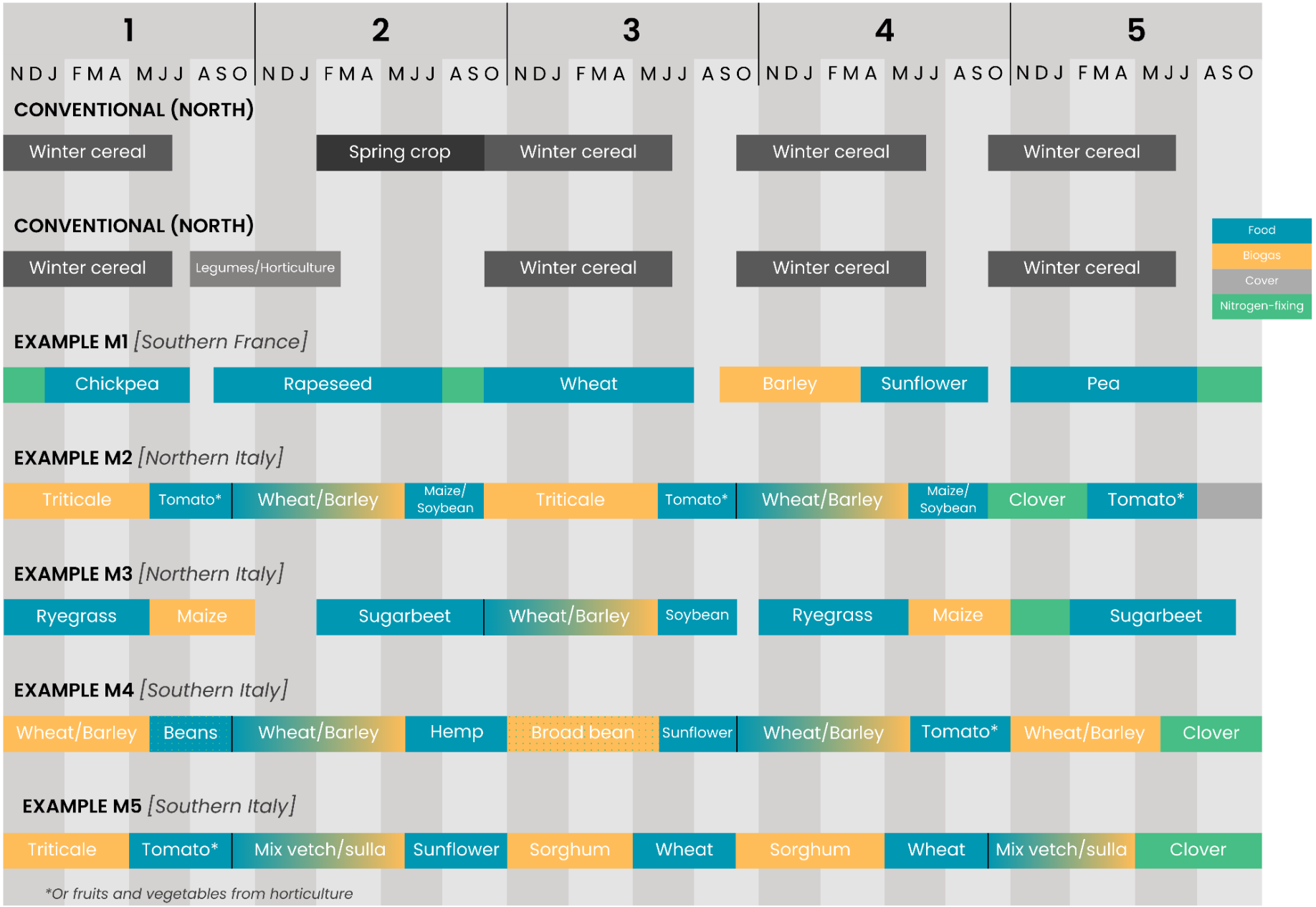


FIGURE 7 EXAMPLES OF POTENTIAL MEDITERRANEAN CROPPING SYSTEMS

TABLE 3 EXAMPLES OF POTENTIAL MEDITERRANEAN CROPPING SYSTEMS

	Potential subregions	Description	Advantages	Disadvantages / Trade-offs
Conventional	*All*	*Consecutive cereal production with a single break crop grown every 3-5 years; soil is often left uncovered between crops.* Cereals are often favoured due to their comparatively high profitability, thus supporting farmers' short-term financial security. However, this monocropping approach is **unsustainable** over time, greatly reducing the farm's resilience to environmental and economic stresses.	+ [Short-term] Relatively profitable	- Reduces crop yields over time - Increases GHG emissions from crop production - Increases the vulnerability to extreme weather events - Depletes soil nutrients, increasing the dependence on artificial fertilisers - Depletes soil carbon, reducing its ability to retain water and sequester carbon - Increases crops' susceptibility to pests and diseases, increasing the dependence on chemical inputs - Increases financially vulnerable to volatility in cereals market
Example M1 France	*France, Spain, Portugal*	*Diverse crop rotations comprising 4+ different crop types; nitrogen-fixing crops used intermittently improve soil fertility between cultivation.* Crop rotations retain a strong focus on cereal production. Cereals are highly versatile, being suitable for food/feed or biogas production, thus mitigating risk and improving profitability. Purpose-grown bioenergy crops (e.g., maize) can be planted intermittently as a break crop, preventing the development of cereal-based disease/pests.	+ Delivers sustainable food and fuel + Offers greatly flexibility + Increase crop yields + Improves soil health + Diversify agricultural income + Reduces demand for pesticide/herbicides + Reduces demand for artificial fertilisers	- [Short-term] reduction to income - May require training farmers about regenerative farming techniques - [Short-term] May require more water availability for irrigation
Example M2 Northerly	*Northern Italy, Croatia*			
Example M3 Northerly	*Northern Italy, Croatia*			
Example M4 Southerly	*Southern Italy, Greece*			

Example M5 Southerly	*Southern Italy, Greece*	Similarly, beans may be grown for biogas or for food, while also improving soil fertility by fixing nitrogen. This significantly reduces the need for artificial fertilisers during the subsequent harvest. Digestate is also spread back to land to replenish soil carbon and provide a renewable source of nutrients (EJP, 2024). These rotations **sustainably** produce food and energy.	+ Enhances biodiversity + Supports the decarbonisation of agricultural (and energy) + Increase job in agriculture + Reduce depopulation of rural areas	

Further to the sequential cropping systems detailed above, the following identifies some of the key summer and winter crops which may be alternated each year for food/feed (**blue**) and biogas (**orange**) end-uses:

TABLE 4 KEY SUMMER AND WINTER CROPS IN THE MEDITERRANEAN

	WINTER CROPS	SUMMER CROPS
Po River Valley	Triticale	Maize or Soy or Tomato
	Ryegrass	Maize or Soy or Tomato
	Wheat, Barley	Sorghum
	Forage mixes	Maize or Soy or Tomato
	Wheat, barley	Maize grain
	Horticultural crops	Sorghum
	Wheat	Maize silage
Central-South Italy	Legumes mixtures/grains	Legume grains / Sorghum
	Wheat	Italian sainfoin
	Wheat	Sorghum

Source: *Selvaggi et al. (2017)*

These different crops may be substituted into the sequential crop rotation, in place of similar summer or winter crops. Again, this approach greatly improves agricultural resilience, as the farmer can respond to environmental and economic conditions, adapting the rotation to maximise output.

Biomethane potential

Based on the potential Mediterranean sustainable crop rotations explored here, the region's biomethane potential can be estimated by country:

TABLE 5 BIOMETHANE POTENTIAL PER COUNTRY IN THE MEDITERRANEAN

Country	Total arable land (ha)	Proportion of land in Mediterranean's biogeographical region (%)	Crop rotation assumed	Average annual biomass grown for AD (tonnes)	Biomethane max potential per year (bcm)
Croatia	856,740	40%	2	2,313,198	0.7
Cyprus	95,240	100%	5	642,870	0.2
France	18,044,450	20%	1	7,939,558	2.4
Greece	1,696,550	100%	4	9,331,025	2.8
Italy	6,905,950	90%	3 (50%) & 4 (50%)	42,730,566	12.7

Malta	7,780	100%	5	52,515	0.0
Portugal	967,280	90%	1	1,915,214	0.6
Spain	11,732,660	90%	1(50%) & 5(50%)	27,813,714	8.2

MEDITERRANEAN-SPECIFIC ASSUMPTIONS

Biomethane content in biogas	= ***52%***	*Dinuccio et al. (2010)*
Biomass yield of barley	= ***11.0*** *tDM/ha*	*L'Informatore Agrario (2015)*
Biogas yield of barley	= ***570*** *m^3/tDM*	*L'Informatore Agrario (2015)*
Biomass yield of triticale	= ***13.5*** *tDM/ha*	*L'Informatore Agrario (2015)*
Biogas yield of triticale	= ***570*** *m^3/tDM*	*L'Informatore Agrario (2015)*
Biomass yield of maize	= ***16.5*** *tDM/ha*	*Grillo et al. (2021)*
Biogas yield of maize	= ***620*** *m^3/tDM*	*Grillo et al. (2021)*

In total, the Mediterranean region has a maximum biomethane potential from sequential cropping of **27.5 bcm** per year.

