agronomy

Article

The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe

Francesca Magnolo [1,]*, Harmen Dekker [2], Mieke Decorte [2], Guido Bezzi [3], Lorella Rossi [3], Erik Meers [4] and Stijn Speelman [1]

[1] Department of Agricultural Economics, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, 9000 Gent, Belgium; stijn.speelman@ugent.be
[2] European Biogas Association, Rue d'Arlon 65, 1050 Brussels, Belgium; dekker@europeanbiogas.eu (H.D.); decorte@europeanbiogas.eu (M.D.)
[3] CIB—Consorzio Italiano Biogas e Gassificazione, 26900 Lodi, Italy; g.bezzi@consorziobiogas.it (G.B.); l.rossi@consorziobiogas.it (L.R.)
[4] Green Chemistry and Technology Department, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, 9000 Gent, Belgium; erik.meers@ugent.be
* Correspondence: Francesca.magnolo@ugent.be

Abstract: Sequential cropping in the Biogasdoneright™ (BDR™) system in Italy has recently gained attention to combine food and renewable energy production in a sustainable way, as well as for carbon sequestration. However, little is known on the potential to expand the practice in other regions of Europe. In this paper, sequential crop calendars were developed for different EU climate regions, and the EU biomethane potential of the anaerobic digestion (AD) of sequential crops was estimated for a *Conservative_Scenario* and a *Maximum_Scenario*, assuming different percentages of primary crop land dedicated to the practice and biogas yields. A total EU biomethane potential of 46 bcm/yr and 185 bcm/yr was estimated from the AD of sequential crops in the two scenarios, respectively, and the Continental region registered the highest potential compared to the other regions. The additional benefits of the combination of sequential cropping with other agricultural conservation practices and digestate use included in BDR™ systems were also discussed. In conclusion, the paper shows that with appropriate innovations in crop management, sequential cropping could be applied in different agroclimatic regions of Europe, contributing to climate and renewable energy targets.

Keywords: Biogasdoneright™; biomethane; carbon sequestration; circular bioeconomy; sequential cropping

Citation: Magnolo, F.; Dekker, H.; Decorte, M.; Bezzi, G.; Rossi, L.; Meers, E.; Speelman, S. The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe. *Agronomy* **2021**, *11*, 2102. https://doi.org/10.3390/agronomy11112102

Academic Editors: Fogarassy Csaba, Csaba Gyuricza and Richard Cruse

Received: 31 August 2021
Accepted: 18 October 2021
Published: 20 October 2021

1. Introduction

Agriculture is at the heart of the most important global challenges mankind is currently facing and will face in the future, including food security, environmental degradation, economic development and climate change [1]. Agriculture is highly exposed to climate change, as its activities directly depend on climatic conditions [2]. At the same time, the agricultural sector itself is responsible for direct GHG emissions, such as nitrous oxide emissions from soils, fertilizer application and livestock farming, as well as indirect GHG emissions from land-use changes, such as land clearing and deforestation [3]. Nevertheless, agriculture holds the potential to also help mitigate climate change by reducing GHG emissions and sequestering carbon. The magnitude of the net effect is determined by different factors, such as land-use changes that are directly or indirectly caused by cultivation and the fossil energy input required [4]. In turn, these factors are influenced by the type of farming practices used [5]. In order to reach the climate-neutral goal of the Green Deal by 2050 and cut European GHG emissions by 55% by 2030 [6], while establishing a sustainable and circular bioeconomy [7], agricultural practices need to increasingly adapt to play a positive role in tackling climate change while concurrently providing quality food, materials and sustainable bioenergy. To achieve this aim, the new Common Agricultural Policy (CAP) [8] seeks to create the necessary conditions for farmers to use natural resources prudently, producing food while simultaneously protecting nature and safeguarding biodiversity.

Today, bioenergy and biofuel production systems have been criticized for interfering with food production and for having potential negative environmental [9,10] as well as socio-economic impacts [11]. It is therefore crucial to focus on solutions that are able to restructure agricultural systems that reconcile bioenergy production with everything else that can be simultaneously produced from biomass, lowering the dependency on fossil fuels. Moreover, agricultural and bioenergy systems need to increasingly enhance resilient and circular value chains by allowing farmers and rural areas to go beyond the role of mere raw material providers and ensure that value, materials, nutrients and energy can be made to flow back to the primary sector [12]. In this way, a more equitable participation of bioeconomy value chains' actors could be ensured. At the same time, the development of new bioeconomic systems in Europe have to establish a so called "equalizing development", avoiding the risk of shifting the burden to third world countries [4].

The potential to allow simultaneous biogas and food production with no indirect land-use change risk (ILUC risk), along with biomass and soil biodiversity benefits [13–15], soil structure and fertility, control of weeds, pests and diseases in addition to reducing the number of external inputs into the system has recently drawn attention to the agricultural practice of sequential cropping [16–20]. ILUC is an important factor to take into account in bioenergy production, since the emissions associated with ILUC can potentially negate any GHG savings from the use of bioenergy as a substitute for fossil fuels [21]. Moreover, ILUC-free feedstocks are currently being prioritized by the European Commission as a method of finding a solution to land-use issues and to reduce environmental impacts [22]. The CAP that will be implemented in 2023 will include the sustainable ambitions of the Green Deal [6], supporting environmentally and carbon-friendly farming practices, including agroecological principles that can contribute to carbon sequestration and storage, the protection of biodiversity, the enhancement of ecosystem services and the preservation of habitats and landscapes [23]. The policy aims to integrate sustainable energy production into the agricultural sector while ensuring food security and sustainable management. To do so, the revised Renewable Energy Directive (EU) 2018/2001 (RED II) sets limits on the use of biomass feedstock with high ILUC risk to enable a shift to renewable energy via agricultural crops managed in a climate-friendly way [24]. In this setting, sequential cropping constitutes an interesting case to study among the agricultural practices that could contribute to the goals mentioned above. The combined production of food, biomethane and fertilizers directly on farms, coupled with the application of precision agriculture practices, can potentially accelerate the transition to a circular bioeconomy based on the use of sustainable and local resources [25,26].

1.1. Sequential Cropping in a Changing Climate

Sequential cropping is a form of multicropping where two or three crops in two years are grown in sequence on the same field. The second crop is planted after the primary crop has been harvested [27]. As with other multicropping practices, sequential cropping is one of the oldest forms of agriculture. In history, sequential cropping has always played a fundamental role in adapting to changing climatic conditions [28]. Today, climate change and its associated rise in temperature are increasing the duration of the thermal growing season, leading to the northward expansion of areas that are suitable for sequential cropping. It is widely agreed that crop productivity will improve in northern Europe as the growing season lengthens and the frost-free time extends [29]. At the same time, in southern parts of Europe, increased temperatures will cause a deterioration of agroclimatic conditions. Therefore, the implementation of sequential cropping is particularly interesting to study because it is becoming possible in previously less suitable areas, and because the interaction between different crop species could be designed and managed to improve crop production and provide important ecosystem services [30]. In this regard, sequential cropping can be used for its potential stability and greater yields compared to monocropping, as well as for reducing the risk of complete crop failure in variable environments [31]. Besides the direct benefits of crop production, sequential cropping systems were observed to improve the functioning of agricultural systems, reducing the environmental impacts associated with agricultural production [30]. In addition, although sequential cropping has traditionally been mainly implemented in small farms and low-input production systems, it holds lessons in both structure and function that can also advise a more sustainable design of larger scale farming systems [32]. Over the previous decades agriculture has been focused on the provisioning of food, feed, fibers and energy to meet the demand of an increasing population [33]. This has led to intensive agricultural systems that rely on the use of large amounts of external inputs, mainly agrochemicals and synthetic fertilizers, using a limited number of cultivars. Without the implementation of such a type of system, world food production could have not increased at the rate it did and more natural ecosystems would have been converted to agriculture [3]. However, this has come with a cost in terms of environmental degradation [34–38], reducing biodiversity and all its related ecosystem services [30–32,34]. Hence, the challenge of agriculture today is to contribute to current and future food security with the implementation of more sustainable and resilient practices [39,40].

1.2. The Biogasdoneright™ Model

In Italy, sequential cropping has been widely adopted through a new model for sustainable food, feed and biogas production, called Biogasdoneright™ (BDR™) [26]. In this system, the primary crop produces food or feed while the sequential crop can be co-digested with other agricultural or agro-industrial residues to produce renewable energy (biomethane) and digestate [41]. Instead of using chemical- or fossil-based fertilizers bought from external markets, the digestate produced is used on the farm as an organic fertilizer to recycle mineral nutrients, and the liquid fraction is returned to the land for fertigation. By carrying out these measures and by decomposing roots from the sequential crop, soil carbon levels and soil fertility can be enhanced [17]. The sequential crop also has positive effects related to the prevention of soil erosion and soil moisture [42]. All these positive effects are further enhanced by combining other practices derived from conservation agriculture, such as minimum tillage, strip tillage and sod seeding [43]. Overall, the system functions as a biological carbon capture and sequestration (BECCS) process [44]. BDR™ is currently being applied in more than 600 farms in Italy, and its model is becoming a globally recognized blueprint for sustainable agriculture and the production of biogas, with $10 m being invested in pilot studies in the US. In Europe, its application is mainly limited to Italy and France [45].

