



Accounting for the systemic effects of anaerobic digestion on the practices of farmers

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Abstract

The rate of on-farm biogas production by anaerobic digestion has increased in Europe since the beginning of the twenty-first century, largely due to policies supporting low-carbon energy production. Anaerobic digestion farms are farms where farmers invest in biogas production mainly from agricultural feedstock, and remain the main investors. Biogas production brings new challenges to agriculture, and current scientific literature does not provide clear conclusions on its agri-environmental effects. Current studies focus on one or more of the agri-environmental effects of on-farm biogas development (mainly greenhouse gas balance, carbon storage, and nitrogen losses), assuming that the farming system as a whole remains unchanged. However, they rarely investigate how biogas production performance relates to indirect changes in farm practices and activities. To better understand the changes in farm practices linked to biogas production, we surveyed 23 biogas farmers operating 19 different on-farm biogas units in two areas of northeast France. We aimed to cover various configurations (e.g., farm activities, digester capacity, number of farmers involved, and energy recovery methods) to capture a diversity of farm functioning. We analyzed these qualitative data by identifying recurring examples of practice changes (or lack thereof). Our results show that biogas development led to various changes in nitrogen fertilization practices, forage and permanent grassland management, and cultivation practices. Biogas production can induce both minor and significant changes on farms, with a variety of drivers of change. These changes depend on the farm characteristics and activities that biogas farmers can develop. The novelty of our research lies in highlighting this diversity of practices and drivers, which are generally not considered in the literature on the agri-environmental assessment of biogas, even though they could significantly affect the results of such assessments. Biogas sustainability research must better consider the dynamics of farming systems and farmers' agency in on-farm biogas development.

Keywords Biogas · Environmental assessments · Practices' change · Diversity · Farming system · AD farm

1 Introduction

Since the beginning of the twenty-first century, biogas produced from anaerobic digestion (AD) has expanded worldwide. This expansion is due to the contribution of biogas to the energy transition as a renewable, decarbonized gas.

The environmental impacts of AD vary significantly from country to country, according to the feedstock digested (crops, manure, agricultural residues, biowaste), technical options (AD unit technology, digestate management practices), and the rate of its development. In Europe, Germany is an example of high AD development as it has facilitated an increase in decarbonized electricity production. However, at the same time, this development has led to negative impacts on biodiversity because of an increase in maize production as a dominant feedstock, leading to the

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development of maize monoculture (Vergara & Lakes 2019). Moreover, such development could significantly affect food prices due to competition for land between crops for energy and crops for food (Britz & Delzeit 2013). In France, in the 2010s, AD was developed in agriculture (Fig. 1) to support low-carbon energy production, manure digestion for better nitrogen management, and farmers' incomes. To avoid the negative agri-environmental impacts observed in Germany, the French government's biogas policy has supported biogas production in order to support sustainable agriculture.

The current environmental balance of biogas in France is under debate, and the scientific literature has failed to draw clear conclusions on its agri-environmental impacts (Moinard 2021; Malet 2022; Cadiou et al. 2023). In this paper, we identify two main categories of studies that address this issue. The first category, which is the largest of the two, focuses on one or more of the agri-environmental effects of on-farm biogas development (mainly greenhouse gas balance, biodiversity, carbon storage, and nitrogen losses), assuming that the farming system as a whole remains unchanged. The literature in this category tends to assess direct changes limited to a few agricultural practices, such as new methods of digestate fertilization, the introduction of energy cover crops, and manure digestion (Quakernack et al. 2012; Möller 2015; Bacenetti et al. 2016; Nicholson et al. 2017; Paolini et al. 2018; Greenberg et al. 2019; Launay et al. 2020; Esnouf et al. 2021). Although these assessments analyze various practices, they do not consider the systemic interactions between them. In general, the literature assumes that farmers adopt the "best practices" recommended by agronomists, which are practices recommended for positive environmental impacts (Cadiou et al. 2023). Consequently,

specific agri-environmental effects linked to the adoption of these good practices are widely accepted. For example, according to many authors, adopting best practices reduces the greenhouse gas (GHG) emissions (Hijazi et al. 2016; Bacenetti et al. 2016; Ingraio et al. 2019; Malet 2022); and increased use of digestate fertilizer decreases the need for synthetic nitrogen, if the best spreading practices are adopted (Clements et al. 2012; Nkoa 2014; Koszel and Lorencowicz 2015; Guilayn et al. 2019). Without the adoption of best practices, increased use of digestate could increase the risk of air (Nkoa 2014; Carton and Bulcke 2021; Moinard 2021) and water pollution (Möller 2015; Nicholson et al. 2017, 2018; Rübiger et al. 2020; Purswani and Llorente 2021). Other issues lack consensus, such as the effects of digestate on soil carbon, which depend considerably on return-to-soil practices (Moinard 2021). Finally, the literature contains much uncertainty on some issues, because the long-term perspective remains poorly documented, such as the impacts of digestate spreading on soil compaction and soil biology (Sadet-Bourgeteau et al. 2020; van Midden et al. 2023), and the impact of AD on land use and regional biodiversity.

The second category of literature, which is much smaller, identifies indirect mechanisms that can influence the adoption of practices. In addition to direct changes studied by the first category, this second category highlights how the development of AD on farms sometimes triggers changes in practices in other farm activities. Thus, Beausang et al. (2021) show that the sustainability of grass silage used as an AD feedstock depends on whether it indirectly displaces feed for livestock elsewhere. Carton and Levavasseur (2022) show that soil carbon storage and biodiversity vary from one farm to another, with the introduction of energy cover

Fig. 1 AD unit developed by a group of farmers in northeast France. A group of farmers developed this AD unit to diversify their income and produce renewable gas. Photo credit: Jeanne Cadiou, June 2021 (Cadiou and Meynard 2026).



crops to supply the AD unit. In Germany, Siegmeier et al. (2015) and Blumenstein et al. (2018) show, through qualitative modelling, that in some farms developing AD (referred to as AD farms in the rest of this article), higher crop yields and improved nitrogen management are coupled with reduced labor and lower energy costs. This body of research shows that the environmental performance of biogas can be related to other changes in the farm's activities or regional agricultural context, even though few studies explore these links. Other papers show unexpected social, economic, and ecological outcomes. For example, in Italy, an increase in a farm's energy crop production (Carrosio 2014; Cavicchi 2016) or a regional-level increase in the need for biomass as an AD feedstock can lead to increases in the price of farmland rent, which in turn can influence the profitability of agricultural systems. In Germany, in the 2010s, AD development led to a significant increase in maize production, land prices, and food prices (Lüker-Jans et al. 2017; Vergara and Lakes 2019). Based on these two categories of literature, it is difficult to draw clear conclusions on the environmental impacts of on-farm biogas development. It is also difficult to understand the effects of AD on farmers' practices. Very few studies empirically assess the impacts of AD, looking at systemic mechanisms and their influence on different agricultural practices. Given the growing use of biogas as a substitute for fossil gas, this article aims to contribute to understanding the effects of AD on farming practices and, therefore, on the sustainability pathways of farms by answering the following question: *how does on-farm AD development change farm practices?*

To this end, we mobilize the “farming systems studies” framework, which assumes that a system approach is necessary to capture the underlying reasoning behind practices and their evolution (Sebillotte 1974; Biggs 1985). It considers the agricultural system through the interaction between three scales: technical systems (field scale), production systems (farm scale), and regional agricultural systems (landscape scale) (Darnhofer et al. 2012; Cochet 2012). Technical systems include highly interconnected cropping, livestock, and fodder systems; changing a practice in one technical system often affects other practices within the system, as well as other systems (Meynard et al. 2001). This approach also enables us to understand the trade-offs between production factors (labor, land, expertise) on a farm, and how this influences technical systems. AD is a new farm technical system that can modify the existing links between and within other technical systems. Beyond considering AD as a technical system, its development necessarily requires allocating production factors. This allocation, in turn, has consequences for the overall functioning of the farming system (Cochet et al. 2007). Such changes must be understood through “the meaning that actors give to [them]” (Darnhofer et al. 2012). The concept of “situated rationality” puts farmers' strategies

at the heart of the evolution of farming systems, viewing them as stakeholders and drivers of the emergence of new forms of socio-technical organization (Osty et al. 1998). This framework moves us away from analyzing biogas development based on “rational modernization” and towards understanding the underlying “logic” of farmers, knowing that they may have conflicting goals. Finally, this article puts forward the following hypothesis: changes in practices associated with the management of AD units can be linked to indirect mechanisms involving other practices, other farm activities, and even regional dynamics, resulting in a much more diverse range of environmental impacts than the effects generally documented in the literature.

2 Material and methods

We surveyed 23 AD farmers in two French municipal districts in northeast France, Vosges and Bas-Rhin, corresponding to 19 different on-farm AD units. The two areas differed in terms of (i) how biogas from AD is recovered (in the electric network with combined heat and power (CHP) mostly in Vosges, or the gas network with biomethane injection mostly in Bas-Rhin) and (ii) agricultural context (predominantly crop-livestock farming in Vosges compared to more diversified production in Bas-Rhin, with field crops, crop-livestock farming, mixed livestock farming market gardening, pigs and poultry). The aim was to cover a diversity of configurations based on the following criteria:

- Activity of the farm contacted (suckler, dairy, mixed livestock farming, pig farming, cereals)
- Number of AD unit project owners (individual or collective)
- Installed capacity of the unit (in kW by unit for CHP and in Nm³h by unit for injection)
- Energy recovery method (CHP or injection, and on-farm energy recovery activity)

We selected the surveyed units based on the digested feedstocks, insofar as we were able to gather information on this criterion before the survey. We also selected biogas plants with a start-up date, preferably before 2018, to gain long-term perspective on how farming systems have changed.