2.2 Continental

TABLE 6 OVERVIEW CONTINENTAL (ADAPTED FROM EUROPEAN ENVIRONMENT AGENCY, 2017)



CLIMATE

- Warm summers and cold winters
- Rainfall most abundant in the summer

SOIL

- Highly fertile and well-suited to arable agriculture
- Moisture surplus in the north, declining to the south
- High organic content (particularly in the south)

GEOMORPHOLOGY

- Generally flat in the north; hilly further south
- Large floodplains surround key rivers: Danube, Desna, Dnepr, Dnestr, Elbe, Loire, Oder, Pripyat, Rhine, Vistula and Volga
- Shallow lakes are common

Area	2,700,000 km^2
EU27 countries	Germany, Poland, France, Romania, Bulgaria, Czech Republic, Italy, Austria, Belgium, Denmark, Croatia, Luxembourg, Sweden, Slovakia, Slovenia
BIP Task Force 6	Ukraine
Primary habitat types	Agriculture and gardens (52%) Forest / other woodland (27%) Grassland (14%)

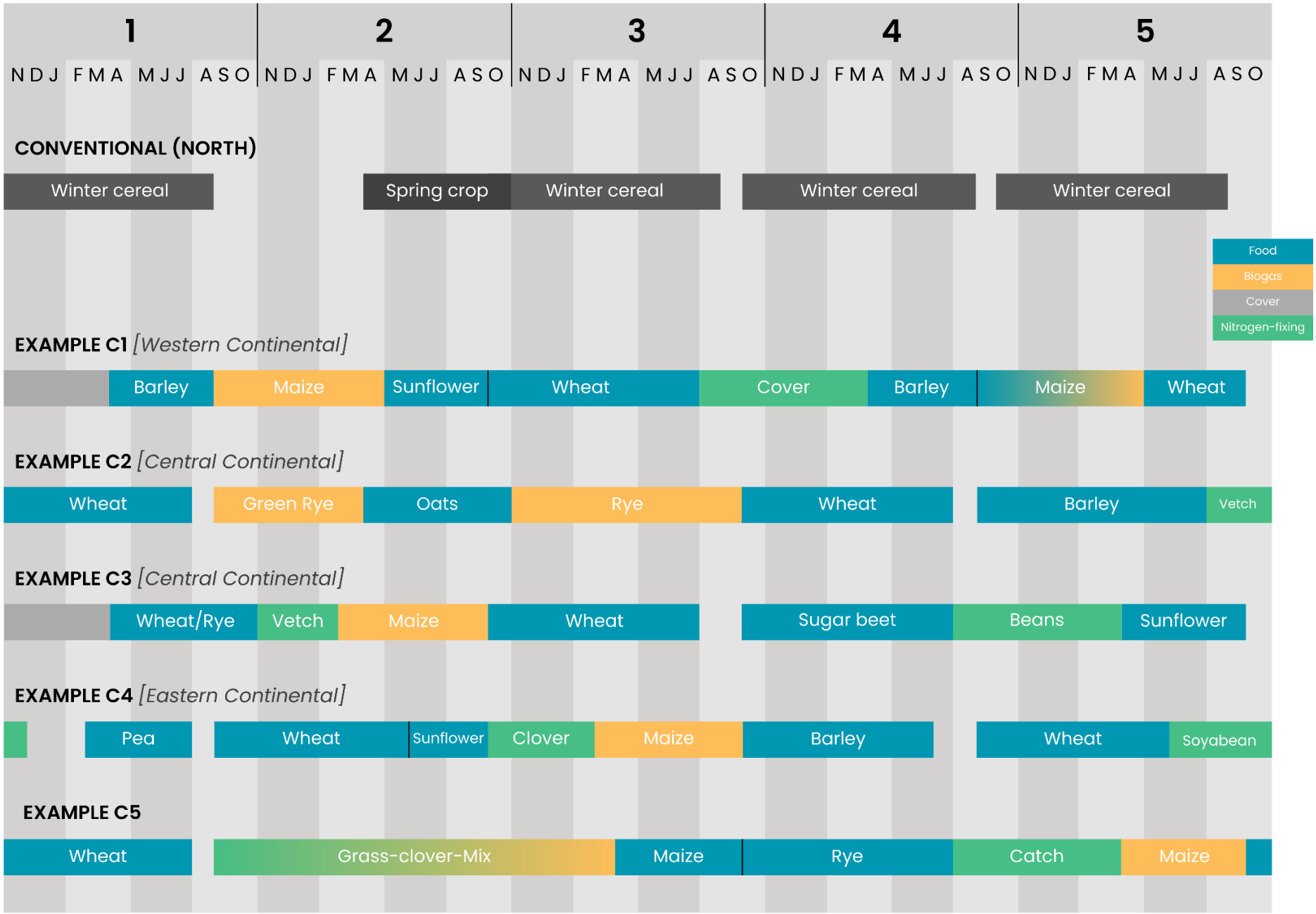


FIGURE 8 EXAMPLES OF POTENTIAL CONTINENTAL CROPPING SYSTEMS

TABLE 7 EXAMPLES OF POTENTIAL CONTINENTAL CROPPING SYSTEMS

	Potential subregions	Description	Advantages	Disadvantages / Trade-offs
Conventional	All	*One crop is grown per year, typically within the summer growing season. Soil is often left uncovered between harvests.* Cereals are consecutively grown for 3-5 year, with little or no change in crop variants over time. Intensive agricultural practices may be deployed to maintain high crop yields; these may include excessive use of artificial fertilisers, pesticides and herbicides, and extensive tillage before cultivation. Cereals are preferentially grown due to their relatively high profitability. However, this approach is environmentally **unsustainable** over time.	+ [Short-term] Relatively profitable + [Short-term] High food production + Relatively simple to deploy	- Reduces crop yields over time - Increases GHG emissions from crop production - Increases the vulnerability to extreme weather events - Depletes soil nutrients, increasing the dependence on artificial fertilisers - Depletes soil carbon, reducing its ability to retain water and sequester carbon - Increases crops' susceptibility to pests and diseases, increasing the dependence on chemical inputs - Increases financially vulnerable to volatility in cereals market
Example C1 *Western continental*	*France, Germany, Belgium*	*Long and diverse crop rotation comprising 5+ different crop types. Nitrogen-fixing crops provide cover between harvests. Biogas crops may be established over summer or winter.* To optimise food production and profitability, crop rotations maintain a strong focus on cereal growth, often wheat. A variety of biogas crops may be grown as a primary or	+ Delivers sustainable food and fuel + Increase crop yields + Improves soil health + Diversify agricultural income + Reduces demand for pesticide/herbicides	- [Short-term] reduction to income - May require training farmers about regenerative farming techniques
Example C2 *Central continental*	*Germany, Poland, Denmark, Czechia*			
Example C3 *Central continental*	*Germany, Poland,*			

	Denmark, Czechia	break crops, namely rye or maize respectively.	+ Reduces demand for artificial fertilisers + Enhances biodiversity + Supports the decarbonisation of agricultural (and energy)	
Example C4 *Eastern continental*	*Bulgaria, Romania, Slovenia, Ukraine*	Cover crops contain nitrogen-fixing species to improve soil fertility and reduce the demand for carbon-intensive artificial fertilisers. Certain variants can further offer food/feed output, such as beans. Digestate is also spread back to land to replenish soil carbon and provide a renewable source of nutrients. These rotations **sustainably** produce food and energy.		
Example C5	*All*	*Crop rotation includes an extended 18-month period of grass-clover-mix – the duration of which can be increased further to 3-5 years.* This approach represents a modification to Examples C1-4 to include a prolonged period of mixed grass-clover growth. This biomass is harvested 2-3 times per year for food/feed or biogas purposes. This plant mix offer substantial benefits to soil health, enriching its nitrogen content, sequestering carbon, and improve its structure.		