In the European context, according to the EU methane strategy [46], sequential cropping used in combination with manure as feedstock for sustainable biogas production, while contributing to sustainable farming practices, should be further incentivized. The potential for biomethane production from the AD of sequential crops has been indicated in the grey literature as the highest compared to other production routes and feedstocks, such as the anaerobic digestion of agricultural residues, manure, food waste or sewage sludge [47]. This potential was calculated by taking into account the implementation of sequential cropping on primary crop areas corresponding to wheat and maize, which leaves room for further expansion of the potential by including the area dedicated to other types of crops. Moreover, most of the literature on BDR™, academic [17,41,44,48] and non-academic [18], focuses on examples in the Mediterranean region, in both the northern and southern parts of Italy, which despite their differences share similar agroclimatic conditions. With a broader perspective on the topic, Dale et al. [16] evaluated the biomethane potential of expanding the BDR™ concept in different European countries (Italy, France and the UK), based on Ecofys' calculations [47]. Ecofys [47] describes the overall biomethane potential of EU-28 and non-European countries (the US and Argentina). However, they specifically highlight the need for a more detailed assessment of biomethane potential from sequential cropping, looking at a range of possible crop combinations in sequential cropping schemes. To the best of the authors' knowledge, no academic literature has focused specifically on sequential cropping and its potential for biomethane production by taking into account the optimization of cropping calendars and agronomic differences among different climatic regions of the European continent.

As of today in Europe, sequential cropping is mostly adopted in Mediterranean regions, particularly in Italy [26] as well as in France, where the Culture Intermédiaire à Vocation Energétique (CIVE) is applied [45]. In the face of a climate crisis that is rapidly altering global and local environmental conditions, it is important to understand where sequential cropping could be used as a helpful strategy for the adaptation and mitigation of climate change, especially in areas where mono-cropping systems are being used, to satisfy rising demands for food and bioenergy.

The aim of this paper is to develop exemplary cropping calendars for different EU climate regions, including sequential crops, and evaluate the biomethane potential that would derive from the AD of sequential crops across different agroclimatic conditions. Finally, it also explores existent scientific literature that shows the benefits of sequential cropping in BDR™ systems in terms of carbon sequestration and emission reductions where this practice is already implemented, providing recommendations for further research directions on the topic.

2. Materials and Methods

Firstly, a literature review on the agroclimatic conditions of all the European climatic regions was performed to understand the suitability of implementing sequential cropping. Both the current conditions and future prospects of climate change were considered. The latter included the scenario of rising temperatures, whose agroclimatic impacts were evaluated by Trnka and Kersebaum [49] for 2030 and 2050. A description of the agroclimatic conditions of all the EU regions including their expected climate changes is provided in Section 2.1. The presentation of the expected climate changes was included as this could facilitate the implementation of sequential cropping in areas where it is currently more difficult to apply this practice, allowing us to validate the development of sequential cropping calendars, especially in the Atlantic and Continental regions. The Boreal region, presented in Section 2.1.4, was consequently excluded from the assessment because of the unsuitable conditions identified in the area, due to the short growing season [50]. The Mountain and Coastal areas shown in Figure 1 were also excluded since the extensive cultivation of herbaceous crops, which constitute the basis of sequential cropping, is not possible there. Subsequently, as explained in Section 2.2., exemplary classic crop rotation calendars were drawn for each region over a period of 4 years, using the Agri4Cast dataset [51], a well-documented portal widely used for agricultural research because of its accuracy and consistency from a spatiotemporal standpoint [52]. Then, according to the most common primary crops used in the classic crop calendars, an inventory of suitable sequential crops for each region was developed, including specific regional yields and biogas yields. Suitable sequential cops and their related yields inserted into the inventory were based on the published literature and on consultations with expert agronomists and experts in the biogas sector in each climate region. The papers were selected according to the country which the data was referring to, corresponding to a specific agroclimatic region. Since the literature data on biomass yield were country-specific, agronomist and biogas experts from the Italian Biogas Consortium, Fachverband Biogas and Deutsches Biomasseforschungszentrum recommended values that could be extended to each agroclimatic region. Finally, the inventory was used to develop sequential crop rotation calendars and estimate the biomethane potential of the anaerobic digestion of the sequential crops in each climate region, as shown in Section 2.3.

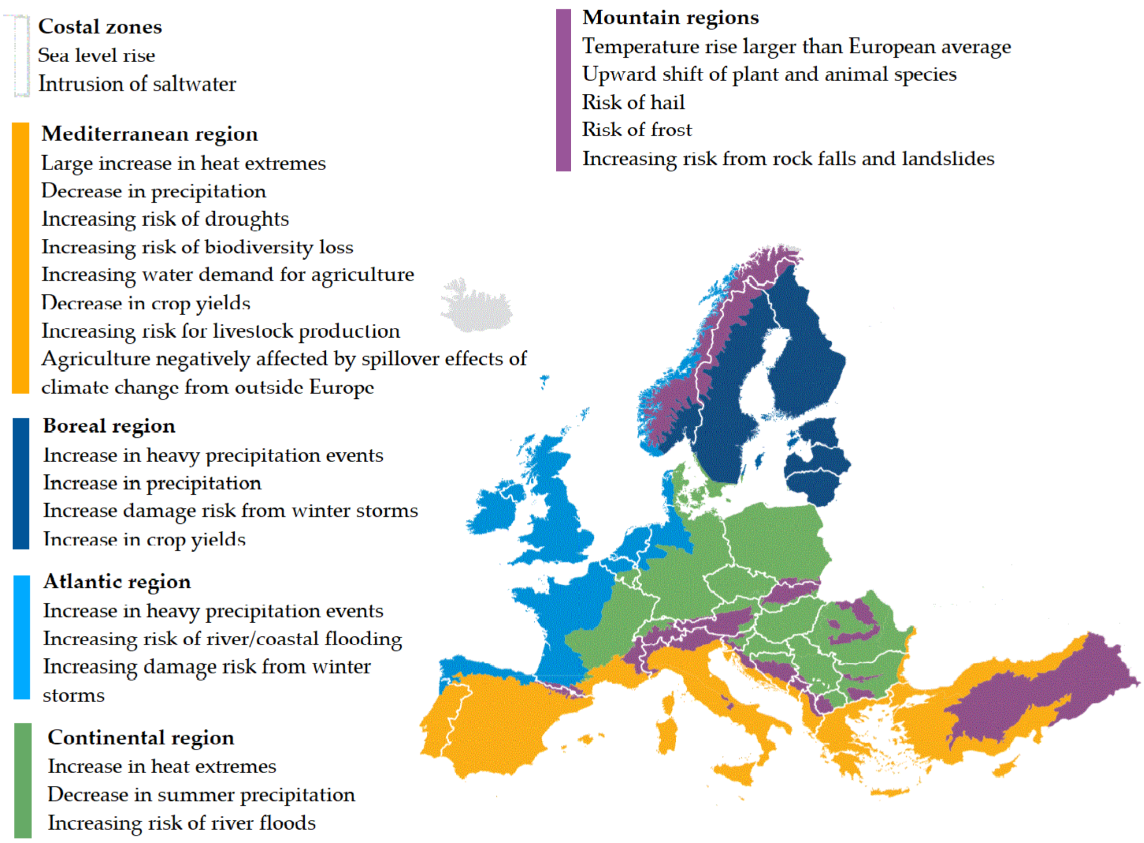

Figure 1. Main biogeographical areas in Europe and projected climate change impacts. Reprinted from European Environment Agency (2017) [29].

2.1. European Climate Regions

The climatic regions initially considered are equivalent to the climatic zoning reported by the DLO [53], the European Environment Agency [29,54] as well as Trnka and Kersebaum [49], which identified four main agroclimatic regions in Europe: Mediterranean, Atlantic, Central European (Continental) and Boreal. The climatic regions and their differences in terms of responses to climate change are shown in Figure 1. There is high variability in climatic conditions, soils and land use across the European continent, which also has a significant impact on the regions' ability to respond to climate change in agriculture [55,56], thus to the implementation of sequential cropping in the coming decades. Due to climate change, a "Mediterraneization" process is affecting many areas of the world [57]. For a large part of Europe, the length of the growing season is determined by the duration of the period when the temperature exceeds a certain threshold. For many plant species the duration of the frost-free season is regarded to be a suitable time for growth (e.g., for flowering). However, active plant growth necessitates higher temperatures, between 15 and 25 °C [58], required for the majority of temperate crops, and 5 °C is considered as a threshold temperature [49]. The growing season is projected to begin sooner in spring and last longer in the autumn as temperatures rise globally. In most of Europe, there has been a trend of anticipation of the flowering date of winter wheat in the period 1985–2014 [29]. With the continued increase in temperatures globally, the timing of the last spring frost is also expected to anticipate by roughly 5–10 days by 2030, and by 10–15 days by 2050 [49]. This has direct consequences on classic crop rotations and on the possibility of implementing sequential cropping. Since winter crops can be harvested earlier in the agricultural year and their crop cycle becomes shorter, the temporal gap available to grow a sequential crop will tend to increase. The solutions that enable the implementation of this practice vary among climate regions depending on their characteristics, and will change over time as temperatures rise.

2.1.1. Mediterranean Region

The Mediterranean climatic region includes Central and Southern Spain, Portugal, Southern France, Italy, Greece and Albania [54]. Its climate is characterized by dry summers with drought periods and a high summer temperature (average of 21 °C) [59]. Winters are often moderate and humid, with an average temperature of 6 °C. Rainfall is limited to the winter months and is spread irregularly (with storms) during the autumn, winter and spring, ranging from 300 to 500 mm, although there are also areas that can reach 700 mm (e.g., the Po Valley) [53,60]. Precipitation is a crucial variable in the Mediterranean area since its future decline might impact human activities, and it could lead to more frequent droughts worsened by rising temperatures [61,62]. With rising temperatures, the suitability of soil for harvest as well as sowing is expected to increase in the early spring and fall. As a result of the spring droughts, the late-spring sowing window will become unreliable, making sowing and other tilling operations difficult [56]. Moreover, climate change is expected to reduce the total sum of effective global radiation and increase the fraction of dry days in the early growing season [63].