The choice of respondents therefore followed the “snowball sampling” method, to enable evolution in our field of investigation (Biernacki and Waldorf 1981; Handcock and Gile 2011); this approach involves making contact with an initial farmer, who then refers us to other farmers, from whom we get further referrals, and so on. In parallel, we gathered information on AD units and farms from technical publications, AD unit websites, and interviews with local

stakeholders to better select the farms surveyed according to our criteria. We stopped snowball sampling once we had covered a diverse range according to our different criteria for the choice of farms, and new interviews did not extend the range of criteria (11 farms in the Vosges and 12 farms in Bas-Rhin). Each farmer was interviewed for 2 to 3 h, in two stages: a semi-structured interview in 2021, including a visit to the AD site, except for three farmers for whom we conducted the interviews by phone; followed by a semi-structured phone interview between January and June 2022. Our follow-up interviews deepened the analysis of some practices and changes, through asking questions on some mechanisms not yet identified at the beginning of the fieldwork. The authors transcribed the interviews. Throughout this article, farmers are represented by letters.

Interviews began by gathering data on (i) current farming systems and the technical AD system; and (ii) the origin and history of the AD project. The interview then moved to a discussion of how AD had modified the farm, focusing on the following points:

- Whether or not the farming system, technical systems, and practices had changed following the start of the AD project, under which conditions, levers, and constraints influencing the practice changes;
- The interactions between farming system components, and potentially the interactions between other regional variables/components (other farms, food industry);
- The rationale behind these changes, or the maintenance of previous practices.

We analyzed the data by looking for recurring examples of changes in practices (or lack of change) and the drivers of the identified changes. In this way, we have identified three main areas of technical change: crop rotations, fertilization, and fodder and permanent grassland management. Data collected in the interviews on the description of practices were mainly qualitative and based on farmers' observations. During the initial interviews, there was a back-and-forth with the literature to identify variables accessible to farmers, which

enabled us to describe practices. To characterize the fertilization practices, we collected data on the digestate doses, application calendar, application equipment, changes in mineral nitrogen fertilization, constraints, and levers for implementing good practices, and estimated nitrogen fertilizer savings on farms. Regarding the evolution of cropping systems, we collected data on crop succession, technical interventions (pesticide application, tillage), and the links between AD supply and crop rotation planning. Regarding fodder management, we collected data on the evolution of fodder cultivation (surface area, species, technical interventions) and the established links between anaerobic digestion and livestock farming.

3 Results

To better understand the results exposed below, the three following tables (Table 1, Table 2, and Table 3) provide information about the farms we worked on, and about the AD units associated with the farms.

3.1 Changes in crop rotations

In Vosges and Bas-Rhin, AD is developing by valorizing livestock manure, supplemented by more methanogenic feedstock such as energy crops, cover crops, crop residues, biowaste, and by-products (see Table 4). The French government supports manure digestion by providing incentives where a farmer can earn the maximum bonus if the digester is supplied with at least 60 percent manure.

These differentiated supplies depend on the available feedstock in the area, which in turn influences strategies for changing cropping systems. We have identified four different patterns of change.

3.1.1 Patterns of change in crop rotations

Pattern 1: Maintaining previous crops and marginal changes to the cropping system—two farmers The initial rotation

Table 1 Characteristics of AD units surveyed (from Cadiou (2023)).

Region	Vosges	Bas-Rhin
Number of farmers having invested in an individual unit ($N = 1$)	6	5
Number of farmers having invested in a collective unit ($N = [2-7]$)	4	4
Number of AD units surveyed	10	9
Number of AD farmers surveyed	11	12
Year of unit start-up: interval between the oldest unit and the most recent unit	[2013-2019]	[2012-2020]
Average installed capacity (kW) of cogeneration of heat and power units surveyed	404	542
Average installed capacity (Nm ³) of biomethane injection units surveyed	140	218
Biogas recovery method: number of cogeneration units out of the total number of units	9 out of 10	5 out of 9

Table 2 Characteristics of farms surveyed in the Vosges region (from Cadiou (2023)). ^aConcerned acreage if partial conversion of the farm to organic farming.

Farm	Agricultural activity	Livestock characteristics	Main crops	Total cultivated area (ha)	Area of permanent grassland (ha)	AD installed capacity	Organic farming ^a
A	Mixed crop-livestock	25 suckler cows, 100 dairy cows, 375 bull calves	Maize, wheat, barley, triticale	155	180	499 kW	
B	Mixed crop-livestock	150 dairy cows, 20 suckler cows, 200 bull calves, 160 heifers, 170 calves	Rapeseed, wheat, barley, maize	235	165	250 kW	
C	Multi-crop dairy	80 dairy cows	Maize, wheat, barley	100	80	140 Nm ³	
D	Cereal	/	Wheat, spring barley, oat, sunflower, lentil	195	25	250 kW	x
E	Mixed crop-livestock	90 dairy cows, 45–50 bull calves, 90 heifers	Maize, rye, raygrass	110	90	200 kW	
F	Multi-crop dairy	120 dairy cows, 60 heifers	Wheat, triticale, temporary grassland	110	190	500 kW	x
G	Mixed crop-livestock	200 dairy cows, 100 bull calves, 300 heifers and calves	Maize, wheat, barley, triticale	250	60	500 kW	
H	Grass-fed meat farming (sheep and cattle)	Cattle herd of 620 pieces: suckler cows and bull calves	Maize, triticale, red clover, sorgho	135	360	720 kW	
I	Multi-crop dairy	35 dairy cows, calves	Triticale, peas, maize, temporary grassland	32	48	720 kW	
J	Mixed crop-livestock	250 dairy cows, 850 bull calves, 200 heifers	Wheat, sorgho, maize, barley, alfalfa, temporary grassland, rye	539	141	520 kW	
K	Mixed crop-livestock	150 dairy cows, 150 bull calves, 15 heifers	Maize, triticale, barley, wheat, rapeseed, alfalfa, meslin	300	125	195 kW	

changed little because the introduction of new energy cover crops (ECC) for the AD plant remained marginal. Q and R farmers have only modified their summer ECC for biogas production (maize, sorghum, or mixed crops), as they did not want to affect the yields of their spring crops. However, they did not rely on these summer ECC crops to supply the biogas plant because of their low yields due to summer drought. These farmers feed their AD unit with a diversified mix of feedstock harvested in the area: agricultural by-products (maize stover (R), livestock effluents (Q, R)), biowaste (R), agro-industrial by-products (Q).

Pattern 2: Maintaining previous crops and developing ECC—three farmers Farmers J, O, and T have chosen to produce more biomass via winter or summer ECC, for biogas production, without, however, modifying the succession of main crops. T and J cover their soils extensively in winter with rye and ryegrass (80 ha and 40 ha respectively at J), while farmer O has introduced around 20 ha of winter ECC, and

has increased his summer ECC area further—even though their ECC are not very productive. The most methanogenic feedstocks come partly from off-farm purchases, such as biowaste (O) and agro-industrial by-products (J, O, T), which winter ECC supplements.

Pattern 3: Modifying the cropping system to contribute to biogas production by introducing energy crops and ECC—12 farmers Most farmers have modified their rotations to introduce energy crops and ECC to supply the AD units. Eleven farmers have increased their area under maize silage, and two farmers have introduced a triticale and rye mix intercrop. These crops replace cash crops, mainly cereals (A, C, E, H, I, V), but also rapeseed (B, G), and grain maize (K, L, M, S, V) (see Table 5). As in pattern 2, farmers have introduced ECC between their main crops or following energy crops. Most farmers chose winter ECC such as rye, triticale, meslin, or temporary ryegrass-type meadows (A, B, C, E, G, H, I, M, S, V, W), which are methanogenic, and whose

Table 3 Characteristics of farms surveyed in the Bas-Rhin region (from (Cadiou (2023))). ^a Concerned acreage if partial conversion of the farm to organic farming.

Farm	Agricultural activity	Livestock characteristics	Main crops	Total cultivated area (ha)	Area of permanent grassland (ha)	AD installed capacity	Organic farming ^a
L	Crops and monogastric livestock	140 000 laying hens	Maize, wheat, rye	140	0	90 Nm3	
M	Multi-crop dairy	70 dairy cows, 100 suckler cows, 60 heifers	Maize, wheat, beetroot, rapeseed. In organic farming: spelt, potatoe, cabbage	260	110	90 Nm3	x (30 ha)
N	Cereal	/	Triticale, wheat, buckwheat, red clover, temporary grassland	60	4	215 Nm3	x
O	Multi-crop dairy	190 dairy cows	Maize, wheat, barley	82	38	500 kW	
P	Grass-fed meat farming (sheep and cattle)	185 sheep	/	0	40	140 Nm3	
Q	Crops and monogastric livestock	650 sows	Maize, wheat, barley	85	0	500 kW	
R	Multi-crop dairy	110 dairy cows	Maize, wheat, beetroot, temporary grassland	150	240	200 Nm3	
S	Cereal	/	Maize, sunflower, wheat, beetroot	95	6	140 Nm3	
T	Mixed crop-livestock	100 dairy cows, 250 heifers + calves, 70 suckler cows, 2800 chickens	Maize, wheat, barley	150	150	360 kW	
U	Mixed crop-livestock	120 dairy cows, 50 bull calves, few suckler cows	Meslin	50	50	250 kW	
V	Crop and only monogastric livestock	350 sows	Maize, wheat, barley, potato, rapeseed, soybean	120	0	1100 kW	x (52 ha)
W	Mixed crop-livestock	60 dairy cows, 7 suckler cows, 10 heifers	Maize, wheat/triticale, beetroot	29	35	215 Nm3	

production per hectare is regarded as good (A, B, E, G, H, M, S, V, W). Compared with pattern 2, some farmers have accepted that double cropping affects maize yield (main crop) because the average net margin per hectare is better from their point of view (B, C, G, H, I, S, V, W). Others have preferred not to grow a double crop including maize, as the double crop affects the maize yield too significantly (A, E, L), so they have switched to an energy winter crop that is maintained on the field for longer. Therefore, they chose to grow a winter rye followed by a temporary grassland or a summer ECC (A, E). Growing these crops on their own ensures autonomy in supplying the AD unit and means that

they are not dependent on the availability and price of feedstocks purchased locally.