Biomethane potential

Based on the Continental's possible sustainable crop rotations, the biomethane potential across Europe's continental regions can be explored:

TABLE 8 BIOMETHANE POTENTIAL PER COUNTRY IN THE CONTINENTAL REGION

Country	Total arable land (ha)	Proportion of land within the Continental biogeographical region (%)	Crop rotation assumed	Average annual biomass grown for AD (tonnes)	Biomethane max potential per year (bcm)
Austria	1,322,920	20%	2	714,377	0.2
Belgium	870,420	50%	1	1,827,882	0.6
Bulgaria	3,487,750	90%	4	8,789,130	2.8
Croatia	856,740	50%	3	1,199,436	0.4
Czechia	2,480,940	100%	4	6,946,632	2.2
Denmark	2,357,950	70%	2	4,456,526	1.3
France	18,044,450	30%	1	22,736,007	7.3
Germany	11,657,900	80%	$2^{(50\%)}$ & $3^{(50\%)}$	25,647,380	7.6
Hungary	4,141,840	100%	3	11,597,152	3.7
Lithuania	2,277,030	20%	3	1,275,137	0.4
Luxembourg	62,710	100%	2	169,317	0.1
Poland	11,078,760	100%	3	31,020,528	10.0
Romania	8,587,740	80%	4	19,236,538	6.2
Slovakia	1,326,480	10%	3	371,414	0.1
Slovenia	175,270	80%	3	392,605	0.1

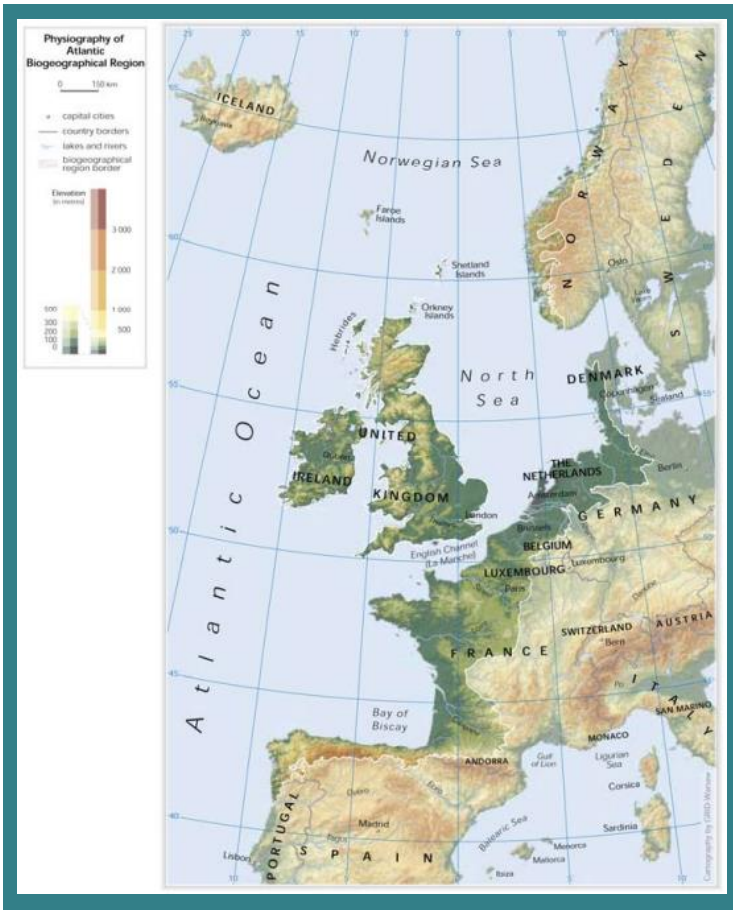
CONTINENTAL-SPECIFIC ASSUMPTIONS

Biomethane content in biogas	= ***52%***	*Dinuccio et al. (2010)*
Biomass yield of maize	= ***14.0*** *tDM/ha*	*Marsac et al. (2019)*
Biogas yield of maize	= ***620*** m^3*/tDM*	*Marsac et al. (2019)*
Biomass yield of rye	= ***9.0*** *tDM/ha*	*Marsac et al. (2019)*
Biogas yield of rye	= ***570*** m^3*/tDM*	*Marsac et al. (2019)*

In total, the Continental region has a maximum biomethane potential from sequential and rotational cropping of **42.9 bcm** per year (EU27).

2.3 Atlantic

TABLE 9 OVERVIEW ATLANTIC (ADAPTED FROM EUROPEAN ENVIRONMENT AGENCY, 2017)



CLIMATE

- Temperate maritime
- Mild and humid throughout year
- High rainfall (particularly in west)
- Exposure to westerly winds

SOIL

- High variation across the region
- Often well-mixed with well-developed humus content
- Acidic soils characteristic in the region

GEOMORPHOLOGY

- Rocky coastlines with peninsulas, islands and fjords
- Mix of large low-lying plains and hilly ranges and uplands

Area	830,000 km^2
EU 27 countries	France, Ireland, Germany, Spain, The Netherlands, Belgium, Denmark and Portugal
Primary habitat types	Agriculture and gardens (38%) Grassland (30%) Forest / other woodland (13%)

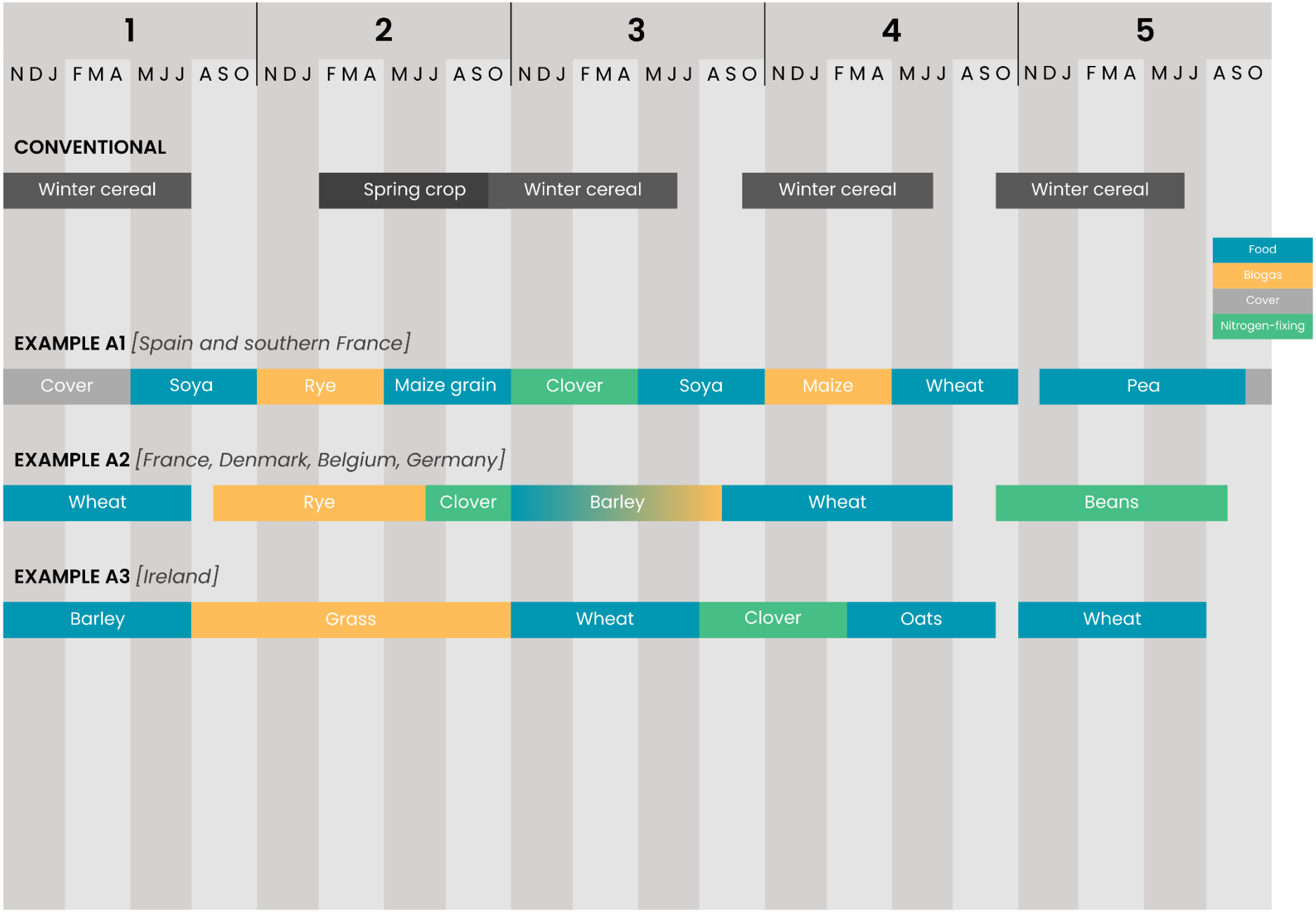


FIGURE 9 EXAMPLES OF POTENTIAL ATLANTIC CROPPING SYSTEMS

TABLE 10 EXAMPLES OF POTENTIAL ATLANTIC CROPPING SYSTEMS

	Potential subregions	Description	Advantages	Disadvantages / Trade-offs
Conventional	All	*Consecutive cereal production with a single break crop grown every 3-5 years; soil is often left uncovered between crops.* Cropping systems strongly focus on cereal production, typically wheat. As one of the most profitable crops, this monocropping approach can offer farmers' short-term financial security. However, this approach is **unsustainable** over time. Monocropping greatly reduces a farm's resilience to environmental and economic stresses.	+ [Short-term] Relatively profitable + [Short-term] High food production + Relatively simple to deploy	- Reduces crop yields over time - Increases GHG emissions from crop production - Increases the vulnerability to extreme weather events - Depletes soil nutrients, increasing the dependence on artificial fertilisers - Depletes soil carbon, reducing its ability to retain water and sequester carbon - Increases crops' susceptibility to pests and diseases, increasing the dependence on chemical inputs - Increases financially vulnerable to volatility in cereals market
Example A1 Warmer, drier	*Spain and southern France*	*Diverse crop rotations comprising 4+ different crop types; cover crops used to protect and improve soil health between cultivation.* Crop rotations retain a strong focus on cereal production to maximise profitability. Bioenergy crops, such as maize and grass, grown intermittently as a break crop, preventing the	+ Delivers sustainable food and fuel + Increase crop yields + Improves soil health + Diversify agricultural income + Reduces demand for pesticide/herbicides + Reduces demand for artificial fertilisers + Enhances biodiversity	- [Short-term] reduction to income - May require training farmers about regenerative farming techniques
Example A2 Warmer, drier	*France, Denmark, Belgium, Germany*			
Example A3 Cooler, wetter	*Ireland*			

		development of cereal-based disease/pests. Nitrogen-fixing plants are grown to improve soil fertility and significantly reduce the need for artificial fertilisers during the subsequent harvest; beans and clover may be selected as a food/feed and cover crops respectively. Digestate is also spread back to land to replenish soil carbon and provide a renewable source of nutrients. These rotations **sustainably** produce food and energy.	+ Supports the decarbonisation of agricultural (and energy)	