2.1.2. Continental Region

The Continental climatic region includes Germany, Luxembourg, Denmark, Poland, Austria, Switzerland, Czechia, Slovakia, Hungary, Romania, Bulgaria and the Balkan area [54]. In the winter, temperatures often range from −1 to −5 °C [53]. Several months of persistent freezing and snow can also characterize the winter months. The summer months are hot and often dry, with an average temperature of 16 °C [64]. The average rainfall usually does not exceed more than 600 mm/year [65]. Precipitation occurs all year, though it is mostly in the form of snow in the winter [53]. Climate change is predicted not to have a significant impact on the effective global radiation sum and number of effective growth days; however, the sowing window in early spring should become longer (on average) and more steady [49].

2.1.3. Atlantic Region

The Atlantic region includes Central and Northern France, Ireland, the UK, Belgium and the Netherlands [54]. During the winter, the relatively warm temperature of the coastal seas and neighboring Atlantic Ocean has a significant impact on this region [66]. In general, the temperature differences between winter and summer are limited. Summer averages between 15 and 20 °C, while winter averages between 1 and 7 °C [53]. Rainfall occurs throughout the year, with slight peaks in the autumn and winter. Nonetheless, it differs greatly from one location to the other [67]. Rainfall is substantially high (>3000 mm/year) in western hilly regions [53]. Precipitation can be relatively high in the winter in the most southern section of the Atlantic climate area, but there is very little frost and snow [68]. When compared to other European locations, the high number of effective growing days and, to a lesser degree, the effective global radiation levels result in high yields of major field crops [55]. With climate change, the amount of effective global radiation is unlikely to vary much, but the number of dry days is likely to rise [49].

2.1.4. Boreal Region

The Boreal region includes Norway, Sweden, Finland, Estonia, Latvia and Lithuania [54]. In this area, the average temperature is around 15 °C [53]. Except in hilly areas, rainfall is relatively modest, rarely exceeding 500 mm per year on average [67]. The majority of the rainfall is in the late summer, but under the current climate circumstances, the number of effective growing days is low [53]. Currently, only the late-spring sowing window is being employed, and most sowing takes place far into the summer. This is due to wet soils that must dry before heavy machinery can plant, low temperatures that slow germination and a higher danger of night frosts, making early sowing economically risky [69]. As a result, yields in this region are generally much lower than in other European regions [70], and it has been evaluated that its agricultural potential will remain comparatively low, even in a scenario of 5 °C climate change [49].

2.2. Cropping Rotations and Sequential Crops Inventory

The primary crops considered for developing the crop rotation calendars and calculating the biomethane potential are shown in Table 1.

Table 1. Surface area of primary crops, Eurostat [71].

Crop Type/Land Use	Surface 0.000 Ha				
	EU-28	Mediterranean	Atlantic	Continental	Boreal
Arable land	105,020.5	22,227.5	26,601.5	52,010.8	9674.9
Irrigated land	15,689.3	9651.4	3711	2120.5	164.5
Irrigated land (% arable land)	15%	43%	14%	4%	2%
Cereals	55,437	10,280.1	12,892	30,724.9	4396.3
Wheat	25,499.4	4382	7347.1	12,887.7	1894
Barley	12,282.8	2985.1	3169.3	5070.6	1396.6
Triticale	2610.5	261.7	300.1	2015.2	82
Maize	8259.5	1164.5	1501	6816.9	14.5
Sorghum	147.8	48.2	60.8	38.6	-
Grain pulses/proteins	2365.6	747.6	500.8	810.9	363.4
Potatoes	1702.8	161.2	605.7	955.6	88.8
Sugarbeet	1735.6	71.8	747.9	927.3	55
Rapeseed	6900.6	96.4	2223.5	4102.4	553.8
Soybean	955.4	328.9	154.4	677.3	1.9
Green maize	6355.9	681.6	2037.4	3694.9	81.6
Sunflower	4025.6	887.5	552.8	2832.9	-
Total primary crops	88,324.7	13,255.3	19,715.6	44,726.1	5541.9

The data on the surface area of the crops were retrieved from Eurostat [71], aggregating the total land use of each crop in the countries belonging to different EU climate regions. The crop calendars regularly adopted in each EU climate region were developed using the Agri4Cast dataset [51]. Its Crop Calendar portal [51] holds the option of building maize and winter crop calendars for different countries, considered as food crops. It reports the crop calendars in the EU at the national level for winter wheat (soft and durum), grains, maize and rice. The calendars developed for the EU climate regions are reported in Figure 2, considering crop rotations over a period of four agricultural years (from November to October of the following year) and describing how farmers are currently alternating crops between winter and spring.

In Figure 2, the periods in which each crop is cultivated is differentiated with three colors, corresponding to the vegetative season when the plant is sown (Seeding—early vegetative), grows (Growing) and finally harvested (Ripening—Harvest).

For the Atlantic and Continental regions, among the winter crops, rapeseed was considered as an alternative to wheat and barley [72]. As for spring crops in these two areas, maize, potato, sugar beet and soya were considered [71]. In the Mediterranean region (North), the spring crops considered were maize and sorghum [17]. For each region, there are temporal ranges in which no crops are grown and the soil is left to rest in preparation for the next crop, and their duration varies according to the region [51]. From these gaps, for each specific climate region suitable sequential crops to incorporate into the defined time frames were defined using the available literature reported in Table 2 and consultations with expert agronomists. In general, the gaps represented in the classic crop rotation calendars could be windows for the sequential crops proposed, which must then be chosen in accordance with the local agronomic characteristics. The inventory of suitable crops, their yield and their biogas yield are shown in Table 2. The crops included in Table 2 were subsequently used for developing the sequential cropping calendars shown in Figure 3 and for calculating the biomethane potential derived from using the sequential crops for biogas production in each region.

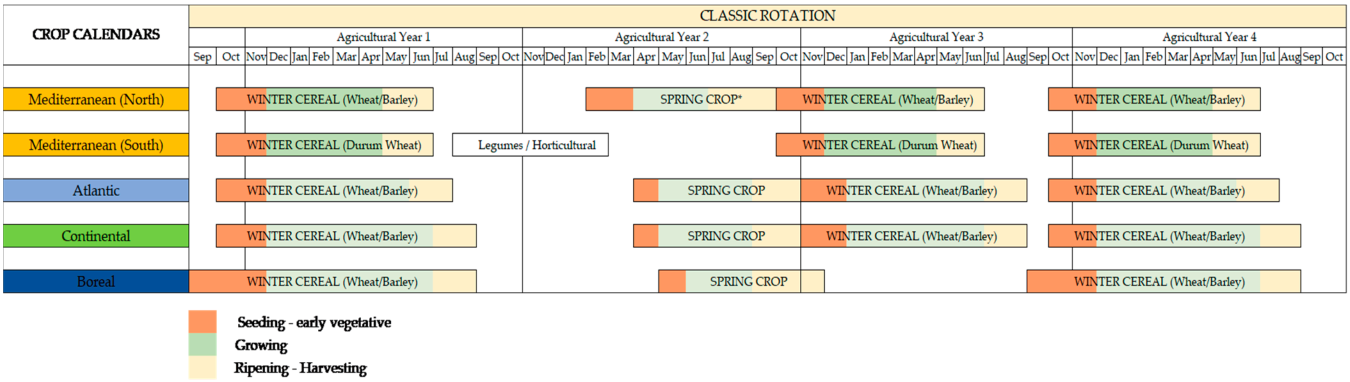

Figure 2. Classic calendar crop (Agri4Cast data). The periods in which each crop is cultivated is differentiated with the three colors.

Table 2. Sequential crop inventory.

Sequential Crop	Average Biomass Yield (T DM/ha)	Biogas Yield [1,2] (m^3/t DM)	References for Biomass Yield
Mediterranean (North and South)			
Maize	16.5	620	[73]
Triticale	13.5	570	[74]
Barley	11	570	[74]
Sorghum	13.5	570	[17]
Legume cover crops	8.5	510	[75]
Atlantic			
Sorghum	7	570	[76,77]
Maize	14	620	[77]
Oats	7.6	570	[77]
Triticale	9.3	570	[77]
Barley	4.5	570	[77]
Continental			
Maize	14	620	[78]
Green rye (early harvest)	6.5	570	[79]
Sorghum	10	570	[78,80]
Ryegrass	9	570	[78,80]

[1] Based on Murphy et al. [81] and on CRPA [74] for triticale and barley. Following Murphy et al. [81], the biogas yield in m^3/t DM were calculated assuming 90% VS content. [2] The biomethane yield considered was 52% [82].

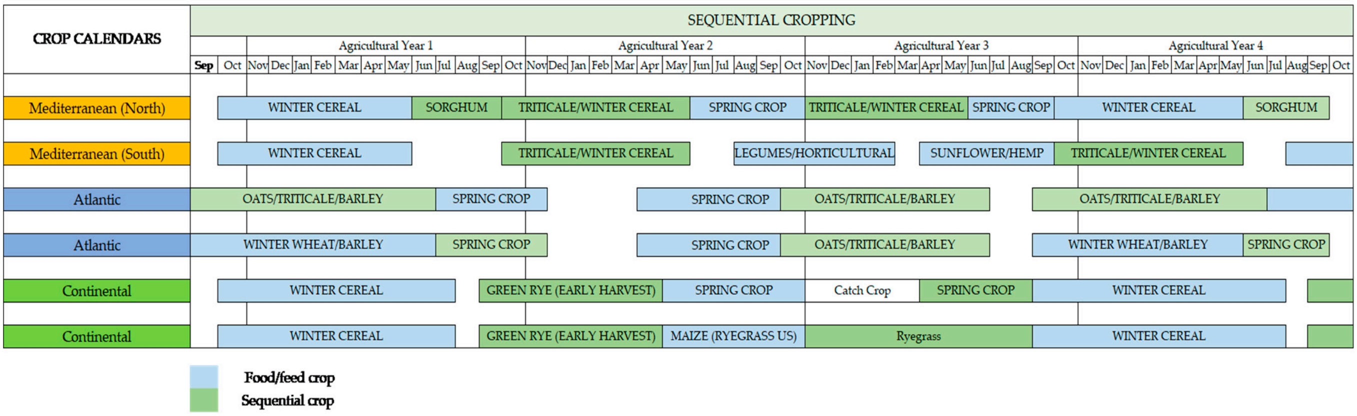

Figure 3. Sequential cropping calendars.