Pattern 4: A major transformation of the cropping system linked to the dynamics of the agricultural activity in which AD takes place—four farmers: D, F, N, U For some farmers, the development of AD is associated with major changes in their production activities. Three farms converted to organic farming in connection with AD. By fertilizing their organic crops with digestate, these farmers have significantly increased their yields (close to conventional farming yields), enabling them to make significant economic gains.

Table 4 Supply of surveyed AD plants (average percentage by volume of raw material according to feedstock category and ranges of variation in our sample). ^a Biowaste: waste from organic origin (for example processed food like pizza or sewage sludge residues). ^b An energy crop is a crop dedicated to energy production. Source: farmers.

Average percentage [variation range] per area	10 Vosges units	9 Bas-Rhin units
Livestock manure	71% [35–83%]	66% [30–90%]
By-product (agricultural or agro-industrial) and biowaste ^a	8% [0–16%]	22% [5–60%]
Energy crops ^b	12% [5–45%]	4% [3–17%]
Energy cover crops	6% [4–18%]	7% [0–42%]

We wondered about going organic at the same time. The Chamber of Agriculture told us that we were crazy, that we would never grow enough to feed the AD plant, but then after a year of operation (...) we said to ourselves, why not go organic, especially because the digestate solves the fertilizer problem. And we also said to ourselves, if a crop fails in organic farming, we'll still be able to make the AD plant work, we won't have any dry losses. So finally, the conversion went more smoothly (Farmer D)

Farmer U chose to remain in conventional production but saw that AD opened an opportunity to transform his whole farming activity: he diversified by introducing new activities (AD unit, milk processing workshop) and changed his cropping system to supply AD and make his dairy farm more resilient.

Table 5 Changes in crop rotation for Pattern 3 farmers with the development of AD

Farmer	Crops stopped (ha)...	Replaced by...	Insertion of ECC (ha) and strategy of double cropping (if concerned)
A	5–6 ha of cereals 7–8 ha of permanent grassland	12–14 ha of rye Few ha of maize	Double cropping possible depending on the year and the plot with a maize or another ECC after the rye
B	15–20 ha of rapeseed	15–20 ha of maize	Double cropping before maize: 10–15 ha of ryegrass (ECC), 50 ha of summer ECC after cereals (mix of grasses and legumes)
C	20 ha of barley	20 ha of maize	Double cropping (partial reintroduction of temporary grassland (alfalfa, clover)) with yield loss on the following maize crop
E	30–40 ha of cereals	40 ha of rye, followed by a three-year ryegrass	No double cropping because of the maize yield loss
G	15 ha of rapeseed	15 ha of maize	Double cropping before maize: 65 ha of winter cover crops (15 ha of rye, 50 ha of ryegrass) Few ha of summer ECC after cereals.
H	x ha of permanent grassland, (25-x) ha of triticale and clover	25 ha of maize/sorghum	Double cropping with yield loss on the following maize crop: 25 ha of rye (ECC)
I	4–5 ha of permanent grassland 2 ha of barley	6–7 ha of maize Few ha of temporary grassland cover	
K	25 ha of permanent grassland 10 ha of maize	10–15 ha of alfalfa + 10 ha of cash crops 10 ha of rye followed by clover temporary grassland	Increase in summer ECC
L	15 ha of grain maize	15 ha of silage maize	Summer ECC species adapted for biogas production
M	20 ha of grain maize	20 ha of silage maize Few ha of ryegrass	15 ha of rye (ECC)
S	10 ha of grain maize	10 ha of silage maize	Double cropping with yield loss on the following maize crop: 20–30 ha of rye or ryegrass (ECC)
V	Varies from year to year: a few ha of irrigated grain maize	Variable from year to year: a few ha of irrigated silage maize or sorghum	Double cropping only on conventional crops. Various surface of winter ECC from year to year, irrigated summer ECC (maize, sorghum, or other species)
W	12 ha of wheat and barley	12 ha of triticale-rye	Double cropping with yield loss on the following maize crop

As part of these structural transformations, farmers have developed ECC cultivation in different ways. In organic arable farming, farmer D opted for ECC followed by temporary grassland, as double cropping significantly reduced maize yields. He also buys conventional maize silage to supply his AD unit. Farmer N has integrated ECC into his rotation because he is due to supply the collective unit. To do so, he has diversified his rotation from *maize//wheat and green manure crop//beet*; to *wheat/rye (ECC)//buckwheat/triticale (ECC)//temporary grassland with clover (one year)* (where “/” denotes intra-annual succession and “//” is inter-annual succession). For farmers F and U, the evolution of the rotation is more closely linked to changes in their livestock farming. Both farmers switched from maize-based animal feed to a grass-based diet (F, U) combined with a cessation of maize in the crop rotation. Farmer F did not introduce energy crops or ECC as he was already supplying his AD unit without difficulty, as he has links with a biowaste processing company through which he has access to the biowaste and agro-industrial by-products market. Farmer U, on the other hand, has introduced meslin energy crops into his rotation. To increase his crop production (for AD and cows), he plowed up 10 ha of permanent grassland.

3.1.2 Key drivers of observed changes in crop rotations

Beyond the specific characteristics of the farms, our interviews show that three drivers influence the patterns of change.

Driver 1: Access and/or dependence on a market for methanogenic feedstocks The farmers with the oldest AD units, beginning in 2012–2016, stress the fact that the price of by-products and biowaste has risen considerably in recent years. Eleven farmers mention that, 8 years ago, they were able to obtain these products at low cost or even free of charge, whereas now they face ever-increasing prices. For example, in 2021, farmer E bought mustard by-products for €56/ton, compared to €28/ton in 2013. The calculation of the biogas generated from a feedstock is at the heart of the construction of the supply of biogas plants. Faced with the rising price of by-products, farmers adopted various strategies and decided whether to buy by-products, and whether to produce crops on their farms. Farmer T, for example, explained that to keep costs under control, he shifted his AD supply away from by-products and towards ECC and energy crops (corn)—which equates to a recent change from pattern 2 to pattern 3. Conversely, farmer R, who does not want to produce more crops on his farm, has tried to diversify his supply with biowaste, which is less expensive than by-products (pattern 1). These dynamics show the importance of the structuring of the regional biomass market in the development of

crop successions. Depending on a farmer’s objectives and the market for feedstocks, this quest for feedstock autonomy opens up different rotation patterns—in accordance with the law that limits at maximum 15% energy crops in the supply.

Driver 2: The profitability requirement of the biogas plant For farmers heavily dependent on ECC, the management of ECC is guided by the objective to produce as much biogas as possible. Since cultivating ECC requires more work than buying feedstock from outside the farm, it must be profitable. Farmers therefore often choose cereal (rye, triticale, meslin) for winter ECC and corn for summer ECC, which produce a lot of biomass. Among the farmers surveyed, two introduced legumes, marginally, via their summer (B) or winter (I) ECC. Reintroducing legumes does not serve their main objective, which is to produce as much biomass as possible.

Driver 3: Synergy between organic farming and AD We observed synergies between AD and organic farming, involving the use of digestate as fertilizer. Among AD farmers who were converting to organic, this process leads to systemic changes in production systems, such as the lengthening and diversification of cropping systems. However, as two farmers demonstrated, the joint economic optimization of food and biogas production may rely on the purchase of non-organic crops from neighboring farmers (via biowaste for F, or via the purchase of manure and maize silage for D).

3.2 Changes in fertilization practices

Fertilization practices have evolved from the start of AD for almost every farmer surveyed, since there is an increasing need to manage digestate on their farms. Farmer P is the exception: as a mountain sheep farmer, it would not be feasible to spread digestate on his grassland. The way each farmer uses digestate influences, to a greater or lesser extent, his consumption of synthetic mineral nitrogen, depending on whether he replaces his mineral fertilizer applications with digestate.

3.2.1 A diversity of synthetic fertilizer reduction related to the difficulties of spreading digestate

A first group of six farmers do not reduce their use of synthetic fertilizer, or make only marginal reductions. They adopt the following practices: spreading digestate on crops before sowing corn, or when sowing cereals in autumn (E, H, Q, I), the remaining digestate is spread on grassland in autumn (C, E, K, I). There are three main reasons for the limited application of digestate to cereals in spring: (i) soils often have a low carrying capacity in spring, whereas spreading equipment is heavy (C, E, H, I, K, Q) and large volumes

are needed to reach the necessary nitrogen supply for cereals, (ii) spreading takes a long time in spring because of large volumes of digestate (E, H, K), and (iii) farmers are concerned that spreading could damage seedlings that have just emerged (I). In autumn, on the other hand, farmers E, K, H and I spread their digestate because there is a need to empty the slurry pit before winter. New requirements for mineral nitrogen have also arisen on these farms, with the use of mineral nitrogen on crops destined for AD (E, H, I, K).