Biomethane potential

Based on the Atlantic's possible sustainable crop rotations, the biomethane potential across Europe can be explored:

TABLE 11 BIOMETHANE POTENTIAL PER COUNTRY IN THE CONTINENTAL REGION

Country	Total arable land (ha)	Proportion of land within the Atlantic biogeographical region (%)	Crop rotation assumed	Average annual biomass grown for AD (tonnes)	Biomethane max potential per year (bcm)
Belgium	870,420	50%	2	1,175,067	0.3
Denmark	2,357,950	30%	2	1,909,940	0.6
France	18,044,450	50%	$1^{(10\%)}$ & $2^{(90\%)}$	26,976,453	8.7
Germany	11,657,900	20%	2	6,295,266	1.9
Ireland	434,940	100%	4	1,043,856	0.2
Netherlands	1,003,450	100%	2	2,709,315	0.8
Spain	11,732,660	10%	1	6,570,290	2.1

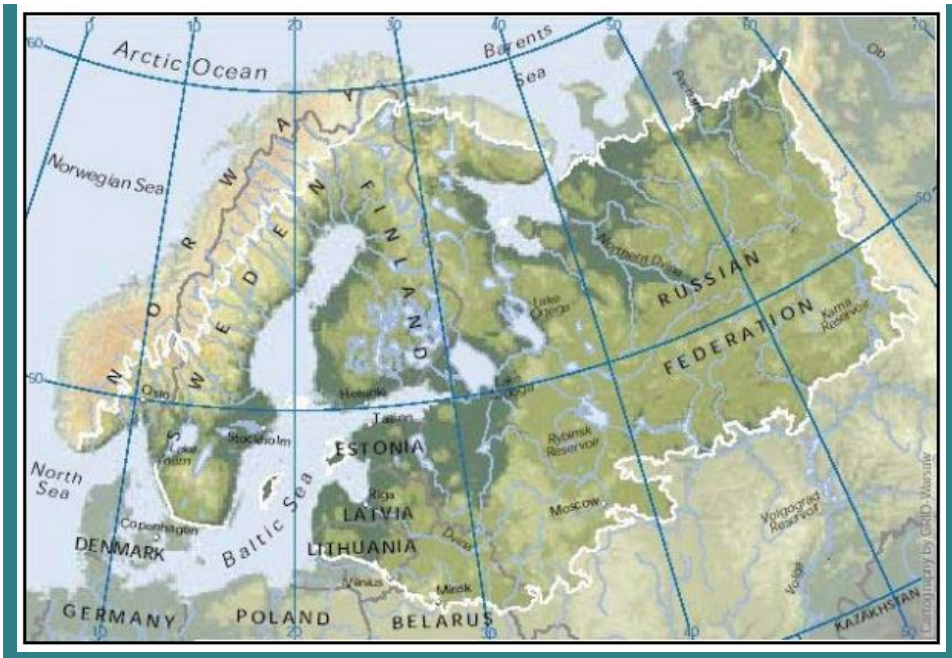
ATLANTIC-SPECIFIC ASSUMPTIONS

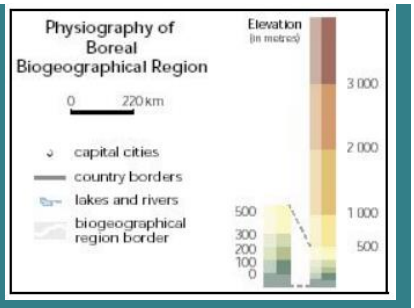
Biomethane content in biogas	= ***52%***	*Dinuccio et al. (2010)*
Biomass yield of maize	= ***14.0*** *tDM/ha*	*Marsac et al. (2019)*
Biogas yield of maize	= ***620*** m^3*/tDM*	*Marsac et al. (2019)*
Biomass yield of rye	= ***9.0*** *tDM/ha*	*Marsac et al. (2019)*
Biogas yield of rye	= ***570*** m^3*/tDM*	*Marsac et al. (2019)*
Biomass yield of grass	= ***8.0*** *tDM/ha*	*Prade et al. (2014)*
Biogas yield of grass	= ***383*** m^3*/tDM*	*Prade et al. (2014)*

In total, the Atlantic region has a maximum biomethane potential from rotational cropping of **14.6 bcm** per year (EU27).

2.4 Boreal

Table 12 Overview of the boreal region (adapted from European Environment Agency, 2017)





Climate

- Agriculture is generally concentrated in the south where it is becoming more intensive. The growing season here is 200 days compared to 100 days in the north. This is influenced not just by temperature and soil quality but also by the number of daylight hours and length of snow cover.
- Strong seasonal variation with short, moderately warm**,** and moist summers and long, extremely cold and dry winters.
- To the north, the zone merges with the forest-tundra of the Arctic, to the west the ground rises up onto the Fennoscandian mountains and, in the south, there is a transition to the deciduous forests of the Continental Region.
- The most significant climatic factor for biodiversity is the length of the growing season, which defines the productive period, and the amount and duration of snow cover.

Soil

- The young soils formed after the glaciation are generally shallow, with a poorly developed organic component.
- High variation across the region common soil groups (WRB classification): Podzols, Histosols, Luvisols, Albeluvisols, and Fluvisols.

Geomorphology

- The region has relatively flat lands, mostly below 500 meters.
- Vast expanse of coniferous forests, mires and lakes form the characteristic mosaic landscapes of the Boreal region.
- Ragged coastline with thousands of islands and a brackish sea.

Area	830,000 km^2 (19% of EU territory)
EU27 countries	Sweden, Finland, Estonia, Latvia, Lithuania
Primary habitat types	Forest / other woodland (60 %)
	Agriculture and gardens (10 %)
	Grassland (Temporary 3% & Permanent 5%)

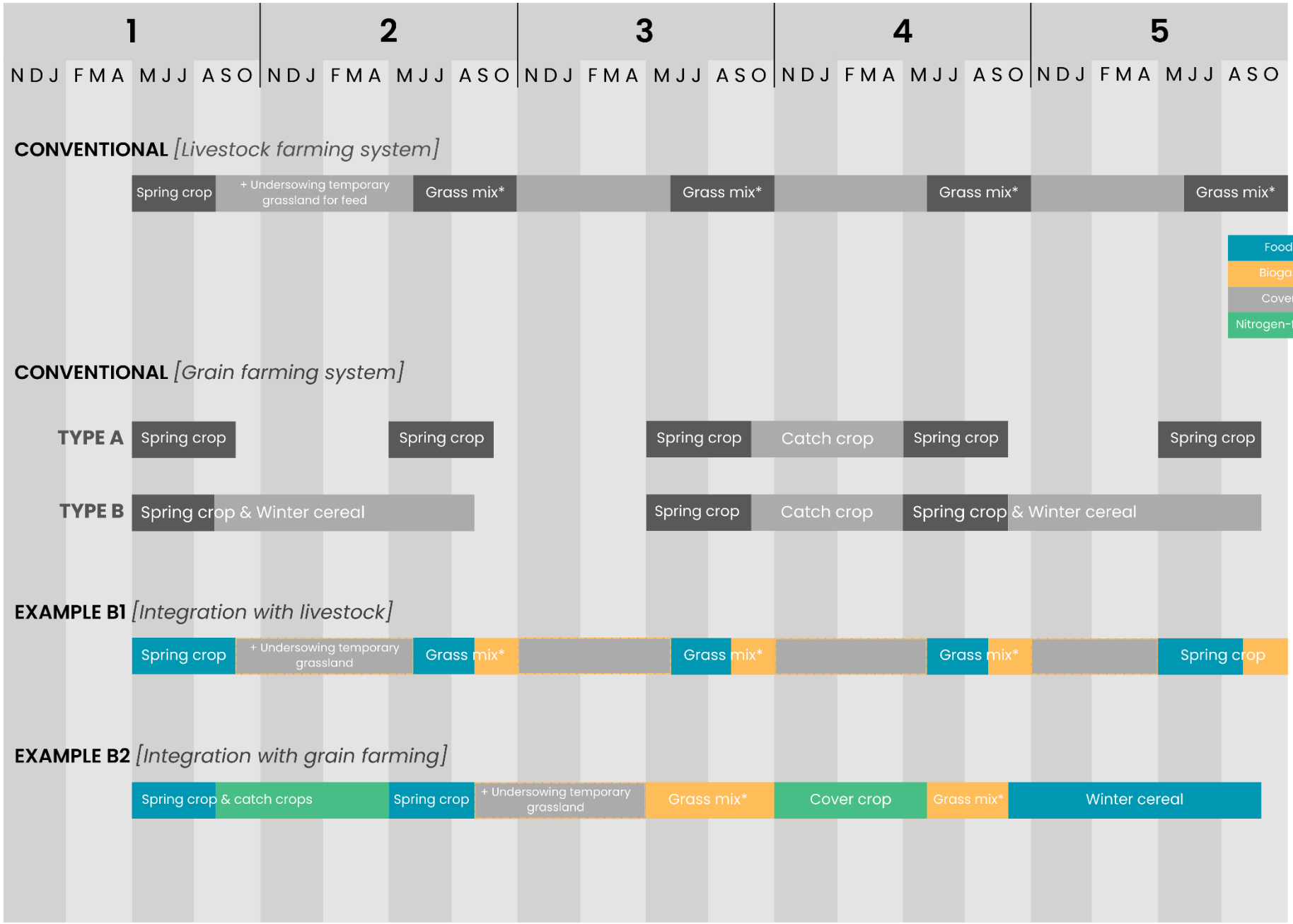


FIGURE 10 EXAMPLES OF POTENTIAL BOREAL CROPPING SYSTEMS (*GRASS MIX CAN INCLUDE NITROGEN-FIXING LEGUMES)