2.3. Biomethane Potential Calculation

The biomethane potential was calculated for two different scenarios, *Conservative* and *Maximum* scenarios, as shown in Table 3.

Table 3. Percentages of land dedicated to sequential cropping in *Conservative_Scenario* and *Maximum_Scenario* and corresponding hectares.

	Conservative_Scenario % Summer Crops—Maize, Sorghum, Soybean, Sunflower and Green Maize	Conservative_Scenario (20% of Primary Crop Land) Ha	Maximum_Scenario (80% of Primary Crop Land) Ha
Mediterranean	23%	2,651,058	10,604,232
Atlantic	22%	3,943,126	15,772,504
Continental	31%	8,945,212	35,780,848
	≈20%		

The criteria used to define the two different scenarios are explained below:

The *Conservative_Scenario* was considered to investigate practically feasible conditions under which sequential cropping could be applied. In this scenario, the land considered suitable for sequential cropping was estimated for each EU climate region as the percentage of specific summer crops (maize, sorghum, soybean, sunflower and green maize) over the total primary crop land in each region.

The final percentage chosen for all regions to estimate the land suitable for sequential cropping was 20% of primary crop land, as a conservatively rounded average of the percentages found in each region, as shown in Table 3. The specific summer primary crops considered for the calculation of the percentage were chosen according to the following criteria that allow the scenario to be considered as a realistic one:

(1) Account for the water limitation in the Mediterranean region, selecting irrigated land for summer primary crops which allows the use of that portion of irrigated land to be excluded for sequential crops. In this way, the hectares dedicated to sequential cropping in the Mediterranean region would only account for 30% of the total irrigated land. In the other two regions the hectares considered exceed the hectares of irrigated land, due to the fact that the higher rainfall lessens the issue of water availability. However, in these areas the limiting factors to sequential cropping are temperature and solar radiation affecting the length of growing seasons. In fact, with low temperatures, the productive capture of light energy via the photochemical reactions of photosynthesis declines [83]. Solar radiation is one of the most important factors that influences crop development, bringing energy to the metabolic process of the plants, and the amount of dry matter produced is linearly related to the amount of solar radiation intercepted by the crop [84]. The problems related to low temperatures and solar radiation in the Atlantic and Continental regions have been addressed in the development of the crop rotation calendars, as explained in Section 3.1.

(2) Take into account only primary crops on which the practice of sequential cropping is most established and commonly practiced.

(3) Consider a number of hectares suitable for sequential cropping smaller than the total summer crop area for each of the EU regions. Since the area dedicated to summer crops is irrigated land, the area that is left available could still be used for the cultivation of both summer and winter crops (according to regional conditions) without the need of additional irrigation.

The *Maximum_Scenario* was developed to estimate a theoretical maximum potential that would derive from the application of sequential cropping in EU. It considers 80% of the primary crop land as dedicated to sequential cropping, excluding marginal and small fields.

In these two scenarios, the biomethane potential for each region was calculated as follows:

First, for both scenarios and for the different regions, the biogas yield (m^3/ha) was estimated for summer and winter sequential crops, respectively, taking into account the total average yield (t DM/ha) and biogas yield (m^3/t DM). Then, the suitable land for summer and winter sequential crops was estimated. In the *Conservative_Scenario*, it was calculated considering the same probability for summer and winter crops to be cultivated on the total suitable land (50% of total suitable land in both cases), as in practice it is not possible to state a priori that irrigated land will not be used for winter crops. In the *Maximum_Scenario*, first the suitable land for winter sequential crops was estimated as the total land dedicated to primary summer crops in each region, the latter being the maximum expansion for winter sequential crops. Subsequently, the suitable land for sequential summer crops resulted as the difference between the total suitable land and the land for winter sequential crops. Finally, the biomethane potential for each region was derived, considering biomethane as 52% of biogas content [82–84].

3. Results and Discussion

3.1. Sequential Crop Calendars

The sequential crop calendars developed are shown in Figure 3, where the blue bars represent primary crops used for food and feed, and green bars are energy crops. The sequential crops inventoried in Table 2 were placed in the fallow period identified in Figure 2. As is possible to observe, winter cereal harvest or sowing is anticipated in all the different EU regions, since the product is silage that is harvested earlier than complete maturation for grain production. In the Mediterranean regions, the harvest of winter cereals is anticipated from June to May, in the Atlantic region the sowing date is anticipated from October to September and in the Continental region the harvest date is anticipated from August to July [29,49]. Spring crops also have shorter cycles (from seeding to harvesting) from a maximum of 8 to a minimum of 5 months of cultivation in the Mediterranean region [85] and from a maximum of 7 to a minimum of 6/5 months of cultivation in the Atlantic and Continental regions [29]. This allows the sequential crop to be cultivated already in June in the case of the Mediterranean region (North), July in the Atlantic region and in September in the Continental region. It is important to note that the cropping calendars developed are exemplary for the regions they represent. Within each climatic region, different areas will have different principal crops.

In the Mediterranean region, where sequential cropping has been widely implemented through the BDR™ concept, the temporal gaps for the addition of sequential crops are already defined since timings and climatic conditions allow for manageable cycles, and the winter crops can be harvested already in May [17]. At higher latitudes, as in the Atlantic and Continental areas, the winter crop cycles are longer and winter cereals are harvested in June or July. Hence, it becomes more difficult to add a sequential crop within the agricultural year [51]. The authors of this research determined that the solutions in the Atlantic and the Continental areas can be double: the first one is to cultivate three crops in two years and the second one is intercropping, as shown in Figure 3 in the second alternative crop calendar for the Continental area. At the end of the second agricultural year, ryegrass is undersown to the spring primary crop to anticipate the cycle. Both these solutions require farmers to acquire additional agronomic knowledge and practical help to be able to adapt their traditional crop calendars and choose appropriate sequential crops that can be suitable for local conditions. In the last four–five decades, the use of sequential crops has mainly been focused on soil protection only (cover crops) rather than on the simultaneous production of additional biomass [86]. Additionally, the use of sequential crops for ruminant nutrition has phased out during the 1960s because of the shift from grazing to stabling systems and, for these reasons, until recently there has been little attention on ensuring high biomass yields of sequential crops [87]. Hence, there are several management improvements that are still possible to be applied to generate higher crop yields in sequential cropping systems. For example, a difference of 2–3 tons DM/year of yield could be achieved by the pre-swelling of the sequential crops (intercropping) or by quick seeding directly after the harvest of the winter cereal [87]. This could strongly enhance the yield, especially under water limitation conditions as the immediate seeding after harvest reduces the loss of soil moisture. Moreover, the anticipation of the seedling time in summer of even one day would make a difference in terms of solar radiation, allowing for higher yields [88].

The arrangement of the cropping calendars and the choice of the final use of the crops is very complex and dynamic during the year. For instance, if in winter wheat is cultivated with the aim of using it as food crop, in March–April the market for seeds might not be convenient anymore, or the quality of the crop might not be excellent. Thus, the farmer could choose to use the crop as fodder, anticipating the harvest, shortening the cycle and making room for a sequential crop. Therefore, the sequential cropping rotations developed can be interpreted as a general scheme whose boundaries are fixed by classic crop rotations, and according to local environmental and economic conditions they can be adjusted by choosing the sequential crops that are suitable for the area.

Growing a second crop may require more resources such as labor, water, energy, agro-chemicals or all the above. However, as observed by Waha et al. [19], these problems are not specific to sequential cropping systems but to intensively managed systems when incentives to overuse fertilizer, pesticides and water are high. In BDR™ systems, these aspects are intentionally minimized through the use of second crops that can enhance ecosystem services, while producing biomethane and digestate used as fertilizer (both the solid and liquid fraction), reducing the input of agro-chemicals and the use of fossil energy [48].

3.2. Biomethane Potential

The biomethane potential of the different EU regions and the total EU biomethane potential for each scenario are shown in Table 4.

As is possible to observe, the Continental region shows the highest potential (25.8 bcm/yr and 104.9 bcm/yr in the *Conservative* and *Maximum* scenarios, respectively), mainly due to the higher number of hectares of suitable land for sequential cropping compared to the other two regions (three times more than the Mediterranean region and double that of the Atlantic region). The Mediterranean region registered the lowest potential (9.9 bcm/yr and 37.9 bcm/yr in the two scenarios), because it had the least primary crop land considered suitable for sequential cropping. In the *Conservative_Scenario*, this accounts for ≈2.6 million hectares, corresponding to about 30% of the total irrigated land in the region (≈9.6 million hectares). Moreover, in the same scenario, the summer sequential crops that would need irrigation would only require 13% of the irrigated land, while in the *Maximum_Scenario* they would take 67% of it. These conditions allow biomethane potentials that take into consideration the importance of water limitations in this region to be found, always leaving part of the irrigated areas available. The Atlantic region presents a similar potential to the Mediterranean region (10.2 bcm/yr and 42.5 bcm/yr in the two scenarios), sharing similar extensions for suitable land and also crop distribution, with 70% of the land for winter crops and 30% for summer crops, as shown in Table 5.

Table 4. Biomethane potential calculation for different EU climate regions.