We don't want to spread at all in winter, so in October the tank has to be empty (...) because in spring we're not sure we'll be able to spread, and then in spring I do all the fields that have a sufficient soil bearing capacity (Farmer C).

Nine other farmers identify similar constraints influencing their practices (B, G, J, M, O, R, S, T, U). However, they are able to make bigger reductions in synthetic nitrogen use because of their willingness to spread digestate on winter wheat or barley in spring, whenever possible. Their success in this regard is linked to manpower, work schedules, and spreading techniques (see below). Farmer U has been able to make even greater reductions in synthetic fertilizer use as a result of decreasing his milk production, and therefore adopting a spreading system that is sufficient for his low production objectives.

The other four farmers (D, F, N, V) face similar spreading constraints but have significantly reduced their consumption of mineral nitrogen as they have partially or fully converted to organic farming.

3.2.2 Different strategies for managing the constraints of digestate spreading

Choice of slurry tanks size and organization of digestate spreading These different levels of reductions in nitrogen consumption are linked to the equipment and organization of spreading.

- **Equipment and practices adopted due to “low resources”**—Farmer I (Table 6, column 2) decided to

invest in a small slurry spreader (11 m³), because he could not afford a larger one, and its output is sufficient to spread on his small, grouped fields. Even though the spreader is light, nitrogen savings are limited because nozzle spreading can increase digestate nitrogen volatilization.

- **Equipment and practices adopted to achieve “weight-rate compromise”**—Farmers B, C, E, F, H, K, L, M, N, Q, S, T, U, and W have sought a compromise between flow rate (hence working time and spreading efficiency) and equipment weight (risk of compaction). This choice is associated with a diversity of practices linked to personal objectives and resources. Farmers B, C, K, M, S, and W spread in spring when they consider compaction risk to be limited. Farmers H and U practice minimum tillage to improve carrying capacity. Farmers B, C, H, K, and L have invested in technical solutions to limit compaction (polypropylene tank, 3-axle tank, “low-pressure” tyres, decompaction tools). Farmer S increased site efficiency by transporting digestate to the field with a larger slurry tank (24 m³), and then spreading with an 18-m³ tank. Farmer T has a self-propelled machine that enters the field without a tank, but which has storage for digestate that he fills up off the field. Farmers E and Q have opted for high throughput spreading (21–28-m³ tank), with the aim of spreading large volumes of digestate and limiting spreading time. However, this practice limits the areas that can be spread in spring, and therefore also limits potential reductions in mineral fertilizer use. For these farmers, such practices result in a range of reductions in nitrogen fertilizer use (Table 6, column 3). Other farmers, such as M, N, and F, consider that it is in their economic interest to spread at the optimum time for the crop, which is spring, even if this takes time and increases the risk of compaction. Overall, these practices can reduce mineral nitrogen use considerably (Table 6, column 3, lines 3–4).
- **“Optimization of valorization” practices**—Farmers D, G, J, O, R, and V have sought to extend their spreading window by investing in slurry tanks of dif-

Table 6 Diversity of relationships between fertilization practices and choice of spreading equipment and strategy. Farmer A is excluded from the classification as his fertilization system is too unstable to be analyzed. Farmers L and W are included in the analysis, even though

the recent and still incomplete implementation of certain practices suggests that these practices are likely to evolve in time. Farmer P is not included as he does not spread digestate on his farm

Savings/spreading practices	“Low resource”	“Weight-rate compromise”	“Optimization of valorization”
0% or slight diminution	I	C, E, H, K, L, Q, W	
Significant decrease (between 30 and 60%)		B, M, S	G, J, O, R
Strong decrease (between 70 and 100%)		F, N, U, T	D, V

ferent sizes, and/or by combining slurry tank spreading with “tank-free” spreading. Such tank-free equipment transports the digestate to the spreader via hoses, thus greatly reducing the weight in the field. This enables the extension of the spreading window, with less risk of compaction and plant mortality compared to spreading with a tank. As a result, these farmers save more on mineral fertilizers (last column of Table 6). Most use service providers (A, G, J, O), as these operations are more complex and require more manpower and equipment than most farmers have. Over a certain field size, such equipment has a better throughput than equipment with a tank, but it is expensive. This system and equipment enables significant reductions in nitrogen fertilizer use, to a greater or lesser extent, depending on the farm (last column of Table 6).

The different objectives of farmers, as well as their resources and constraints, are therefore translated into a diversity of spreading practices, with various consequences in terms of reducing mineral nitrogen consumption.

Choice of depositing and burying techniques The choice of spreading equipment also includes the choice of techniques for depositing and/or burying digestate. In our surveys, all but one farmer used a dribble bar to limit ammonia volatilization and most bought this equipment when the AD was installed. Farmer I, who did not invest in a dribble bar, did so because he prefers smaller, less expensive equipment, even if it means losing nitrogen through volatilization. Two farmers spoke about problems with clogged pipes (W, H); farmer H prefers to use splash plate spreading in winter, which avoids the risk of frozen digestate clogging the pipes. Eighteen out of 21 farmers, however, have no specific digestate burying equipment because (i) it is too expensive (nine farmers), (ii) it requires too much power, so would require reinvestment in a new tractor (ten farmers), (iii) it spreads over a smaller width, so would require more passes over the field (ten farmers), or (iv) it is not practical for spreading on grassland (S). Seven of these 18 farmers plow the digestate into the land quickly (just after or on the same day) when spreading before sowing by tilling (stubble cultivator, disc, or harrow), to limit nitrogen losses. The work schedule may delay soil preparation, as in the case of farmer M, who harrows when he has available manpower. The last three farmers (C, Q, T) have invested in equipment that can tow a burying ramp and has a high work rate, with the goal of reducing nitrogen losses. All three had sufficient manpower to manage spreading and the economic capacity to invest in this equipment.

3.3 Changes in fodder and permanent grasslands management

3.3.1 Synergies and competition between animal production and AD, around the use of forage crops

With the development of AD, six farmers (A, B, E, G, K, J) have decided to produce more fodder crops (maize, temporary meadows) and to stockpile more in anticipation of potential drought. These farmers report that if stockpiles are not used in livestock farming, a last-resort economic outlet exists in AD. By guaranteeing a way to valorize plant biomass, AD gives these farmers greater flexibility in fodder management.

This year we made a rye-clover mixture to make a second-cut clover. Depending on fodder stocks, the rye may or may not be used for AD (Farmer K).

Conversely, other farmers (B, C, H, J, M) used the crops planned for AD as animal feed, while other farmers (A, B, K, J, Q, R) reported that they could afford to buy external maize or other products for AD—which is less the case for livestock farming. Therefore, this second group of farmers prioritizes the use of farm-grown crops for livestock production. Other farmers (K, O), due to repeated droughts and low ECC and corn production, buy corn silage to supplement their AD crops.

Initially intended for AD, the rye has been partly conserved for cows (5ha). The sorghum produced in 2022 will also be used primarily for cows, depending on needs. AD still requires the purchase of silage maize. (Farmer M)

The economic attractiveness of AD is a key factor in explaining these changes. Seven farmers (B, H, I, J, K, O, T) said that for the same amount of work, an AD unit is more profitable than livestock. Some of these farmers decided to invest in AD rather than livestock. Farmers C and E have also stopped calf fattening to devote more resources (fodder and labor) to AD. Conversely, some of these farmers (B, J, O) emphasize their attachment to the livestock profession and a desire to maintain these activities, even if there would be greater economic benefit in prioritizing AD feeding. Relatedly, some farmers were initially reluctant to use corn or other crops for AD, but ultimately decided to do so (I, K).

3.3.2 An increase in permanent grassland fertilization and changes in grass use

More broadly, the arrival of AD is bringing about changes on farms that are influencing the management of permanent grasslands. In the Vosges and Bas-Rhin areas, farmers

say that they fertilize permanent grasslands more now than before AD. The farmers who significantly increased their grassland fertilization were those who had previously fertilized little (A, E, J, K, T, W) with slurry/manure, and had now started to fertilize with digestate. Other farmers who previously fertilized with mineral nitrogen (between 15 and 65 kgN/ha) also increased their fertilization (B, C, H, M, S). This increase is due to meadows being easily spreadable before winter, when the digestate pit must be emptied (see 3.2). This change in fertilization has resulted in an increase in grass yields, noted by 12 farmers, and consequently a change in grassland management and grass consumption strategies for some of these farmers:

- C and J now sell more grass.
- A, H, I, and K have plowed grassland areas to produce more cash crops, for livestock and for AD.
- A, B, C, D, I, and K use their surplus grass from permanent grassland for AD, generally the 2nd and 3rd cuts, which are of poorer quality for cows.
- Some farmers (E, G, H, J) also use temporary grassland for AD.

AD is therefore indirectly changing grassland management practices in diverse ways, as well as animal feed composition, and land use.

4 Discussion

4.1 Understanding changes in practices involves considering the dynamics of farming systems and the agency of farmers

As discussed in the introduction, there has been little research into the influence of AD on farming practices that also consider the mechanisms of systemic changes at the farm level.