TABLE 13 EXAMPLES OF POTENTIAL BOREAL CROPPING SYSTEMS

	Potential subregions	Description	Advantages	Disadvantages / Trade-offs
Conventional	All	*Annual spring crop grown (May-Sep) for food or feed. Temporary and perennial grasslands, usually 3-4 years, are cultivated for feed.* Climatic conditions severely constrain the growing season such that only one primary crop can be grown each year. Spring crops, often cereals, are selected to maximise profitability and output. Land is often left bare between crops, leaving soils vulnerable to erosion. For this reason, CAP-measures favour using catch crops. Catch crops intermittently are undersown to cover land between harvests and reduce nutrient leaching and erosion but also increasing soil organic carbon input.	+ Predictable + Supports agricultural business case + Using cover crops soil health improves and nutrient savings can be achieved	- Inefficient; land is under-utilised, failing to deliver its full potential - Depletes soil nutrients, increasing the dependence on artificial fertilisers - Depletes soil carbon, reducing its ability to retain water and sequester carbon - Increases crops' susceptibility to pests and diseases, increasing the dependence on chemical inputs - Currently cover crops is not commonly used
Example B1 *Integration with livestock farming system*	*All*	*Crop rotations <u>improve</u> on conventional approaches through the establishment of temporary and perennial grassland. In livestock farming systems grassland is mowed 1-3 times per growing season for feed and surplus grass may be harvested for biogas feedstock.*	+ Delivers sustainable food <u>and</u> fuel + Diversify agricultural income + Reduces demand for pesticide/herbicides + Enhances biodiversity + Supports the decarbonisation of agricultural (and energy)	- May require training farmers about regenerative farming techniques and understanding why grasses are important in crop rotation. - Water is the primary factor limiting the growth of grasses, which is why the yield levels of grasses can vary as much as 4.4 - 14 t DM/ha
Example B2 *Integration with grain agriculture*	*All*			

		Integrating grass cultivation for grain agriculture grasses could be profitably grow for 2 years and harvested 1-3 times per growing season. The integration of grasses into the crop rotation seeks to improve soil health and soil productivity. This biomass can be used to generate biogas. Nitrogen-fixing plants among grasses are grown to improve soil fertility and significantly reduce the need for artificial fertilisers during the subsequent harvest. These rotations **sustainably** produce food and energy.	+ Increase crop yields + Improves soil health + Reduces demand for artificial fertilisers	

Biomethane potential

Based on the Boreal's possible sustainable crop rotations, the biomethane potential across Europe can be explored:

TABLE 14 BIOMETHANE POTENTIAL PER COUNTRY IN THE BOREAL REGION

Country	Total arable land (ha)	Proportion of land within the Boreal biogeographical region (%)	Crop rotation assumed	Average annual biomass grown for AD (tonnes)	Biomethane max potential per year (bcm)
Estonia	698,880	100%	$1^{(10\%)}$ & $2^{(90\%)}$	670 925	0.1
Latvia	1,362,200	100%	$1^{(30\%)}$ & $2^{(70\%)}$	1 046 170	0.2
Lithuania	2,277,030	90%	$1^{(10\%)}$ & $2^{(90\%)}$	1 672 251	0.3
Finland	2,242,800	100%	$1^{(70\%)}$ & $2^{(30\%)}$	3 660 250	0.7
Sweden	2,535,170	80%	$1^{(25\%)}$ & $2^{(75\%)}$	3 894 021	0.8

BOREAL-SPECIFIC ASSUMPTIONS

Biomethane content in biogas	= ***52%***	*Dinuccio et al. (2010)*
Biomass yield of grass mix	= ***8.0*** *tDM/ha*	*Prade et al. (2014)*
Biogas yield of grass mix	= ***383*** m^3*/tDM*	*Prade et al. (2014)*

In total, the Boreal region has a maximum biomethane potential from rotational cropping of **2.2 bcm** per year.

3. Biogas potential across europe



3 Biogas potential across Europe

The previous chapter (Chapter 2) explored how rotational and sequential crops could be sustainably integrated into crop rotations to increase the potential of biogas in Europe. By assuming that these crop rotations are deployed across all arable land, the **maximum biomethane potentials** could be estimated.

Of course, these potentials may not be practicable. There are numerous constraints preventing this level of deployment in Europe.

Methodology for assessing the deliverable biomethane potential

To convert estimates in a *deliverable potential*, research quantified the impact of various environmental and socio-economic constraints, named here as *correction factors*, which may be applied to estimate the **deliverable biomethane potential** for each country.

Five key factors which would impact the deliverability of sequential/rotational cropping across Europe were identified:

1. *Food and fuel*
2. *Competition for biomass from other renewable technologies*
3. *Compatibility with different types of arable farming*
4. *Arable land readiness*
5. *Climate risk*

The impact of each of these factors on the deliverability of rotational/sequential cropping for biogas was quantified using existing data sources. Each factor's impact is presented by a percentage, which was multiplied to the maximum biomethane potential.

> *For example:*
>
> *A correction factor of **100%** would signify no impact on the maximum biomethane potential.*
>
> *A correction factor of **50%** signifies that the deliverable potential is half that of the maximum potential.*

All five correction factors – plus an additional uncertainty factor (80%) - were applied to the maximum biomethane potential to quantify the deliverable potential.

3.1 Food *and* fuel

Long-term food security cannot be assured unless the underlying farming practices are sustainable. Profitable crops (often cereals) are grown as often as possible, and relatively high levels of fossil-derived inputs – fertilisers, herbicides and other pesticides – enable farmers to maintain high yields. However, this intensification of agriculture, ubiquitous across Europe and necessary to feed an ever-increasing population, must transition to a more sustainable footing.

Relying on unsustainable farming practices undermines long-term food security. By definition, production rates cannot be sustained consistently over time, and eventually food security will decline.

To protect and enhance food security across Europe, arable farms must utilise more sustainable farming practices, including, but not limited to, the adoption of longer and more diverse crop rotations.

Moreover, these crop rotations can further develop synergies between multiple sectors. They not only provide agronomical benefits, but also present opportunities to generate renewable energy, enhance energy security, and deliver carbon dioxide removals (CDRs) – all of which are essential for the delivery of Net Zero by 2050.

Biogas is not only essential for energy security and decarbonisation but its co-product, digestate, can be spread back to land, replenishing soils with organic material and key nutrients. This "circular economy" approach can support the decarbonisation of the entire crop rotation, ensuring long-term food production and security.

Clearly, the impact of novel crop rotations on food production should be considered, such that energy production does not disproportionately affect the food market. The following section explores this impact based on sequential and rotational systems across Europe:

Sequential crops

See rotations listed in Mediterranean and Continental regions (Sections 2.1 and 2.2).

Sequential cropping has no impact on total food production, compared to today's conventional farming approach.

Conventional farming grows one food crop per year, leaving the ground inactive between harvests, whereas, sequential farming, where practical, will additionally grow a bioenergy crop between food crops.

In reality, many feedstocks used for biogas production are also food crops (e.g., maize). Consequently, sequential cropping can enhance farms' optionality, ensuring crops can be diverted to one of many different markets, where necessary. For example, if rye was grown for biogas production, but the AD plant was subsequently unable to accept the feedstock, the crop can be sold into the food and drinks market, ensuring the harvest is not wasted. However, under REDII, crops which could be used for food or feed are differentiated from non-edible bioenergy

crops, and regulations limit their use to produce biofuels within the transport sector (more information in Chapter 4).

As a result, a **100% correction factor** – i.e., no change to food production – is assumed for all countries in which sequential cropping may be suitable.

Rotational crops

See rotations listed in Atlantic and Boreal regions (Sections 2.3 and 2.4).

As discussed above, rotational crops are fundamental to sustainable agriculture, and thus to long-term food production.

Conventional farming typically grows one crop per year; many already intermittently grow an energy crop (e.g., rapeseed) to interrupt repetitive cereal harvests. By comparison, novel crop rotations explored here increase the diversity and length of rotations. Over a five-year period, these rotations are capable of maintain similar levels of food production, while additionally producing a crop for biogas production.