	Mediterranean		
	Biogas Yield/Ha (m^3/ha)	*Conservative_Scenario* Suitable Land Considered for Sequential Cropping (Ha) (20% of Primary Crop Land)	*Maximum_Scenario* Suitable Land Considered for Sequential Cropping (Ha) (80% of Primary Crop Land)
Suitable primary crop land		2,651,058 (12% of arable land)	10,604,232 (48% of arable land)
Summer sequential	8925	1,325,529	6,512,732
Winter sequential	6050	1,325,529	4,091,500
Biomethane potential (bcm/yr)		9.9	37.9
	Atlantic		
	Biogas Yield/ha (m^3/ha)	*Conservative_Scenario* Suitable Land Considered for Sequential Cropping (Ha) (20% of Primary Crop Land)	*Maximum_Scenario* Suitable Land Considered for Sequential Cropping (Ha) (80% of Primary Crop Land)
Suitable primary crop land		3,943,126 (15% of arable land)	15,772,504 (59% of arable land)
Summer sequential	6248	1,971,563	9,611,604
Winter sequential	4066	1,971,563	6,160,900
Biomethane potential (bcm/yr)		10.2	42.5
	Continental		
	Biogas Yield/ha (m^3/ha)	*Conservative_Scenario* Suitable Land Considered for Sequential Cropping (Ha) (20% of Primary Crop Land)	*Maximum_Scenario* Suitable Land Considered for Sequential Cropping (Ha) (80% of Primary Crop Land)
Suitable primary crop land		8,945,212 (17% of arable land)	35,780,848 (69% of arable land)
Summer Sequential	7140	4,472,606	19,026,448
Winter Sequential	4418	4,472,606	16,754,400
Biomethane potential (bcm/yr)		25.8	104.9
Total biomethane potential (bcm/yr)		45.9	185.4

Table 5. Ratios of summer and winter crops on the total primary crop land.

	Mediterranean	**Atlantic**	**Continental**	**Mediterranean**	**Atlantic**	**Continental**
	Ha	**Ha**	**Ha**	**% TOT**	**% TOT**	**% TOT**
Winter primary crops: winter wheat, barley, triticale and rapeseed	9,163,790	13,554,730	27,971,660	69%	69%	63%
Summer primary crops: sorghum, sunflower, maize, sugarbeet, soya, green maize, potatoes and protein	4,091,500	6,160,900	16,754,400	31%	31%	37%
Total	13,255,290	19,715,630	44,726,060			

In the Atlantic and Continental regions, the suitable land for sequential cropping in the two scenarios (Table 4) exceeds the hectares available for irrigated land (Table 1); however, this was not considered an issue in the *Conservative_Scenario*, as water is not the main constraint to the implementation of the practice there [54]. Temperatures and solar radiation here can affect the harvest and sowing periods, making time between one crop and the other the most important factor affecting the feasibility of sequential cropping in these regions [45]. This constraint is included in the *Conservative_Scenario* where the percentage of suitable land arrives to be a maximum of 17% of the arable land (Table 4), excluding the possibility of implementing sequential cropping in extreme areas of the regions. In these extreme regions, the sequential crop calendars proposed in Figure 3 might be impossible to implement as solutions due to climatic conditions [49]. Overall, looking at the percentages of suitable land for sequential cropping over the total arable land in all the different regions, it was found an average of 15% of suitable land in a *Conservative_Scenario*, and that an average of 60% in a *Maximum_Scenario* could be considered as the upper limitof suitable land.

Compared to the latest EU biomethane potential estimate by Navigant [89] of 41 bcm/yr, the current study found a comparable total biomethane potential in a *Conservative_Scenario* equal to 45.94 bcm/yr, while it was 185.44 bcm/yr in a *Maximum_Scenario*. This means that, looking at a wider range of possible crop combinations in sequential cropping schemes, and considering the possible limitations of the application of the practice in different agroclimatic conditions (water availability in the Mediterranean region and extreme conditions in the Atlantic and Continental regions), the goal set by Navigant [89] of reaching 41 bcm/yr by 2050 falls within the range of a feasible scenario for Europe. This goal could also be extended to ≈46 bcm/yr, considering the current assessment. According to this estimate, and taking into account European gas consumption in 2020 of 394 bcm [90], around 11% of this amount could be covered by renewable gas from sequential cropping. Additionally, by 2050, the EU's annual consumption of biogases (biogas and biomethane) is projected to grow to between 63 bcm and 83 bcm [46], where between 70% and 55% could potentially be covered by sequential crops.

As done in the Navigant study [89], the biomethane potential calculated assumed that the yields from the mono-digestion of feedstocks are the same of the ones in a co-digestion process. Therefore, the possibility of increasing the yield via co-digestion of feedstocks is not taken into account in our estimate. Considering that BDR™ systems use the co-digestion of sequential crops with agricultural and livestock waste, and co-digestion can lead to higher yields [91], there is the possibility of achieving higher potentials in the different regions. However, this aspect was not taken into account, as the extent to which the yield can be increased depends on the type and ratio of substrates used, which can vary among farms and countries. Co-digestion of sequential crops with other substrates available on-farm in BDR™ systems not only contributes to better biomethane yields, but also to a higher potential use of digestate as a soil amendment, due to better nutrient levels and availability [92]. Furthermore, a tighter organization of crop schemes within the agricultural year can also lead to more efficient use of the resources available and drive agricultural innovation.

3.3. Sequential Cropping in Combination with BDR Principles in Europe: Open Questions to Research

3.3.1. Carbon Sequestration and Soil Quality Enhancement

In addition to the benefit of sequential cropping of producing biomethane with no ILUC risks, diversifying crop rotations can increase annual carbon inputs, leading to higher soil carbon stocks compared to high-fallow-frequency systems [93]. Moreover, besides the adaptation of cropping calendars to produce more biogas feedstocks, BDR™ systems combine sequential cropping and its advantages in terms of capturing nutrients, enhancing soil fertility and reducing erosion, with a circular management of all the resources used and produced at the farm level, such as the continuous restitution of organic matter to the soil through the digestate, and with practices derived from conservation agriculture—such as minimum tillage, strip tillage and sod seeding, among others. Overall, the system functions as a biological carbon capture and sequestration (BECCS) process with positive impacts on climate change mitigation. BDR™ comprises different types of complementary adaptation strategies for crop production, including crop varieties with higher residue and root production, while reducing fossil fuel dependence by avoiding synthetic chemicals, increasing efficiency and using renewable energy [94]. A resulting increase in soil organic carbon has been registered in different case studies applying the BDR™ concept in the Mediterranean region. In the case of Bezzi [44], where a farm in the West Po Valley in Italy was studied, both an increase in organic matter (0.5%) and soil organic carbon (0.3%) was observed over a period of six productive years (2009–2015). In the Palazzetto Farm in Cremona, North Italy, a similar increase of 0.5% in soil organic carbon was registered between 2009 and 2016 on two out of three pilot fields considered in the study [18]; the substantial increase was linked to the introduction of sequential cropping. Valli et al. [48] also observed an increase in soil organic carbon (0.2–0.3 t C/ha per year) for sequential cropping schemes compared to a reference system of maize silage monocrop, linking such an increase to the addition of digestate and organic matter from crop residues arising from sequential crops. The return of the digestate to the soil can stimulate this process while also reducing GHG emissions, as shown by [95], and enhance agro-environmental sustainability, especially when using the liquid fraction through fertigation [73]. Hence, the application of sequential cropping and BDR principles allows soils to be better adapted to environmental and climate change, insuring farmers against risk of crop failures in the future [96].

The European Commission is aiming to launch an EU carbon farming initiative by the end of 2021, offering farmers the possibility to access result-based payment schemes for carbon farming (as a reduction in GHG emissions on farms and/or carbon sequestration) [97]. This research showed that calendar crops could be adapted to apply sequential cropping in different agroclimatic regions of Europe. It remains the case that little is known on the carbon sequestration effects of combining sequential cropping with BDR™ principles in regions outside of the Mediterranean region, where all existing case studies are placed. Further research is needed to investigate if under different agroclimatic conditions this system can lead to the same benefits, or if additional agricultural management strategies should be adopted. This could be particularly important at the EU level to give farmers more tools to implement sustainable practices that contribute to removing CO2 from the atmosphere while being able to economically benefit from it [98].

3.3.2. Avoidance of Emissions from the BDR™ System

In addition to the targets of renewable energy production, the RED II [24] have introduced sustainability and GHG criteria for bioenergy production from agricultural biomass, setting limits on the use of high-ILUC-risk biomass fuels and requiring producers of renewable energy from agricultural crops to certify their feedstock as climate friendly.

In a BDR™ system, some of the traditional steps for biogas production are avoided, resulting in a shortening of the supply chain, hence in a reduction in GHG emissions, as observed by the study of Valli et al. [48]. In the latter, a lifecycle approach was applied, a methodology very similar to the emissions calculation approach on which the RED II criteria are based. From this study, the following lifecycle steps were avoided, and thus their relative emissions were as well: the production and use of chemical fertilizers, manure storage and byproduct handling in addition to the use of fossil resources.

The avoidance of emissions from avoided lifecycle steps, the combined application of sequential cropping for biomethane production with farming practices such as organic fertilization through the digestate, minimum tillage techniques, and the application of innovative agricultural practices such as high-efficiency digestate distribution and fertigation, are predicted to reduce the emissions of the Italian agricultural sector by 30%, as shown in the latest Farming For Future report [24,99]. As sequential cropping and BDR™ systems are currently mainly applied in Mediterranean countries, the predicted reduction in emissions of the agricultural sector in other European countries linked to the implementation of these practices is currently missing. Therefore, further research should focus on understanding, for each country or region, what aspects of BDR™ systems can contribute more to emission reductions in specific agroclimatic conditions, and the total emission reduction that could be achieved.

Finally, it is important to note that the revised RED II [24,99], setting limits on the use of high-ILUC-risk biofuels, bioliquids and biomass fuels, does not recognize the ILUC-free potential of multiple cropping practices, such as sequential cropping for biogas production. This type of biogas feedstock production is still not included in the list of feedstocks for advanced biofuels in Annex IX [24,99]. Additional research on the benefits of sequential cropping biogas production in terms of avoided ILUC emissions could provide scientific tools to both policy makers and farmers to certify sequential crops as advanced feedstocks with low ILUC risk.