4.1.1 The importance of farming systems dynamics to understand changes in practices

We showed that the evolution of the organization of farm activities with AD plays a role in the development of a diversity of practices. The production or purchase of crops for AD (3.1), the organization of the work for digestate spreading and choice of spreading techniques (3.2), and the synergies or competition between AD and livestock farming, in forage and grasslands management (3.3) are all areas where different dynamics open up different choices of practices. These results are in line with the few studies that have highlighted how the creation of AD on a farm has a significant influence on the farming systems through an evolution of

its socio-economic organization (Emmann et al. 2013; Carrosio 2014; Grouiez et al. 2020). The synergies or competition between livestock rearing and AD on fodder management illustrates the importance of considering interactions between farm activities to assess AD impacts on practices. Some mechanisms have been identified, such as the increase or loss of fodder autonomy (Solagro 2018), and the increase in animal husbandry (Carrosio 2014), while structural synergies between AD and organic farming have already been studied in Germany (Siegmeier et al. 2015). Our empirical work also shows that digestate production on AD farms can facilitate the transition to organic farming. At the regional level, to our knowledge, there has been no research into the regional dynamics of AD development, and how this can influence farm practices. We show that the availability of methanogenic feedstock at the regional level can influence the evolution of cropping systems. This result is in line with Cadiou (2023), which demonstrates that a rapid increase in the number of AD units in the agricultural area could create competition among farmers for access to feedstock (agro-industrial by-products, manure from surrounding farms and maize).

4.1.2 The importance of the agency of farmers to understand changes in practices

Regarding digestate spreading, we have shown that farm characteristics (field size, economic resources, farmer knowledge, manpower) make certain technical solutions either beneficial or feasible. The choice of spreading equipment and techniques depends on a multiplicity of factors linked to the farm, which are independent of the AD system. On this subject, our results converge with those of Carton and Levavasseur (2022) and Markard et al. (2016), and with the Farming System Research literature (Ingram 2008; Tofolini et al. 2017), which show that farmer's choices depend not necessarily on the best available or recommended technical solutions, but primarily on their previous knowledge and practices. Farmers may also pursue diverse farm management objectives (maintenance of livestock, increased income, better allocation of work time, etc.) that open up additional digestate management options. For example, some farmers view digestate as a cumbersome by-product that requires a lot of work, while for others (such as organic farmers), digestate is a new fertilization opportunity that offers economic gains and greater autonomy. As a result, the nitrogen in digestate would be used inefficiently by the former, while the latter would opt for practices that optimize nitrogen use. In this way, a better understanding of the agency (i.e., his/her ability to act intentionally on his/her environment) of AD farmers can help identify the obstacles and levers to good practices. In fact, our results take issue with the hypotheses of economic rationality

and technique optimization—which are established in the technology development literature (Geels and Smith 2000; Wangel 2011)—by highlighting the importance of the diversity of situations faced by farmers as well as their motivations. Thus, considering the diversity of farms and farmers' agency, we show that actual practices can be more varied than previously documented.

These results suggest that AD sustainable development needs to involve more specific support for agricultural situations, and for the regional context in which AD is being developed. By understanding the farmer's rationality, farming advisory services could play a major role in the sustainable development of biogas units.

4.2 Discrepancies between observed farming practices and those reviewed in AD assessments literature: implications for environmental assessments

Compared to the practices generally assessed in the scientific literature, we observed a larger diversity from farm to farm.

4.2.1 Energy cover crops are cultivated to produce energy and not to optimize their environmental benefits

There is a large volume of literature on ECC and the practices to maximize their environmental benefits and limit risks for the agri-environment (Beillouin et al. 2021; Launay 2023). According to this literature, farmers are generally supposed to avoid treating ECC with pesticides, fertilize them with digestate only, and avoid competition with other crops. Under those conditions, cover cropping can have positive impacts on plot biodiversity, soil fertility, soil carbon storage, and diseases, as well as weed and pest management. However, we have shown that although ECC was a common option for supplying the AD units, not all farmers decided to develop this type of crop on their farms. Farmers who have cultivated ECC have adopted a diversity of practices (fertilization, species choice, acreage), depending also on their rotation. We have identified two trends in crop rotation evolution, which have already been described in some empirical studies. The first trend is the development of winter energy cover crops in double cropping systems, as observed in other French regions (Carton and Levvasseur 2022; Réguer and Garambois 2023), and as promoted in other countries like Austria (Szerencsits et al. 2015). These cropping systems have advantages in terms of soil cover and can help store more carbon in the soil (Launay et al. 2020; Carton and Levvasseur 2022; Malet 2022). The choice of ECC species can lead to a reduction in the diversity of crops with an increase in the proportion of grasses (Carton and Levvasseur 2022). In addition, ECC require additional water, which for some farmers means a drop in the yield of

their main crop because the ECC have mobilized part of the available moisture capacity (Launay et al. 2022). Ultimately, the magnitude of these effects will depend on a farmer's technical management skills, the acreage concerned (see Table 4), and production objectives. The second trend is the development of maize, which is an excellent crop in terms of energy produced per hectare. As a result, in regions where biogas units are being developed, maize planting is increasing (Herrmann 2013; Lüker-Jans et al. 2017; Vergara and Lakes 2019; Ruf et al. 2021; Réguer and Garambois 2023; Levvasseur et al. 2023). According to our 2021 surveys, maize is an economically attractive crop for AD in France; however, the increase in maize acreage is much less than that observed in Germany. Conventional maize growing in the studied regions tends to perpetuate conventional cultivation practices with synthetic input use, as also shown in the Ile-de-France region by Carton and Levvasseur (2022). Despite a smaller presence of maize, this crop development explains increasing societal criticisms of AD in France regarding the competition between crops used for energy production or for feed/food production. However, we have also shown that some farmers make major changes to their crop rotations in relation to their conversion to organic farming. In these cases, AD, as a lever of organic conversion, brings diversification to the rotation—often as legume reintroduction—and as a result reduces the use of pesticides. Outside of organic farming, on the surveyed farms, AD does not appear to be a direct lever of legume reintroduction through cover crops. Some technical and scientific literature on cover crops assess the value of choosing legumes to improve farm GHG balance (Stinner 2015) and nitrogen management (Stinner et al. 2018). Marsac et al. (2019) have also shown that a legume association (up to 40%) with cereal is possible with no yield loss for the cover crop. However, we have not observed the development of legumes in cover crops. Therefore, we observed a diversity of mechanisms driving the evolution of farm practices, which are rarely assessed in the literature, and suggest that agri-environmental effects of AD could vary greatly from farm to farm.

4.2.2 Digestate use: discrepancies between practical implementation and "optimized" use

The literature on digestate documents the technical conditions of optimized fertilization. Optimized nitrogen fertilization means optimizing chemical and physical fertility and minimizing nutrient losses to water and air. Therefore, in addition to the substitution of synthetic nitrogen, good spreading practices include application according to the needs of the crop (at the end of winter and in spring for cereals and oilseed rape, before planting or during the first 6 to 8 weeks for maize), equipment that limits nitrogen volatilization (using a dribble bar and burying digestate

immediately after spreading), and limiting compaction (monitoring the weight of the tank, using remote inflation, “tank-free” spreading) (Lukehurst et al. 2010; Severin et al. 2016; Nicholson et al. 2017, 2018; Carton and Bulcke 2021). In the literature, agri-environmental assessments of biogas plants are often carried out on the assumption that these conditions are met (Vaneekhaute et al. 2018; Grillo et al. 2021; Moinard 2021; Esnouf et al. 2021; Cadiou et al. 2023; Caquet et al. 2024). However, we have shown that these conditions are not always met, and sometimes cannot be met by farmers. Varying responses to spreading constraints lead to a diversity of fertilization practices and different ways of implementing recommended practices to optimize the use of digestate. These obstacles mentioned by the farmers (insufficient soil bearing capacity, cost of spreading equipment, work schedule burden) lead to varying degrees of substitutions of mineral nitrogen with digestate, ranging from very low substitution to total replacement of the mineral nitrogen consumed. These results are a testament to the possible discrepancies between practical implementation and theoretical “optimized” projections. Moreover, we observed there can be a trade-off between digestate use on farm and risk of soil compaction. If public policy supports digestate use, then public subsidies, advisory supports, and technical literature must consider the techno-economic conditions to promote digestate use while preventing associated possible soil compaction.

The literature demonstrates how the combination of organic farming and anaerobic digestion may help promote nitrogen circularity. In our three surveys of “organic” AD, organic conversion appears to be a strong driver of lengthening the rotation, reintroducing legumes, and managing weed populations. However, the farms we surveyed also show that two out of three organic farmers base their production on the import of external nitrogen. As Dumont et al. (2020) and Nowak et al. (2015) have shown, assessing the sustainability of these systems requires quantifying the dependence of organic farming with AD on conventional farming.

Regarding soil fertility, the issue of soil compaction is still poorly addressed in empirical studies. Our results on spreading practices show that these compaction risks can exist and vary greatly from one farmer to another, depending on whether they are able to invest in certain technical solutions (tank-free spreader, “low-pressure” tyres, decompaction tools) recommended in the literature (Carton and Bulcke 2021).

4.2.3 The impacts of AD on permanent grassland: a need for more research on the diverse practices observed

The literature on the impacts of AD on permanent grassland is poor in France, and generally in Europe. In Germany, Lupp et al. (2014) showed that under AD development—and

under the policy framework of the time—the need for biomass and increased grassland yields can lead farmers to plow permanent grasslands. The plowing of permanent grassland in connection with AD has not been shown to be a significant phenomenon in France at the national level (Levavas-seur et al. 2023), but our results show that this situation does occur, driven by the same practices as in Germany. Since 2013, grassland plowing has been subject to regulation at the European level (European Parliament and Council 2013). In France, one argument for developing AD is that it could support the maintenance of permanent grassland (and all of its environmental benefits on biodiversity and carbon storage). This argument is that in the context of decreasing livestock, the digestion of grass could economically justify grassland conservation (Couturier et al. 2016). However, this mechanism has not been empirically assessed and should be the subject of further research in order to show the real-world conditions for the development of these practices.