For simplicity, novel rotations within Atlantic and Boreal regions produce 4-5 food crops over a five-year period. Consequently, total food production may be nominally reduced by 0-20%. By taking this range's mid-point, growing rotational crops for biogas may reduce total food production by 10%, compared to a more conventional (and possibly unsustainable) arable farm. Consequently, a **90% correction factor** is applied to countries in which rotational cropping may be suitable.

Again, it is important to note that these novel crop rotations can promote long-term food security. Their food production is compared against conventional farming practices which can rely on practices which cannot be sustained indefinitely – namely intensive farming with a dependence on fossil-derived chemical inputs.

CHANGING DIETS

To help deliver Net Zero targets, countries across Europe are initiating efforts to reduce meat consumption. The EU's cow herds are expected to decrease by 7% from 2018 to 2031 (EC, 2021), with the Farm to Fork (2020) strategy outlining a general reduction in red meat consumption and improved sustainability of remaining livestock farming*.

Cow, sheep, and pig farming require significant areas of land, both to keep them and to grow crops to feed them. While some herds (particularly in the uplands) are grazed all-year around, millions of tonnes of crops are either fed to animals housed overwinter or fed to animals housed year-round in more-intensively farmed systems. As reflected in the Farm to Fork (2020) strategy, reduced livestock numbers and/or a move to less intensive animal rearing could reduce the demand for feed crops – thus result significant land use change.

A reduction to livestock numbers and/or a move to less intensively reared livestock across Europe could reduce the amount of arable land required to produce feed crops. Consequently, this arable land could instead produce food crops, increasing the efficiency of production. Food crops offer a greater calories per hectare, compared to red meat.

However, the impacts of changing European diets on land use are complex. It is not clear how changes in livestock farming will impact the arable sector. The following highlights key areas of uncertainty:

- **Soil organic carbon**. Livestock, and its production of organic-rich manure, is critical for soil health and carbon sequestration. These manures are a key resource required to replace non-renewable artificial fertilisers – as targeted within the Farm to Fork (2020) strategy.
- **New products**. There is an increasing demand for new products which require organic compounds, such as meat-replacement proteins and bioplastics.
- **Rewilding**. There is the opportunity to increase biodiversity through the establishment of new natural habitats.
- **Global livestock market**. Reducing livestock in Europe will not necessarily reduce meat and dairy consumption in Europe. The EU may risk offshoring emissions associated with its production and transportation. Decarbonisation in Europe must NOT result in other countries having to increase their GHG emissions to compensate.

** This may include the management of livestock waste via anaerobic digestion (AD), recycling its nutrients and producing biogas.*

3.2 Competition for biomass from other renewable technologies

Around 60% of the EU's renewable energy may be derived from biomass, where different technologies produce different energy products – the most common being, heating and cooling (75%), bioelectricity (13%) and transport fuels (12%) (EC, 2023).

Around a quarter of the EU's bioenergy is derived from liquid biofuels, in the form or biodiesel/HVO and bioethanol (13%; ~222 TWh), and biogas (11%; ~195 TWh) (IEA, 2021)[3].

A deliverable biomethane potential must account for these alternative pathways for biomass. Today, an estimated 1.4 million hectares of arable land is used to grow rapeseed for biodiesel, and 0.6 million hectares are used to grow maize, wheat and other cereals for bioethanol across the EU27+UK (T&E, 2023). By subtracting this land use from the total arable land available in Europe, modelling negates any impact on their production.

Total arable land in EU27	= 98.4 million ha
Total arable land used to grow crops for biodiesel or bioethanol	= 2.0 million ha
Proportion of arable land which can supply biogas plants	**= 98%**
	Correction factor

In summary, 2% of arable land can be used to maintain today's production of crop-based biodiesel and bioethanol. Consequently, a **98% correction factor** is applied to each country's maximum biomethane potential. It is worth mentioning that this correction factor does not consider SAF (Sustainable Aviation Fuels) production, but only a scenario producing biomethane for grid injection or non-aviation transports.

[3] Note, figures include bioenergy imported from non-EU countries.

ELECTRIFICATION OF VEHICLES

To decarbonise transport, the EU is phasing out the sale of new petrol and diesel cars by 2035 – favouring the uptake of electric cars, vans and potentially HGVs.

This will significantly reduce the demand for diesel (and biodiesel) and petrol (and bioethanol) over time. Consequently, fewer crops may be grown for the production of these biofuels; instead, these farmers can grow for biomethane production.

This will increase countries' deliverable biomethane potential.

GROWING DEMAND FOR BIOMASS IN NOVEL MARKETS

Carbon forms the building to countless products in today's economy, from building materials to transport fuels. Historically, most of this carbon is derived from fossil resources. Consequently, the creation and use of these fossil-derived products is unsustainable, typically resulting in harmful GHG emissions.

As companies start replacing fossil carbon with renewable alternatives, industries are seeking new sources of carbon derived from the atmosphere. In general, they have two options:

a) **Capture carbon dioxide directly from the atmosphere**. Considering air is only 0.04% carbon dioxide, capturing it requires large quantities of energy, and the captured gas may only be considered sustainable if this energy is derived from renewable sources. However, with the growing demand for green electricity across all sectors, using it to capture carbon dioxide from the atmosphere is rarely economically viable.

b) **Capture biogenic carbon from plant biomass**. All plants are composed of atmospheric carbon, captured via photosynthesis. Biogenic carbon presents a key opportunity for companies to manufacture new, sustainable products – including bioplastic, biofuels, and biogases.

Within an anaerobic digestor, the concentration of carbon dioxide is 1000 times greater than the air, thus making it a highly efficient process to capture atmospheric carbon.

Task Force 4 of the Biomethane Industry Partnership (BIP) explores the value of biogenic CO_2 within new markets in more detail.

3.3 Compatibility with different types of arable farming

Sequential and rotation cropping systems capable of producing feedstock for AD are best suited to arable land used to grow annual, above-ground crops. Within these rotations, bioenergy crops can be intermittently grown between food/feed and cover crops.

They are *not suitable* for land used for permanent crops (e.g., grapes from vineyards); however, this kind of land use is not considered within the EU's *Arable Land* classification.

Within the EU, there is around 98 million hectares of *Arable Land* – of which, 53 million hectares is used to grow cereals, 20 million hectares to grow fodder and 25 million to grow industrial/other crops (EC, 2020). The novel crop rotations proposed within this report are generally best-suited farms producing cereals, fodder or industrial crops[4] – these crops represent **70-96% of arable land (average 87%).** The exact proportion for each country is used to correct their maximum biomethane potential (data sourced from EC, 2020; see following graph).

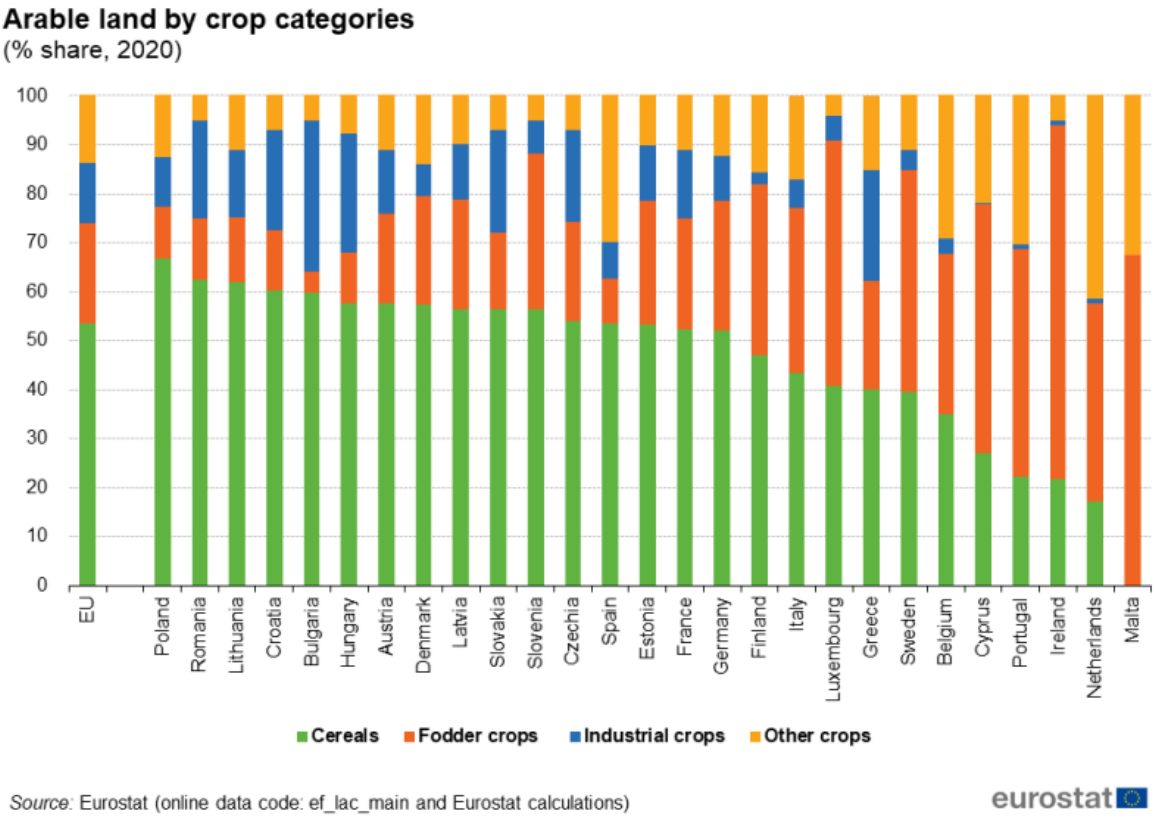


FIGURE 11 ARABLE LAND BY CROP CATEGORIES

[4] Industrial crops relate to those which are normally not sold directly for consumption because they need to be industrially processed prior to final use. This includes oilseeds, tobacco, hemp, aromatic or medicinal plants, hops, and energy crops.