4. Conclusions

This paper showed that tailored solutions to different agroclimatic conditions in Europe can be found in terms of crop management to expand the application of sequential cropping. Different sequential crops and calendars were proposed according to the region, taking into account their specific needs and limitations in terms of the length of growing seasons. In the Atlantic and Continental regions, where winter crop cycles are longer than in the Mediterranean region, two different solutions were considered: the cultivation of three crops in two years and intercropping. Additionally, in order to increase the yields of sequential crops, pre-swelling of the sequential crop and quick seeding after the harvest of the winter cereal were proposed as solutions. In the assessment of biomethane potential, different biogas yields (m^3/ha) were considered according to the characteristics of the region. The biomethane potential found in the *Conservative_Scenario* accounts for an additional ≈46 bcm/year that could be unlocked by the AD of sequential crops, and a maximum of 185 bcm/yr when using 60% of arable land. This confirms the importance of considering biomethane produced from sequential crops as an essential element for renewable gas production and for achieving European decarbonization targets, which manure, agricultural residues and food waste could not reach alone [89]. The analysis also showed that it is possible to produce biomethane from crops in different European regions without any ILUC effect. Moreover, this study highlighted the additional benefits that sequential cropping practices can provide when applied in circular systems such as the BDR™ in Mediterranean case studies, in terms of carbon sequestration and soil fertility, due to the use of the sequential crops both for energy and digestate application, and for the combination with precision farming practices. Recommendations in terms of further research needed to expand the knowledge on the topic at the European level were provided, including the carbon sequestration effect in different agroclimatic conditions and emission reductions in the agricultural sector in different countries. In conclusion, this study showed that the application of sequential cropping in BDR™ systems could be agronomically feasible for at least 15% of arable land in Europe, contributing to a more sustainable, circular and optimized use of biomass feedstock for the European bioeconomy.

Author Contributions: Conceptualization, F.M., H.D., M.D., G.B. and L.R.; Methodology, F.M., G.B. and L.R.; Software, not applicable.; Validation, H.D., E.M. and S.S.; Formal Analysis, F.M. and G.B.; Investigation, F.M.; Resources, F.M. and M.D.; Data Curation, F.M. and G.B.; Writing—F.M.; Writing—Review and Editing, F.M; Visualization, F.M.; Supervision, H.D., E.M. and S.S.; Project Administration, F.M., H.D., M.D. and E.M.; Funding Acquisition, E.M. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon 2020 research and innovation program AgRefine, under the Marie Skłodowska-Curie grant agreement (no. 860477).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors acknowledge the support provided by Fachverband Biogas and Deutsches Biomasseforschungszentrum.

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

References

1. Agovino, M.; Casaccia, M.; Ciommi, M.; Ferrara, M. Agriculture, Climate Change and Sustainability: The Case of EU-28. *Ecol. Indic.* **2019**, *105*, 525–543. [CrossRef]
2. Aydinalp, C.; Cresser, M.S. The Effects of Global Climate Change on Agriculture. *Eurasian J. Agric. Environ. Sci.* **2008**, *3*, 672–676.
3. Tilman, D.; Cassman, K.G.; Matson, P.A.; Naylor, R.; Polasky, S. Agricultural Sustainability and Intensive Production Practices. *Nature* **2002**, *418*, 671–677. [CrossRef]
4. Bastos Lima, M.G. *The Politics of Bioeconomy and Sustainability: Lessons from Biofuel Governance, Policies and Production Strategies in the Emerging World*; Springer Nature: Stockholm, Sweden, 2021; ISBN 9783030668365.
5. Wollenberg, E.; Richards, M.; Smith, P.; Havlíc, P.; Obersteiner, M.; Tubiello, F.; Herold, M.; Gerber, P.J.; Carter, S.; Reisinger, A.; et al. Reducing Emissions from Agriculture to Meet the 2 °C Target. *Glob. Chang. Biol.* **2016**, 3859–3864. [CrossRef]
6. European Commission. The European Green Deal. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640 (accessed on 9 July 2021).
7. European Commission. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment Updated Bioeconomy Strategy. Available online: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52018DC0673 (accessed on 25 June 2021).
8. European Commission. A Greener and Fairer CAP. Available online: https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/key_policies/documents/factsheet-newcap-environment-fairness_en.pdf (accessed on 9 August 2021).
9. Muscat, A.; de Olde, E.M.; de Boer, I.J.M. The Battle for Biomass: A Systematic Review of Food-Feed-Fuel Competition. *Glob. Food Secur.* **2020**, *25*, 100330. [CrossRef]
10. Thompson, P.B. The Agricultural Ethics of Biofuels: The Food vs. Fuel Debate. *Agriculture* **2012**, *20*, 339. [CrossRef]
11. Dauber, J.; Brown, C.; Fernando, A.L.; Finnan, J.; Krasuska, E.; Ponitka, J.; Styles, D.; Thrän, D.; van Groenigen, K.J.; Weih, M.; et al. Bioenergy from "Surplus" Land: Environmental and Socio-Economic Implications. *BioRisk* **2012**, *50*, 5–50. [CrossRef]
12. European Network for Rural Development. European Rural Bioeconomy: Policy and Tools. Available online: https://enrd.ec.europa.eu/sites/default/files/enrd_publications/bioeconomy-briefing_1_policy-and-tools.pdf (accessed on 1 October 2021).
13. De Pedro, L.; Perera-Fernández, L.G.; López-Gallego, E.; Pérez-Marcos, M.; Sanchez, J.A. The Effect of Cover Crops on the Biodiversity and Abundance of Ground-Dwelling Arthropods in a Mediterranean Pear Orchard. *Agronomy* **2020**, *10*, 580. [CrossRef]
14. Blanchart, E.; Villenave, C.; Viallatoux, A.; Barthès, B.; Girardin, C.; Azontonde, A.; Feller, C. Long-Term Effect of a Legume Cover Crop (Mucuna Pruriens Var. Utilis) on the Communities of Soil Macrofauna and Nematofauna, under Maize Cultivation, in Southern Benin. *Eur. J. Soil Biol.* **2006**, *42*, S136–S144. [CrossRef]
15. Elhakeem, A.; van der Werf, W.; Ajal, J.; Lucà, D.; Claus, S.; Vico, R.A.; Bastiaans, L. Cover Crop Mixtures Result in a Positive Net Biodiversity Effect Irrespective of Seeding Configuration. *Agric. Ecosyst. Environ.* **2019**, *285*, 106627. [CrossRef]
16. Dale, B.E.; Bozzetto, S.; Couturier, C.; Fabbri, C.; Hilbert, J.A.; Ong, R.; Richard, T.; Rossi, L.; Thelen, K.D.; Woods, J. The Potential for Expanding Sustainable Biogas Production and Some Possible Impacts in Specific Countries. *Biofuels Bioprod. Biorefin.* **2020**, *14*, 1335–1347. [CrossRef]
17. Selvaggi, R.; Valenti, F.; Pappalardo, G.; Rossi, L.; Bozzetto, S.; Pecorino, B.; Dale, B.E. Sequential Crops for Food, Energy, and Economic Development in Rural Areas: The Case of Sicily. *Biofuels Bioprod. Biorefin.* **2018**, *12*, 22–28. [CrossRef]
18. Peters, D.; Zabeti, M.; Kühner, A.K.; Spöttle, M.; van der Werf, W.; Stomph, J. Assessing the Case for Sequential Cropping to Produce Low ILUC Risk Biomethane—Final Report. Available online: https://edepot.wur.nl/406739 (accessed on 8 August 2021).
19. Waha, K.; Dietrich, J.P.; Portmann, F.T.; Siebert, S.; Thornton, P.K.; Bondeau, A.; Herrero, M. Multiple Cropping Systems of the World and the Potential for Increasing Cropping Intensity. *Glob. Environ. Chang.* **2020**, *64*, 102131. [CrossRef]
20. European Biogas Association. *Biogas: A Powerful and Safe Enabler of Decarbonisation & Complementing the Zero-Pollution Ambition of the Green Deal*; European Biogas Association: Brussels, Belgium, 2020; Available online: https://www.europeanbiogas.eu/wp-content/uploads/2020/05/FINAL-position-paper_agriculture.pdf (accessed on 15 August 2021).
21. Sammy, A.; Takriti, E.; Malins, C.; Searle, S. Understanding Options for ILUC Mitigation. Available online: https://theicct.org/publications/understanding-options-iluc-mitigation (accessed on 1 July 2021).
22. European Parliament Directive (EU). 2015/1513 of the European Parliament and of the Council. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32015L1513 (accessed on 6 August 2021).
23. Hlaváček, M.; Decerle, J. *ANNEX I: Impact, Result and Output Indicators Pursuant to Article 7*; 2020; Volume 200. Available online: https://www.europarl.europa.eu/doceo/document/A-8-2019-0200-AM-1154-1154_EN.pdf (accessed on 1 October 2021).
24. European Parliament Directive (EU). 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources. *Off. J. Eur. Union* **2018**, *2018*, 82–209. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001 (accessed on 26 June 2021).