We have also observed a possible increase in nitrogen use in the management of permanent grasslands on livestock farms. The increase in digestate fertilization can stimulate grass production. This grassland intensification, by promoting farm protein autonomy, can lower the consumption of animal concentrates. Indirectly, it can improve the GHG balance of feed since animal concentrates have a poor carbon footprint (Boerema et al. 2016) and leads to a reduction of species biodiversity (Plantureux et al. 2005; Pärtel et al. 2015). To our knowledge, these practices and their environmental effects on grasslands are still poorly documented and studied, even though they can have a significant impact on the carbon footprint and biodiversity of these areas. Here again, we can see that AD development on farms can stimulate diverse management strategies of grassland, with different unexpected effects on other practices, most of which are poorly documented.

4.2.4 Diverse impacts of AD on livestock farms

In France, AD development has also been supported by public authorities in order to economically support livestock farms (Ministère de l’écologie, du développement durable et de l’énergie and Ministère de l’agriculture de l’agroalimentaire et de la forêt 2013). Regarding the evolution of livestock farms under AD development, the fact that an AD unit can be more profitable than livestock for the same amount of work raises questions about the effect of energy subsidies on livestock activity. To the best of our knowledge, this phenomenon of possible investment competition has not been documented elsewhere in France, and is not observed in Réguer and Garambois’s (2023) work in Brittany, where, on the contrary, AD seems to be in synergy with dairy farming. It would be interesting to study this point in greater depth, in connection with the logic behind the installation of new workers on farms with AD.

4.2.5 Discrepancies between observed farming practices and those reviewed in AD assessments, analysis in light of socio-technical dynamics

Our sample is not representative of the diversity of French farms that have adopted AD, but it shows that the impacts of AD on farmers' practices can be more diverse than has been documented and assessed to date. It suggests that the necessary conditions to attain the best environmental balance are not always met or aligned with farmers' strategies. These results converge with other empirical studies in France (SOLAGRO et al. 2018; Carton and Levavasseur 2022). We can assume that the environmental impact of AD depends more on the pre-existing practices, production factors, and the norms of the farming systems in which AD is developed, rather than on the AD technology itself (Markard et al. 2016; Cadiou 2023). The concept of socio-technical system groups these different variables (practices, norms, economic logic) that characterize how actors in the agricultural system organize themselves (Rip and Kemp 1998; Geels 2002). AD thus appears to be an innovation compatible with the current dominant farming socio-technical system for arable crops in France. This socio-technical system is characterized by the pursuit of high yields, is specialized in a small number of species, and relies heavily on synthetic inputs (Guichard et al. 2017; Meynard et al. 2018). However, AD also appears compatible with organic farming, which represents a form of sustainable agriculture. These observations question the way AD sustainability has been assessed to date, depending on the agricultural socio-technical dynamics.

4.3 Assessing the sustainability of practices must consider the dynamics of farming systems and the agency of farmers.

We have shown that AD can induce a diversity of mechanisms on farms, which suggests a range of agri-environmental impacts. The Farming System Research framework is a good way of grasping the effects of AD on farming practices, moving away from a technical approach that focuses on the direct benefits and risks of AD technology. This research framework takes into consideration the interactions between practices, and therefore enables us to highlight practices and issues that have been rarely addressed, such as the change of fertilization grassland practices. It also accounts for different AD management strategies, which can be developed depending on the agency of the farmer.

Conducting an impact assessment approach therefore requires (i) documenting the actual practices of farmers in terms of managing AD feedstock and digestate, (ii) documenting the impacts of AD on other farm activities (and even on neighboring farms), and (iii) assessing their agri-environmental implications based on a battery of indicators chosen

according to the evaluators' expectations (as for example the IDEA method) (Zahm et al. 2018). These sustainability indicators must be adapted to the new practices developed by farmers. During these three phases, particular attention must be paid to systemic changes, which may involve more virtuous or less virtuous practices overall (Byerlee et al. 1982; Doré et al. 1997). To make this kind of assessment more actionable (i.e., to support public policy making or farming advisory services), such assessments could be supplemented by an analysis of the underlying logic behind farm changes.

This approach can be developed by mobilizing the tools of agronomic diagnosis that aim to reconstruct the complex direct and indirect links between practices and performance. Indicators can be used to identify agronomic, environmental, and economic benefits and risks, but they do not tell us how practices should evolve (Meynard and David 1992; Doré et al. 1997). Thus, an agronomic diagnosis would provide a better understanding of the role of biogas in maintaining or changing certain practices as well as of the transition of the farm to optimize the impacts associated with biogas.

More generally, the diverse practices we have observed provide new research avenues in AD assessment. AD assessment would benefit from the combination of semi-structured interviews to capture new empirical practices to assess and new indicators to develop, as well as the models developed to link AD practices and their impacts. Regarding LCAs, our work shows that a greater diversity of possible changes in practices and subsystems should be taken into account, considering the implications of functional units.

These principles could be the basis for new research on AD sustainability, but could also support the assessment studies conducted by R&D organizations, such as Chambers of Agriculture or technical institutes. This would help to improve understanding of the levers and constraints that influence the way that AD can lead to sustainable changes in practices.

5 Conclusion

Given the growing use of biogas as a substitute for fossil gas, this article aims to contribute to understanding the effects of AD on farming practices and, therefore, on the sustainability pathways of AD farms. Our research shows that various changes in nitrogen fertilization practices, forage and permanent grassland management, and cultivation practices can follow the development of AD on farms. AD can induce complex, systemic farm-level effects, with a variety of direct and indirect changes in practices. Consequently, our research strongly supports the hypothesis outlined in the introduction, that changes in practices associated with the management of AD units can be linked to indirect mechanisms involving other

practices, other farm activities, and even regional dynamics, resulting in a much more diverse range of environmental impacts than the effects generally documented in the literature. Although our research design did not allow for a thorough environmental assessment of the observed practices, we demonstrate that agri-environmental impacts related to these indirect mechanisms remain insufficiently documented even though they could significantly alter the agri-environmental balance of AD.

Thus, the novelty of our research is to provide new insights into indicators and practices that should be considered in environmental evaluations of AD.

Our results should be complemented by empirical studies in other regions that couple this approach to agri-environmental assessments. This would enable researchers to better document this diversity and identify the most representative practices and impacts.

We have identified the following three avenues for further research. First, farm dynamics are themselves caught up in regional dynamics. AD farmers can establish links with regional stakeholders during the development of an AD project, as well as when managing the AD supply and digestate spreading. Documenting these interactions and how they influence farmers' practices would help us to better grasp the indirect determinants of the impacts of anaerobic digestion. Second, several agri-environmental issues are still very poorly documented empirically, such as soil biodiversity and soil compaction. Researching these dimensions would help researchers and farmers understand how to protect the soil fertility in the future. Third, systemic assessments of the impacts of AD could form the basis for a renewal of biogas public policy. Considering these mechanisms will lead to a better understanding of the factors driving or hampering sustainable biogas development in both energy and agri-environmental terms. Our results can help orient public action towards establishing the conditions for adopting best practices and developing more sustainable AD systems on farms. New research could better inform policy support for sustainable AD units. Moreover, additional research on the impacts of AD in agriculture could question the policy discourse underlying French biogas policy on agriculture and on its contribution to the sustainable transition of agriculture.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due to anonymization needs.

Code availability Not applicable.

Declarations

Ethics approval The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki.

Consent to participate Informed consent has been obtained from all human participants involved in this study.

Consent for publication Consent for publication has been obtained from all individuals whose data is included in this study.

Conflict of interest All authors have no conflict of interest to declare that are relevant to the content of this article, and disclose financial or non-financial interests that are directly or indirectly related to this study. Dr. Jean-Marc Meynard serves as an Editor for Agronomy for Sustainable Development, but was never involved in the assessment of this article. In accordance with indexing service guidelines, he is permitted to submit manuscripts to the journal.