3.4 Arable land readiness

However, over 60% of European soils are now considered unhealthy as they continue to be subject to severe degradation processes, such as erosion, compaction, organic matter decline, pollution, loss of biodiversity, salinisation and sealing. This damage is the result of unsustainable land use and management, overexploitation and emissions of pollutants (see EC, 2023).

While numerous factors determine soil's health, its concentration of soil organic matter (SOM) is typically considered a good proxy; lower concentrations are associated with poorer soil health. Intensive farming practices can drive reductions to SOM, where unprotected and compacted soils have accelerated soil erosion and the use of artificial fertilisers have failed to return organic matter to land.

The health of soil impacts its provision of environment and agricultural services. Healthy soils are more productive, more resilient, and more biodiverse; they are able to sequester more carbon from the atmosphere, retain more water, and better control pests and disease (EC, 2023). Restoring soil health is critical to the long-term production of food (and bioenergy).

> **Restoring soil health is critical to the long-term production of food (and bioenergy)**

Sequential and rotational cropping, in combination with the use of regenerative farming techniques, can restore soil health across Europe, greatly improving agricultural sustainability (see Section 1.3). However, this soil restoration takes time, and many of the unhealthy soils across Europe are not *yet* ready to sustain sequential cropping systems consistently for long periods.

Quantifying the impact of soil degradation of arable farming is difficult. Soil health not only varies significantly spatially across Europe, but its impact on farming will also depend on numerous factors, including crops type, local climate, and geology. Such complexity reduces the ability to reliably quantify its impact on the deployment of sequential and rotational approaches ascribed here.

Consequently, this work assumes that 61% of all European land is affected by soil degradation, in line with EUSO Soil Health Dashboard (2023), distributed evenly across all biogeographic regions and countries.

Next, the impact of soil degradation of crop yield must be quantified to assess the effect of soil health on biomethane potential from sequential and rotational cropping. Again, this relationship is highly complex, varying significantly across European farms due to a multitude of different factors, from the severity of degradation to crop type grown.

Research suggests that a healthy soil, with higher concentrations of SOM, can increase the production of wheat and maize by 23% and 10%, respectively (Oldfield et al. 2019 & 2021). However, this impact varies significantly worldwide, depending on weather, climate, farming practices, and local geography.

To quantify the Arable Land Readiness correction factor, it is assumed that 61% of soils are degraded, and from these soils, it is conservatively assumed that crop yields are 23% lower than possible in a healthier soil (i.e. soil with higher concentrations of SOM). Consequently, the remaining 39% of soil is considered healthy, and therefore exhibits no negative impact on crop yield.

The correction factor is therefore estimated as follows:

Healthy soil		Degraded soil	
(100% x 39%)	+	(77% x 61%)	= **78%**

While assumptions used here have a high degree of error, they help account for the impact of soil health on the immediate deployment of sequential and rotational cropping approaches.

Note, if soil health improves across Europe, the deliverable biomethane potential will also increase. It is also important to note that these estimates are based on limited data applied over large areas. Consequently, these estimates are indicative only, and do not reflect precise changes expected with the implementation of more regenerative practices.

To avoid unrealistic outcomes, conservative estimates are also used to improve the reliability of the resultant 'deliverable potential' – i.e. the impact of land readiness is likely to be less than modelled here. Moreover, it is worth mentioning that these estimates consider all the lands potential dedicated to biomethane production, therefore not considering the use of such biomass for the production of other lignocellulosic biofuels for aviation or maritime purposes.

3.5 Climate risk

Generally, warmer and/or wetter conditions associated with climate change may increase agricultural yields within certain regions. However, the increased frequency and severity of extreme weather events – including the droughts, heat waves, storms, and flooding characterised by those seen in 2023 – will likely counteract any potential gains. Moreover, increased climate variability and uncertainty may exacerbate operational risk, straining farms' business case.

The following map highlights some of projected impacts of climate change according to the biogeographical regions (EEA, 2017):

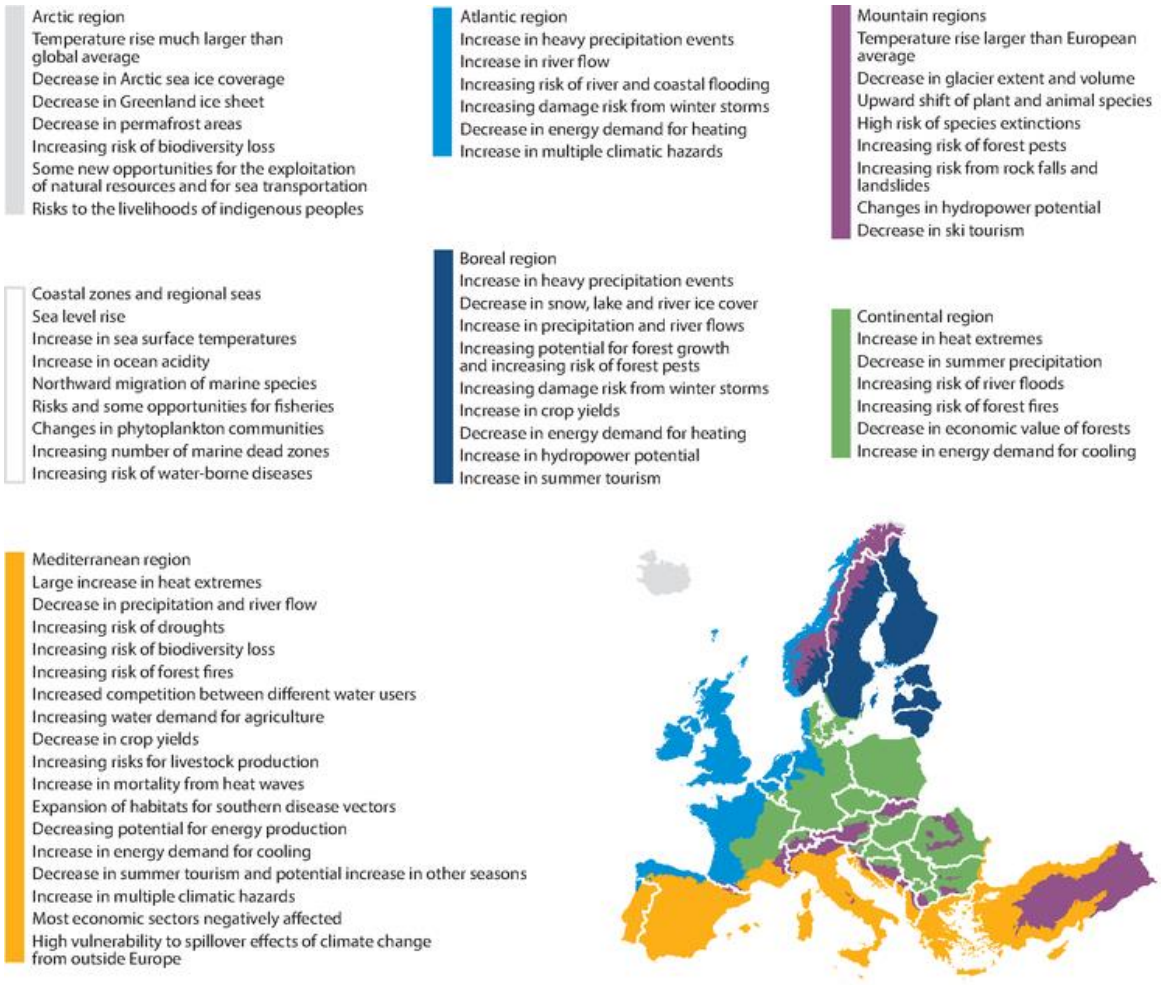


FIGURE 12 PROJECTED IMPACTS OF CLIMATE CHANGE ACCORDING TO THE BIOGEOGRAPHICAL REGIONS

It is very difficult to model how these potential climatic changes will affect European agriculture – its impacts will vary significantly over space and time. Crucially, however, the EU must not assume changes will benefit arable farming and policy must not assume improved yields. Instead, research suggests that climate change will adversely impact agricultural productivity, especially in southern European countries (see JRC Technical Report, 2020).

For the same reason, it is not possible to robustly estimate how climate change will impact the suitability and uptake of novel crop rotations across Europe. Therefore, **the deliverable**

biomethane potential will not be immune from risks associated with climate change – and the correction factor is beyond the scope of this work.