25. Altieri, M.A.; Nicholls, C.I.; Henao, A.; Lana, M.A. Agroecology and the Design of Climate Change-Resilient Farming Systems. *Agron. Sustain. Dev.* **2015**, *35*, 869–890. [CrossRef]
26. Dale, B.E.; Sibilla, F.; Fabbri, C.; Pezzaglia, M.; Pecorino, B.; Veggia, E.; Baronchelli, A.; Gattoni, P.; Bozzetto, S. Biogasdoneright^{TM}: An Innovative New System Is Commercialized in Italy. *Biofuels Bioprod. Biorefin.* **2016**, *10*, 341–345. [CrossRef]
27. Andrews, D.J.; Kassam, A.H. The Importance of Multiple Cropping in Increasing World Food Supplies. *Mult. Crop.* **1976**, *27*, 1–10.
28. Petrie, C.A.; Singh, R.N.; Bates, J.; Dixit, Y.; French, C.A.I.; Hodell, D.A.; Jones, P.J.; Lancelotti, C.; Lynam, F.; Neogi, S.; et al. Adaptation to Variable Environments, Resilience to Climate Change. *Curr. Anthropol.* **2017**, *58*. [CrossRef]
29. European Environment Agency. Climate Change, Impacts and Vulnerability in Europe. 2016. Available online: https://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016 (accessed on 2 June 2021).
30. Gaba, S.; Lescourret, F.; Boudsocq, S.; Enjalbert, J.; Hinsinger, P.; Journet, E.P.; Navas, M.L.; Wery, J.; Louarn, G.; Malézieux, E.; et al. Multiple Cropping Systems as Drivers for Providing Multiple Ecosystem Services: From Concepts to Design. *Agron. Sustain. Dev.* **2015**, *35*, 607–623. [CrossRef]
31. Azam-Ali, S.N. Multicropping. Encyclopedia of Applied Plant Science. In *Production Systems and Agronomy*; Elsevier: Amsterdam, The Netherlands, 2003; pp. 978–984. [CrossRef]
32. Francis, C.A.; Porter, P. Multicropping. *Encycl. Appl. Plant Sci.* **2016**, *3*, 29–33. [CrossRef]
33. FAO. *The Future of Food and Agriculture—Trends and Challenges*; FAO: Rome, Italy, 2017.
34. Tilman, D. Global Environmental Impacts of Agricultural Expansion: The Need for Sustainable and Efficient Practices. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 5995–6000. [CrossRef]
35. Chaplin-Kramer, R.; Sharp, R.P.; Mandle, L.; Sim, S.; Johnson, J.; Butnar, I.; Milà I Canals, L.; Eichelberger, B.A.; Ramler, I.; Mueller, C.; et al. Spatial Patterns of Agricultural Expansion Determine Impacts on Biodiversity and Carbon Storage. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 7402–7407. [CrossRef]
36. Laurance, W.F.; Sayer, J.; Cassman, K.G. Agricultural Expansion and Its Impacts on Tropical Nature. *Trends Ecol. Evol.* **2014**, *29*, 107–116. [CrossRef]
37. Skinner, J.A.; Lewis, K.A.; Bardon, K.S.; Tucker, P.; Catt, J.A.; Chambers, B.J. An Overview of the Environmental Impact of Agriculture in the U.K. *J. Environ. Manag.* **1997**, *50*, 111–128. [CrossRef]
38. Tripathi, S.; Srivastava, P.; Devi, R.S.; Bhadouria, R. Influence of Synthetic Fertilizers and Pesticides on Soil Health and Soil Microbiology. *Agrochem. Detect. Treat. Remediat.* **2020**, 25–54. [CrossRef]
39. Cheo, A.E.; Tapiwa, K.A. *SDG 2—Zero Hunger: Food Security, Improved Nutrition and Sustainable Agriculture*; Emerald Publishing Editing: Bingley, UK, 2021.
40. Romaniuk, W.; Mazur, K.; Borek, K.; Borusiewicz, A.; Wardal, W.J.; Tabor, S.; Kuboń, M. Biomass Energy Technologies from Innovative Dairy Farming Systems. *Processes* **2021**, *9*, 335. [CrossRef]
41. Valenti, F.; Porto, S.M.C.; Selvaggi, R.; Pecorino, B. Evaluation of Biomethane Potential from By-Products and Agricultural Residues Co-Digestion in Southern Italy. *J. Environ. Manag.* **2018**, *223*, 834–840. [CrossRef] [PubMed]
42. Feyereisen, G.W.; Camargo, G.G.T.; Baxter, R.E.; Baker, J.M.; Richard, T.L. Cellulosic Biofuel Potential of a Winter Rye Double Crop across the U.S. Corn–Soybean Belt. *Agron. J.* **2013**, *105*, 631–642. [CrossRef]
43. Tang, K.; Kragt, M.E.; Hailu, A.; Ma, C. Carbon Farming Economics: What Have We Learned ? *J. Environ. Manag.* **2016**, *172*, 49–57. [CrossRef]
44. Bezzi, G. Biogasdoneright® Model: Soil Carbon Sequestration and Efficiency in Agriculture. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016; pp. 4–7.
45. Arec Les Cultures Intermédiaires à Vocation Énergétique (CIVE). Available online: https://www.arec-idf.fr/fileadmin/DataStorageKit/AREC/Methanisation/_Presentation_CIVE.pdf (accessed on 1 July 2021).
46. European Commission. EU Strategy to Reduce Methane Emissions. Available online: https://ec.europa.eu/energy/sites/ener/files/eu_methane_strategy.pdf (accessed on 6 October 2021).
47. Van Melle, T.; Peters, D.; Cherkasky, J.; Wessels, R.; Mir, G.R.; Hofsteenge, W. Gas for Climate: How Gas Can Help to Achieve the Paris Agreement Target in an Affordable Way. Available online: https://gasforclimate2050.eu/wp-content/uploads/2020/03/Ecofys-Gas-for-Climate-Report-Study-March18.pdf (accessed on 19 July 2021).
48. Valli, L.; Ricerche, C.; Animali, P.; Crpa, S.; Emilia, R.; Dale, B.E.; Kim, S.; Ong, R.G.; Engineering, C. Greenhouse Gas Emissions of Electricity and Biomethane Produced Using the Biogasdoneright^{TM} System: Four Case Studies from Italy. *Biofuels Bioprod. Biorefin.* **2017**, *39*, 847–860. [CrossRef]
49. Trnka, M.; Kersebaum, K.C. Agroclimatic Conditions in Europe under Climate Change Agroclimatic Conditions in Europe under Climate Change. *Glob. Chang. Biol.* **2011**, *17*, 2298–2318. [CrossRef]
50. Prade, T.; Björnsson, L.; Lantz, M.; Ahlgren, S.; Prade, T. Can Domestic Production of ILUC-Free Feedstock from Arable Land Supply Sweden ' s Future Demand for Biofuels ? Supply Sweden ' s Future Demand for Biofuels ? *J. Land Use Sci.* **2017**, *12*, 407–441. [CrossRef]
51. European Commission. Agri4Cast Resource Portal. Available online: https://agri4cast.jrc.ec.europa.eu/dataportal/ (accessed on 1 August 2021).
52. Charalampopoulos, I.; Polychroni, I.; Psomiadis, E.; Nastos, P. Spatiotemporal Estimation of the Olive and Vine Cultivations' Growing Degree Days in the Balkans Region. *Atmosphere* **2021**, *12*, 148. [CrossRef]