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References

- Bacenetti J, Sala C, Fusi A, Fiala M (2016) Agricultural anaerobic digestion plants: what LCA studies pointed out and what can be done to make them more environmentally sustainable. *Appl Energy* 179:669–686. <https://doi.org/10.1016/j.apenergy.2016.07.029>
- Beausang C, McDonnell K, Murphy F (2021) Assessing the environmental sustainability of grass silage and cattle slurry for biogas production. *J Clean Prod* 298:126838. <https://doi.org/10.1016/j.jclepro.2021.126838>
- Beillouin D, Pelzer E, Baranger E et al (2021) Diversifying cropping sequence reduces nitrogen leaching risks. *Field Crops Res*. <https://doi.org/10.1016/j.fcr.2021.108268>
- Biernacki P, Waldorf D (1981) Snowball sampling: problems and techniques of chain referral sampling. *Sociol Methods Res* 10:141–163. <https://doi.org/10.1177/004912418101000205>

- Biggs SD (1985) A farming systems approach: some unanswered questions. *Agric Adm* 18:1–12. [https://doi.org/10.1016/0309-586X\(85\)90037-8](https://doi.org/10.1016/0309-586X(85)90037-8)
- Blumenstein B, Siegmeier T, Selsam F, Möller D (2018) A case of sustainable intensification: stochastic farm budget optimization considering internal economic benefits of biogas production in organic agriculture. *Agric Syst* 159:78–92. <https://doi.org/10.1016/j.agsy.2017.10.016>
- Boerema A, Peeters A, Swolfs S et al (2016) Soybean trade: balancing environmental and socio-economic impacts of an intercontinental market. *PLoS One* 11:e0155222. <https://doi.org/10.1371/journal.pone.0155222>
- Britz W, Delzeit R (2013) The impact of German biogas production on European and global agricultural markets, land use and the environment. *Energy Policy* 62:1268–1275. <https://doi.org/10.1016/j.enpol.2013.06.123>
- Byerlee D, Harrington L, Winkelmann DL (1982) Farming systems research: issues in research strategy and technology design. *Am J Agric Econ* 64:897–904. <https://doi.org/10.2307/1240753>
- Cadiou J (2023) Le déploiement de la politique de méthanisation agricole en France : implications pour la transition agroécologique. Université Paris-Saclay. <https://pastel.hal.science/tel-04190138>
- Cadiou J, Aubert P-M, Meynard J-M (2023) The importance of considering agricultural dynamics when discussing agro-environmental sustainability in futures studies of biogas. *Futures* 153:103218. <https://doi.org/10.1016/j.futures.2023.103218>
- Cadiou J, Meynard J-M (2026) Méthanisation et circuits de valorisation des biomasses au niveau des exploitations et des territoires. Exploitations agricoles et territoires. ISTE Editions
- Caquet T, Axelos M, Soussana J-F et al (2024) Enjeux agronomiques, techniques et économiques d'une mobilisation accrue des différents gisements de biomasse et de leur transformation en bioénergies. INRAE. <https://doi.org/10.17180/CVM4-AK69>
- Carrosio G (2014) Energy production from biogas in the Italian countryside: modernization vs. repeasantization. *Biomass Bioenergy* 70:141–148. <https://doi.org/10.1016/j.biombioe.2014.09.002>
- Carton S, Bulcke Q (2021) L'utilisation des digestats en agriculture : Les bonnes pratiques à mettre en oeuvre. <https://methasynergie.fr/guide-lutilisation-des-digestats-en-agriculture-les-bonnes-pratiques-a-mettre-en-oeuvre/>. Accessed 7 Jan 2022
- Carton S, Levavasseur F (2022) Performances agronomiques et environnementales de la méthanisation agricole dans un contexte de grandes cultures céréalières (sans élevage) et recommandations de bonnes pratiques. <https://agriculture.gouv.fr/telecharger/130022>. Accessed 25 Sept 2024
- Cavicchi B (2016) Sustainability that backfires: the case of biogas in Emilia Romagna. *Environ Innov Soc Transit* 21:13–27. <https://doi.org/10.1016/j.eist.2016.02.001>
- Clements LJ, Salter AM, Banks CJ, Poppy GM (2012) The usability of digestate in organic farming. *Water Sci Technol* 66:1864–1870. <https://doi.org/10.2166/wst.2012.389>
- Cochet H, Devienne S, Dufumier M (2007) L'agriculture comparée, une discipline de synthèse ? *Econ Rurale*. <https://doi.org/10.4000/economierurale.2043>
- Cochet H (2012) The systeme agraire concept in francophone peasant studies. *Geoforum* 43:128–136. <https://doi.org/10.1016/j.geoforum.2011.04.002>
- Couturier C, Charru M, Doublet S, Pointereau P (2016) Scénario Afterres 2050. https://afterres2050.solagro.org/wp-content/uploads/2015/11/Solagro_afterres2050-v2-web.pdf. Accessed 9 Sept 2023
- Darnhofer I, Gibbon D, Dedieu B (eds) (2012) Farming systems research into the 21st century: the new dynamic. <https://doi.org/10.1007/978-94-007-4503-2>
- Doré T, Sebillotte M, Meynard JM (1997) A diagnostic method for assessing regional variations in crop yield. *Agric Syst* 54:169–188. [https://doi.org/10.1016/S0308-521X\(96\)00084-4](https://doi.org/10.1016/S0308-521X(96)00084-4)
- Dumont AM, Gasselin P, Baret PV (2020) Transitions in agriculture: three frameworks highlighting coexistence between a new agro-ecological configuration and an old, organic and conventional configuration of vegetable production in Wallonia (Belgium). *Geoforum* 108:98–109. <https://doi.org/10.1016/j.geoforum.2019.11.018>
- Emmann CH, Guenther-Lübbbers W, Theuvsen L (2013) Impacts of biogas production on the production factors land and labour – current effects, possible consequences and further research needs. 13. <https://doi.org/10.22004/ag.econ.164768>
- Esnouf A, Brockmann D, Cresson R (2021) Analyse du Cycle de Vie du BIOMETHANE issu de ressources agricoles - Rapport d'ACV. https://www.inrae.fr/sites/default/files/pdf/Rapport%20ACV_Biomethane%20issu%20de%20ressources%20agricoles_INRAE%20Transfert_GRDF.pdf. Accessed 9 Sept 2023
- European Parliament and Council (2013) Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:347:0608:0670:en:PDF>
- Geels FW, Smith A (2000) Lessons and pitfalls from Failed Technology Futures: Potholes in the Road to the Future. *Contested Futures: A sociology of prospective techno-science*. Ashgate Publishing, Burlington. Singapore, Sydney, pp 129–155. [https://doi.org/10.1016/S0016-3287\(00\)00036-7](https://doi.org/10.1016/S0016-3287(00)00036-7)
- Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res Policy* 31:1257–1274. [https://doi.org/10.1016/S0048-7333\(02\)00062-8](https://doi.org/10.1016/S0048-7333(02)00062-8)
- Greenberg I, Kaiser M, Gunina A et al (2019) Substitution of mineral fertilizers with biogas digestate plus biochar increases physically stabilized soil carbon but not crop biomass in a field trial. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2019.05.051>
- Grillo F, Piccoli I, Furlanetto I et al (2021) Agro-environmental sustainability of anaerobic digestate fractions in intensive cropping systems: insights regarding the nitrogen use efficiency and crop performance. *Agronomy*. <https://doi.org/10.3390/agronomy11040745>
- Grouiez P, Berthe A, Fautras M, Issehnane S (2020) Déterminants et mesure des revenus agricoles de la méthanisation et positionnement des agriculteurs dans la chaîne de valeur « biomasse-énergie » - Scientific report. <https://halshs.archives-ouvertes.fr/halshs-02886217/document>. Accessed 9 Sept 2023
- Guichard L, Dedieu F, Jeuffroy M-H et al (2017) Le plan Ecophyto de réduction d'usage des pesticides en France : décryptage d'un échec et raisons d'espérer. *Cah Agric* 26:14002. <https://doi.org/10.1051/cagri/2017004>
- Guilayn F, Jimenez J, Martel J-L et al (2019) First fertilizing-value typology of digestates: a decision-making tool for regulation. *Waste Manag* 86:67–79. <https://doi.org/10.1016/j.wasman.2019.01.032>
- Handcock MS, Gile KJ (2011) Comment: On the concept of snowball sampling. *Sociol Methodol* 41:367–371. <https://doi.org/10.1111/j.1467-9531.2011.01243>
- Herrmann A (2013) Biogas production from maize: current state, challenges and prospects. 2. Agronomic and environmental aspects. *Bioenergy Res* 6:372–387. <https://doi.org/10.1007/s12155-012-9227-x>
- Hijazi O, Munro S, Zerhusen B, Effenberger M (2016) Review of life cycle assessment for biogas production in Europe. *Renew Sustain*