3.6 General error and uncertainty

Multiple generalisations and assumptions are required to assess the potential of biomethane production from novel crop rotations across Europe. Modelling within this research assumes that crop rotations may be applicable across large areas of land within a particular biogeographical region. In reality, countless social, economic, and environmental drivers will determine their viability and uptake at a much smaller scale.

Many of the key drivers impacting the viability are captured within the other correction factors. To account for any remaining uncertainty to produce a *conservative* estimate of biomethane potentials from novel crop rotations in Europe, an additional 20% error is modelled – equating to an **80% correction factor.**

3.7 Summary

Using these estimated correction factors, the maximum biomethane potential estimates can be converted into deliverable biomethane potential estimates. Here, the maximum potential is multiplied by all of the correction factors to quantify a deliverable potential. The following table displays these estimates for each country:

TABLE 15 DELIVERABLE BIOMETHANE POTENTIALS FOR EU 27

	Correction Factors							
	MAXIMUM biomethane potential from novel crop rotations (bcm)	**Food vs fuel**	**Biomass competition**	**Arable Compatibility**	**Arable land readiness***	**Climate impact**	**Uncertainty**	**DELIVERABLE biomethane potentials from novel crop rotations** (bcm)
Austria	0.2	100%	98%	89%	78%	Unknown	80%	0.1
Belgium	0.9	95%	98%	71%	78%	Unknown	80%	0.4
Bulgaria	2.8	100%	98%	94%	78%	Unknown	80%	1.6
Croatia	1.1	95%	98%	92%	78%	Unknown	80%	0.6
Cyprus	0.2	100%	98%	78%	78%	Unknown	80%	0.1
Czechia	2.2	100%	98%	92%	78%	Unknown	80%	1.2
Denmark	1.9	95%	98%	86%	78%	Unknown	80%	0.9
Estonia	0.1	90%	98%	90%	78%	Unknown	80%	0.0
Finland	0.7	90%	98%	84%	78%	Unknown	80%	0.3
France	18.4	95%	98%	89%	78%	Unknown	80%	9.5
Germany	9.5	100%	98%	88%	78%	Unknown	80%	5.1
Greece	2.8	100%	98%	84%	78%	Unknown	80%	1.4
Hungary	3.7	100%	98%	91%	78%	Unknown	80%	2.1
Ireland	0.2	90%	98%	95%	78%	Unknown	80%	0.1
Italy	12.7	100%	98%	83%	78%	Unknown	80%	6.4
Latvia	0.2	90%	98%	90%	78%	Unknown	80%	0.1
Lithuania	0.3	90%	98%	89%	78%	Unknown	80%	0.1
Luxembourg	0.1	100%	98%	96%	78%	Unknown	80%	0.1
Malta	0.0	100%	98%	68%	78%	Unknown	80%	0.0
The Netherlands	0.8	90%	98%	59%	78%	Unknown	80%	0.3

Poland	10.0	100%	98%	88%	78%	Unknown	80%	5.4
Portugal	0.6	95%	98%	70%	78%	Unknown	80%	0.2
Romania	6.2	100%	98%	95%	78%	Unknown	80%	3.6
Slovakia	0.1	100%	98%	92%	78%	Unknown	80%	0.1
Slovenia	0.1	100%	98%	94%	78%	Unknown	80%	0.1
Spain	10.4	95%	98%	61%	78%	Unknown	80%	3.7
Sweden	0.8	90%	98%	89%	78%	Unknown	80%	0.4
TOTAL [EU27]	**87.0**							**44.0**
	Maximum biomethane potential (bcm)							**Deliverable biomethane potential (bcm)**

**Note, as soil health improves across Europe, the deliverable biomethane potential will also increase.*

Overall, it is estimated that the EU27 has the potential to produce 44.0 bcm of biomethane per year from sequential/rotational crops.

For comparison:

- **Gas for Climate (2022)** estimate that the EU-27 could produce 41.8 bcm of biomethane by 2030 – of which 21% is derived from sequential crops (equating to 8.8 bcm per year). This potential increases significantly by 2050, where 46 bcm of biomethane could be produced from sequential crops, representing 47% of the EU's full potential.

- **Magnolo et al. (2021)** estimate that sequential cropping could generate the following volumes of biomethane in each region, depending on conservative and maximum scenarios:
  - Mediterranean = 9.9 – 37.9 bcm
  - Atlantic = 10.2 – 42.5 bcm
  - Continental = 25.8 – 104.9 bcm

  Total = 45.9 [conservative] – 185.4 [maximum] bcm

- **Dale et al. (2020)** *conservatively* estimate that sequential cropping across the EU-28 (including UK) could sustainably generate over 40.4 bcm of biomethane per year.

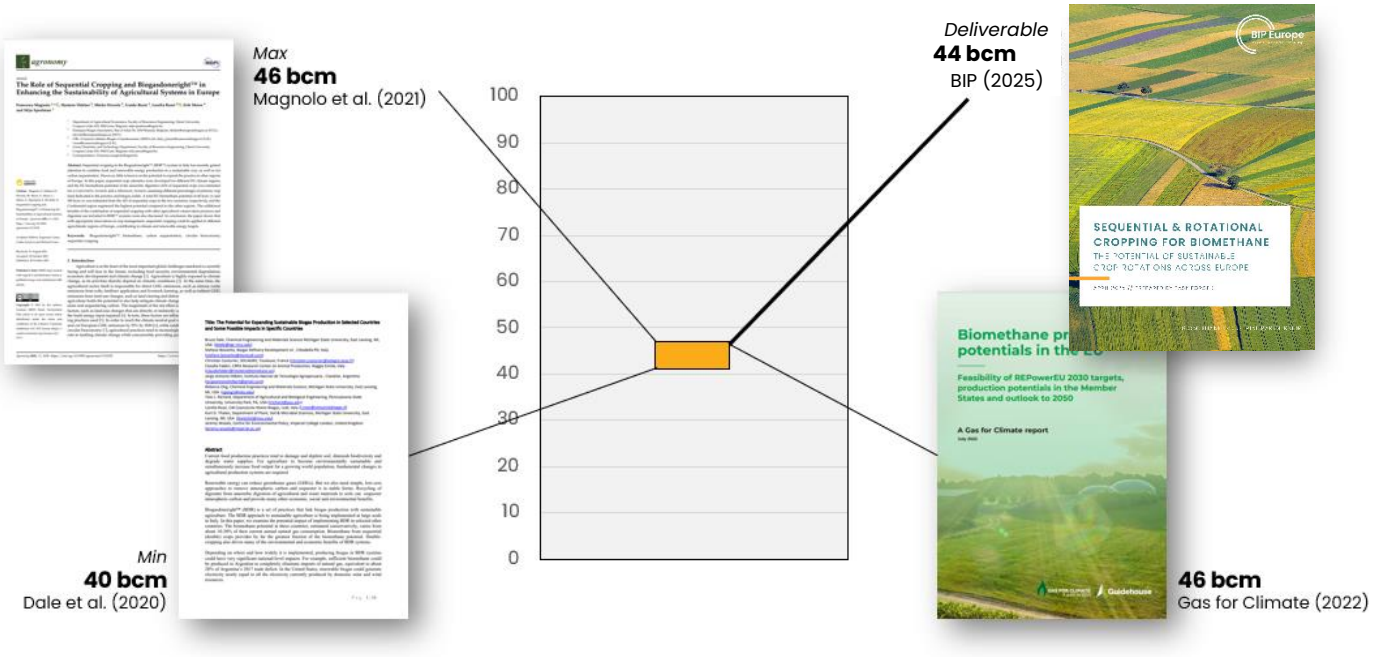


FIGURE 13 ESTIMATED BIOMETHANE POTENTIALS

This report's deliverable estimate of 44.0 bcm biomethane potential (EU27) is consistent with these other estimates, whose deliverable potentials range from 40 to 46 bcm per year.

Variability between estimates is largely derived from two sources:

1. *Number of crops grown for biogas within the rotation.*
   Example crop rotations described within the report maintain a strong focus on food production and consequently include just 1-2 biogas crops within a 5-year period. By comparison, Magnolo et al. (2021) propose 2-4 biogas crops with its 4-year sequential cropping systems. Consequently, the research's more biogas-dominant cropping systems result in higher biogas potentials yet will likely have a greater impact on the quantity and/or type of food produced.

2. *Allocation of land deemed suitable for sequential (or rotational) cropping.*

This report's application of correction factors represents a new approach to assess deliverability. It enables the quantification of different drivers on biogas potentials. Other estimates of biogas potentials from novel crop rotations typically apply a single adjustment to develop different scenarios; Magnolo et al. (2021), for example, develops conversative (20%) and maximum scenarios (80%) broadly based on the proportion of land currently used to grow cereals in the different biogeographical regions.

Despite using different methods, the four studies mentioned above have shown that rotational and sequential crops can be sustainably and practically cultivated across Europe to meet and even exceed the REPowerEU target of 35 bcm biomethane production. Such consistency across these studies indicates the reliability of the results. Next to this, it must be noted that the

availability of sustainable biomethane potential for energy as well as their use, depends on the context where this feedstock is extracted from as well as the legal definition in place and Member State's priorities in the deployment of that potential.

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