53. DLO-Alterra; DLO-Plant Research Internarional; NEIKER; Institute of Agricultural and Environmental Engineering (JTI). Review and Further Differentiation of Pedo-Climatic Zones in Europe; 2011. Available online: https://publications.europa.eu/resource/cellar/e1d06bc3-58c4-43a3-b2bc-6ad6d53d7953.0001.01/DOC_1 (accessed on 1 October 2021).
54. Jacobs, C.; Berglund, M.; Kurnik, B.; Dworak, T.; Marras, S.; Mereu, V.; Michetti, M. *Climate Change Adaptation in the Agriculture Sector in Europe (4/2019)*; EEA Report; European Environment Agency: Copenhagen, Denmark, 2019; p. 112.
55. Olesen, J.E.; Trnka, M.; Kersebaum, K.C.; Skjelvåg, A.O.; Seguin, B.; Peltonen-sainio, P.; Rossi, F.; Kozyra, J.; Micale, F. Impacts and Adaptation of European Crop Production Systems to Climate Change. *Eur. J. Agron.* **2011**, *34*, 96–112. [CrossRef]
56. Olesen, J.E.; Trnka, M.; Ewert, F.; Siebert, S.; Brisson, N.; Eitzinger, J.; van Asselt, E.D.; Oberforster, M. Changes in Time of Sowing, Flowering and Maturity of Cereals in Europe under Climate Change. *Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess.* **2012**, *29*, 1527–1542. [CrossRef] [PubMed]
57. Hernández, L.; Sánchez de Dios, R.; Montes, F.; Sainz-Ollero, H.; Cañellas, I. Exploring Range Shifts of Contrasting Tree Species across a Bioclimatic Transition Zone. *Eur. J. For. Res.* **2017**, *136*, 481–492. [CrossRef]
58. Hatfield, J.L.; Prueger, J.H. Temperature Extremes: Effect on Plant Growth and Development. *Weather Clim. Extrem.* **2015**, *10*, 4–10. [CrossRef]
59. Michaelides, S.; Karacostas, T.; Sánchez, J.L.; Retalis, A.; Pytharoulis, I.; Homar, V.; Romero, R.; Zanis, P.; Giannakopoulos, C.; Bühl, J.; et al. Reviews and Perspectives of High Impact Atmospheric Processes in the Mediterranean. *Atmos. Res.* **2018**, *208*, 4–44. [CrossRef]
60. Bocchiola, D. Impact of Potential Climate Change on Crop Yield and Water Footprint of Rice in the Po Valley of Italy. *Agric. Syst.* **2015**, *139*, 223–237. [CrossRef]
61. Lionello, P.; Abrantes, F.; Gacic, M. The Climate of the Mediterranean Region: Research Progress and Climate Change Impacts. *Reg. Environ. Chang.* **2014**, *14*, 1679–1684. [CrossRef]
62. Hossain, A.; el Sabagh, A.; Barutcular, C.; Bhatt, R.; Çiğ, F.; Seydoşoğlu, S.; Turan, N.; Konuskan, O.; Iqbal, M.A.; Abdelhamid, M.; et al. Sustainable Crop Production to Ensuring Food Security under Climate Change: A Mediterranean Perspective. *Aust. J. Crop Sci.* **2020**, *14*, 439–446. [CrossRef]
63. Bartolini, G.; Morabito, M.; Crisci, A.; Grifoni, D.; Torrigiani, T.; Petralli, M.; Orlandini, S. Recent Trends in Tuscany (Italy) Summer Temperature and Indices of Extremes. *Int. J. Climatol.* **2008**, *1760*, 1751–1760. [CrossRef]
64. Altman, J.; Fibich, P.; Santruckova, H.; Dolezal, J.; Stepanek, P.; Kopacek, J.; Hunova, I.; Oulehle, F.; Tumajer, J.; Cienciala, E. Environmental Factors Exert Strong Control over the Climate-Growth Relationships of Picea Abies in Central Europe. *Sci. Total Environ.* **2017**, *609*, 506–516. [CrossRef] [PubMed]
65. Juhász, C.; Gálya, B.; Kovács, E.; Nagy, A.; Tamás, J.; Huzsvai, L. Seasonal Predictability of Weather and Crop Yield in Regions of Central European Continental Climate. *Comput. Electron. Agric.* **2020**, *173*, 105400. [CrossRef]
66. Sutton, R.T.; Dong, B. Atlantic Ocean Influence on a Shift in European Climate in the 1990s. *Nat. Geosci.* **2012**, *5*, 788–792. [CrossRef]
67. European Environmental Agency. Average Annual Precipitation. Available online: https://www.eea.europa.eu/data-and-maps/figures/average-annual-precipitation (accessed on 1 September 2021).
68. European Environmental Agency. Trend in the Number of Frost-Free Days. Available online: https://www.eea.europa.eu/data-and-maps/figures/rate-of-change-of-frost-1 (accessed on 5 July 2021).
69. Peltonen-sainio, P.; Jauhiainen, L.; Hakala, K. Crop Responses to Temperature and Precipitation. *J. Agric. Sci.* **2011**, *149*, 49–62. [CrossRef]
70. Peltonen-sainio, P.; Jauhiainen, L.; Laurila, I.P. Field Crops Research Cereal Yield Trends in Northern European Conditions: Changes in Yield Potential and Its Realisation. *Field Crops Res.* **2009**, *110*, 85–90. [CrossRef]
71. European Commission. Eurostat. Available online: https://ec.europa.eu/eurostat/data/database (accessed on 8 June 2021).
72. Han, J.; Zhang, Z.; Luo, Y.; Cao, J.; Zhang, L.; Zhang, J.; Li, Z. The RapeseedMap10 Database: Annual Maps of Rapeseed at a Spatial Resolution of 10 m Based on Multi-Source Data. *Earth Syst. Sci. Data* **2021**, *13*, 2857–2874. [CrossRef]
73. Grillo, F.; Piccoli, I.; Furlanetto, I.; Ragazzi, F.; Obber, S.; Bonato, T.; Meneghetti, F.; Morari, F. Agro-Environmental Sustainability of Anaerobic Digestate Fractions in Intensive Cropping Systems: Insights Regarding the Nitrogen Use Efficiency and Crop Performance. *Agronomy* **2021**, *11*, 745. [CrossRef]
74. DAL; CRPA. *Biogas, Potenziale Energetico Dei Cereali Autunno-Vernini*; L'informatore Agrario: Verona, Italy, 2015.
75. Campiglia, E.; Mancinelli, R. Legume Cover Crops and Mulches: Effects on Nitrate Leaching and Nitrogen Input in a Pepper Crop (*Capsicum annuum* L.). *Nutr. Cycl. Agroecosyst.* **2011**, *89*, 399–412. [CrossRef]
76. Debaeke, P. A Rule-Based Method for the Development of Crop Management Systems Applied to Grain Sorghum in South-Western France. *Agric. Syst.* **2006**, *90*, 180–201. [CrossRef]
77. Marsac, S.; Quod, C.; Leveau, V.; Heredia, M.; Delaye, N.; Labalette, F.; Lecomte, V.; Bazet, M.; Sanner, E.A. Optimization of French Energy Cover Crop Production in Double Cropping Systems for On-Farm Biogas Use. In Proceedings of the 27th European Biomass Conference and Exhibition, Lisbon, Portugal, 27–30 May 2019; pp. 27–30.
78. Hartmann, S.; Hofmann, D.; Lichti, F.; Gehring, K. Weidelgras-Untersaaten in Wintergetreide Zur GPS-Nutzung Als Biogassubstrat. Available online: https://www.lfl.bayern.de/mam/cms07/ipz/dateien/leitfaden_2011-16_biogasforum.pdf (accessed on 7 July 2021).

79. LfL Grünroggen Als Biogassubstrate. Available online: https://www.lfl.bayern.de/mam/cms07/ipz/dateien/leitfaden_2009-07_biogasforum.pdf (accessed on 9 June 2021).
80. LfL Weidelgras-Untersaat in Wintergetreide Als Ganzpflanzensilage. Available online: http://www.biogas-forum-bayern.de (accessed on 15 July 2021).
81. Murphy, J.; Bochmann, G.; Weiland, P.; Wellinger, A. Biogas from Crop Digestion. In *IEA Bioenergy—Task 37*; IEA Bioenergy: Paris, France, 2011; p. 24.
82. Dinuccio, E.; Balsari, P.; Gioelli, F.; Menardo, S. Evaluation of the Biogas Productivity Potential of Some Italian Agro-Industrial Biomasses. *Bioresour. Technol.* **2010**, *101*, 3780–3783. [CrossRef] [PubMed]
83. Guy, C.L. Low Temperature and Crop Yield. *Physiol. Determ. Crop Yield* **1994**, 417–424. [CrossRef]
84. Campillo, C.; Fortes, R.; Prieto, H. Solar Radiation Effect on Crop Production. *Sol. Radiat.* **2012**. [CrossRef]
85. Meza, F.J.; Silva, D.; Vigil, H. Climate Change Impacts on Irrigated Maize in Mediterranean Climates: Evaluation of Double Cropping as an Emerging Adaptation Alternative. *Agric. Syst.* **2008**, *98*, 21–30. [CrossRef]
86. Kaye, J.P.; Quemada, M. Using Cover Crops to Mitigate and Adapt to Climate Change. A Review. *Agron. Sustain. Dev.* **2017**, *37*, 4. [CrossRef]
87. Walter Stinner Deutsches Biomasseforschungszentrum. Personal Communication, 31 May 2021.
88. Sinclair, T.R. Limits to Crop Yield? *Physiol. Determ. Crop Yield* **1994**, 509–532. [CrossRef]
89. Terlouw, W.; Peters, D.; van Tilburg, J.; Schimmel, M.; Berg, T.; Cihlar, J.; Ur Rehman Mir, G.; Spöttle, M.; Staats, M.; Buseman, M.; et al. Gas for Climate. The Optimal Role for Gas in a Net-Zero Emissions Energy System. Available online: https://www.europeanbiogas.eu/wp-content/uploads/2019/11/GfC-study-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system.pdf (accessed on 7 July 2021).
90. European Commission. Quarterly Report Energy on European Gas Markets with Focus on the European Barriers in Retail Gas Markets Market Observatory for Energy DG Energy. Available online: https://ec.europa.eu/energy/sites/default/files/quarterly_report_on_european_gas_markets_q4_2020_final.pdf (accessed on 1 October 2021).
91. Zahan, Z.; Georgiou, S.; Muster, T.H.; Othman, M.Z. Semi-Continuous Anaerobic Co-Digestion of Chicken Litter with Agricultural and Food Wastes: A Case Study on the Effect of Carbon/Nitrogen Ratio, Substrates Mixing Ratio and Organic Loading. *Bioresour. Technol.* **2018**, *270*, 245–254. [CrossRef]
92. Karki, R.; Chuenchart, W.; Surendra, K.C.; Shrestha, S.; Raskin, L.; Sung, S.; Hashimoto, A.; Kumar Khanal, S. Anaerobic Co-Digestion: Current Status and Perspectives. *Bioresour. Technol.* **2021**, *330*, 125001. [CrossRef]
93. Paustian, K.; Larson, E.; Kent, J.; Marx, E.; Swan, A. Soil C Sequestration as a Biological Negative Emission Strategy. *Front. Clim.* **2019**, *1*, 1–11. [CrossRef]
94. Aguilera, E.; Díaz-Gaona, C.; García-Laureano, R.; Reyes-Palomo, C.; Guzmán, G.I.; Ortolani, L.; Sánchez-Rodríguez, M.; Rodríguez-Estévez, V. Agroecology for Adaptation to Climate Change and Resource Depletion in the Mediterranean Region. A Review. *Agric. Syst.* **2020**, *181*, 102809. [CrossRef]
95. Béghin-Tanneau, R.; Guérin, F.; Guiresse, M.; Kleiber, D.; Scheiner, J.D. Carbon Sequestration in Soil Amended with Anaerobic Digested Matter. *Soil Tillage Res.* **2019**, *192*, 87–94. [CrossRef]
96. EIP-AGRI. Focus Group Moving from Source to Sink in Arable Farming. Available online: https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_carbon_storage_in_arable_farming_final_report_2019_en.pdf (accessed on 18 August 2021).
97. European Commission. Technical Guidance Handbook Setting up and Implementing Result-Based Carbon Farming Mechanisms in the EU. Available online: https://op.europa.eu/en/publication-detail/-/publication/10acfd66-a740-11eb-9585-01aa75ed71a1/language-en (accessed on 1 October 2021).
98. European Commission. Farm to Fork Strategy. Available online: https://ec.europa.eu/food/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf (accessed on 1 June 2021).
99. Consorzio Italiano Biogas Farming For Future—10 Azioni per Coltivare Il Futuro. Available online: https://farmingforfuture.it/wp-content/uploads/2021/03/Farming_for_Future_Position_Paper_web.pdf (accessed on 1 October 2021).