- Energy Rev 54:1291–1300. <https://doi.org/10.1016/j.rser.2015.10.013>
- Ingram J (2008) Are farmers in England equipped to meet the knowledge challenge of sustainable soil management? An analysis of farmer and advisor views. *J Environ Manage* 86:214–228. <https://doi.org/10.1016/j.jenvman.2006.12.036>
- Ingrao C, Bacenetti J, Ioppolo G, Messineo A (2019) Energy and Environmental Assessments of Agro-biogas Supply Chains for Energy Generation: A Comprehensive Review. In: Basosi R, Cellura M, Longo S, Parisi ML (eds) *Life Cycle Assessment of Energy Systems and Sustainable Energy Technologies: The Italian Experience*. Springer International Publishing, Cham, pp 99–117. https://doi.org/10.1007/978-3-319-93740-3_7
- Koszel M, Lorencowicz E (2015) Agricultural use of biogas digestate as a replacement fertilizers. *Agric Agric Sci Procedia* 7:119–124. <https://doi.org/10.1016/j.aaspro.2015.12.004>
- Launay C, Crépeau M, Girault R et al (2020) MéthaPolSol, impacts de l'introduction de méthaniseurs dans un territoire sur les stratégies de fertilisation des cultures et leurs conséquences sur les dynamiques du carbone et de l'azote dans les sols: cas de la plaine de Versailles. In: JRI2020 ATEE Toulouse Fr. <https://hal.inrae.fr/hal-02951996>. Accessed 9 Sept 2023
- Launay C, Houot S, Frédéric S et al (2022) Incorporating energy cover crops for biogas production into agricultural systems: benefits and environmental impacts. A review. *Agron Sustain Dev* 42:57. <https://doi.org/10.1007/s13593-022-00790-8>
- Launay C (2023) Insertion of energy cover crops in cropping systems in France: multi-scale assessment of potential production and water-nitrogen-carbon impacts. *Agricultural sciences*. Université Paris-Saclay. <https://doi.org/10.70675/5b6f6954zccc4z4275zb0b4z7ca1ecb8126f>
- Levavasseur F, Martin L, Boros L et al (2023) Land cover changes with the development of anaerobic digestion for biogas production in France. *GCB Bioenergy* 15:630–641. <https://doi.org/10.1111/gcbb.13042>
- Lukehurst CT, Frost P, Seadi TA (2010) Utilization of digestate from biogas plants as biofertiliser. https://task37.ieabioenergy.com/wp-content/uploads/sites/32/2022/02/Digestate_Brochure_Revised_12-2010.pdf. Accessed 9 Sept 2022
- Lüker-Jans N, Simmering D, Otte A (2017) The impact of biogas plants on regional dynamics of permanent grassland and maize area—the example of Hesse, Germany (2005–2010). *Agric Ecosyst Environ* 241:24–38. <https://doi.org/10.1016/j.agee.2017.02.023>
- Lupp G, Steinhäuser R, Starick A et al (2014) Forcing Germany's renewable energy targets by increased energy crop production: a challenge for regulation to secure sustainable land use practices. *Land Use Policy* 36:296–306. <https://doi.org/10.1016/j.landusepol.2013.08.012>
- Malet N (2022) Retour au sol ou méthanisation agricole : quelle est la stratégie de gestion de la biomasse la plus efficace pour atténuer les émissions de CO₂ ? Ingénierie de l'environnement. Université de Bordeaux, 2022. Français. <https://doi.org/10.70675/8002ddcbzcec6z49c1zba14z3166a0b4e5c0>
- Markard J, Wirth S, Truffer B (2016) Institutional dynamics and technology legitimacy – a framework and a case study on biogas technology. *Res Policy* 45:330–344. <https://doi.org/10.1016/j.respol.2015.10.009>
- Marsac S, Heredia M, Bazet M et al (2019) Optimisation de la mobilisation de CIVE pour la méthanisation dans les systèmes d'exploitation. Nicolas Delaye, Robert Trochard, Hélène Lagrange, Caroline Quod, Eve-Anna Sanner. https://bibliothèque.ademe.fr/cadic/4557/opticive_optimisation_methanisation_cive_rapport.pdf. Accessed 9 Sept 2022
- Meynard J-M, David G (1992) Diagnostic de l'élaboration du rendement des cultures. *Cah Agric* 1:9–19 (1). <https://revues.cirad.fr/index.php/cahiers-agricultures/article/view/29729>
- Meynard J-M, Doré T, Habib R (2001) L'évaluation et la conception de systèmes de culture pour une agriculture durable. *Comptes Rendus Académie Agric Fr* 87:223–236. <https://agroparistech.hal.science/hal-01382344v1>
- Meynard J-M, Charrier F, Fares M et al (2018) Socio-technical lock-in hinders crop diversification in France. *Agron Sustain Dev*. <https://doi.org/10.1007/s13593-018-0535-1>
- Ministère de l'écologie, du développement durable et de l'énergie, Ministère de l'agriculture de l'agroalimentaire et de la forêt (2013) Le plan Energie Méthanisation Autonomie Azote. <https://agriculture.gouv.fr/telecharger/89917?token=018a247230ac112abbd68747c016c36b>
- Moinard V (2021) Conséquences de l'introduction de la méthanisation dans une exploitation de polyculture-élevage sur les cycles du carbone et de l'azote. Combinaison de l'expérimentation et de la modélisation à l'échelle de la ferme. <https://doi.org/10.70675/1f264fc4z4689z4261zb5b4z72c3256cf14b>
- Möller K (2015) Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agron Sustain Dev* 35:1021–1041. <https://doi.org/10.1007/s13593-015-0284-3>
- Nicholson F, Bhogal A, Cardenas L et al (2017) Nitrogen losses to the environment following food based digestate and compost applications to agricultural land. *Environ Pollut* 228:504–516. <https://doi.org/10.1016/j.envpol.2017.05.023>
- Nicholson F, Bhogal A, Rollett A et al (2018) Precision application techniques reduce ammonia emissions following food based digestate applications to grassland. *Nutr Cycl Agroecosyst* 110:151–159. <https://doi.org/10.1007/s10705-017-9884-4>
- Nkoa R (2014) Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agron Sustain Dev* 34:473–492. <https://doi.org/10.1007/s13593-013-0196-z>
- Nowak B, Nesme T, David C, Pellerin S (2015) Nutrient recycling in organic farming is related to diversity in farm types at the local level. *Agric Ecosyst Environ* 204:17–26. <https://doi.org/10.1016/j.agee.2015.02.010>
- Osty P-L, Lardon S, de Sainte-Marie C (1998) Comment analyser les transformations de l'activité productrice des agriculteurs ? Propositions à partir des systèmes techniques de production. *Études Rech Sur Systèmes Agraires Dév* 397–413. <https://hal.archives-ouvertes.fr/hal-01231629>. Accessed 18 Sept 2023
- Paolini V, Petracchini F, Segreto M et al (2018) Environmental impact of biogas: a short review of current knowledge. *J Environ Sci Health A* 53:899–906. <https://doi.org/10.1080/10934529.2018.1459076>
- Pärtel, Bruun, Sammul (2015) Biodiversity in temperate European grasslands: origin and conservation. *Grasslands Sciences in Europe*. https://www.researchgate.net/publication/266456372_Biodiversity_in_temperate_European_grasslands_origin_and_conservation
- Plantureux S, Peeters A, McCracken D (2005) Biodiversity in intensive grasslands: effect of management, improvement and challenges. *Agron Res* 3:153–164. https://www.researchgate.net/profile/Alain-Peeters/publication/234001901_Biodiversity_in_intensive_grasslands_Effect_of_management_improvement_and_challenges/links/0912f50e2f4a3513f2000000/Biodiversity-in-intensive-grasslands-Effect-of-management-improvement-and-challenges.pdf. Accessed 18 Sept 2023
- Purswani J, Llorente CP (2021) Nitrification and Denitrification Processes: Environmental Impacts. *Nitrogen Cycle*. CRC Press, pp 60–81

- Quakernack R, Pacholski A, Techow A et al (2012) Ammonia volatilization and yield response of energy crops after fertilization with biogas residues in a coastal marsh of Northern Germany. *Agric Ecosyst Environ* 160:66–74. <https://doi.org/10.1016/j.agee.2011.05.030>
- Räbiger T, Andres M, Hegewald H et al (2020) Indirect nitrous oxide emissions from oilseed rape cropping systems by NH₃ volatilization and nitrate leaching as affected by nitrogen source, N rate and site conditions. *Eur J Agron* 116:126039. <https://doi.org/10.1016/j.eja.2020.126039>
- Réguer I, Garambois N (2023) Méthanisation agricole et impact des politiques publiques sur la durabilité de l'agriculture bretonne. https://www.sfer.asso.fr/source/jrss2023/articles/B31_102_Reguer_Garambois_M%C3%A9thanisation%20agricole%20et%20impact%20des%20politiques%20publiques%20sur%20la%20durabilit%C3%A9%20de%20l'E2%80%99agriculture%20bretonne.pdf. Accessed 18 Sept 2023
- Rip A, Kemp RPM (1998) Technological change. In: Rayner S, Malone EL (eds), *Human choice and climate change* pp 327–399. <https://ris.utwente.nl/ws/portalfiles/portal/250328400/Rip1998technological.pdf>. Accessed 18 Sept 2023
- Ruf T, Gilcher M, Udelhoven T, Emmerling C (2021) Implications of bioenergy cropping for soil: remote sensing identification of silage maize cultivation and risk assessment concerning soil erosion and compaction. *Land* 10:128. <https://doi.org/10.3390/land10020128>. Accessed 18 Sept 2023
- Sadet-Bourgeteau S, Maron P-A, Dijon A (2020) Que sait-on vraiment de l'impact des digestats de méthanisation sur la qualité biologique des sols agricoles ? *Rev AES 10-1 Agronomie et méthanisation*:4. https://agronomie.asso.fr/fileadmin/user_upload/revue_aes/aes_vol10_n1_juin_2020/pdf/aes10-1_13_sadet-bourgeteau-et-al.pdf. Accessed 18 Sept 2023
- Sebillotte M (1974) Agronomie et agriculture : essai d'analyse des tâches de l'agronome. *Cahiers de l'ORSTOM* 24:3–25. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_4/biologie/17681.pdf. Accessed 18 Sept 2023
- Severin M, Fuß R, Well R et al (2016) Greenhouse gas emissions after application of digestate: short-term effects of nitrification inhibitor and application technique effects. *Arch Agron Soil Sci* 62:1007–1020. <https://doi.org/10.1080/03650340.2015.1110575>
- Siegmeier T, Blumenstein B, Möller D (2015) Farm biogas production in organic agriculture: system implications. *Agric Syst* 139:196–209. <https://doi.org/10.1016/j.agsy.2015.07.006>
- Solagro (2018) Expertise Agronomique : Résultats de MethaLAE. <https://solagro.org/travaux-et-productions/references/methalae-comment-la-methanisation-peut-etre-un-levier-pour-lagroecologie>. Accessed 9 Oct 2023
- SOLAGRO –, AILE, TRAME et al (2018) La méthanisation, levier de l'agroécologie ? In: Solagro. <https://solagro.org/travaux-et-productions/references/methalae-comment-la-methanisation-peut-etre-un-levier-pour-lagroecologie>. Accessed 18 Sept 2023
- Stinner PW (2015) The use of legumes as a biogas substrate - potentials for saving energy and reducing greenhouse gas emissions through symbiotic nitrogen fixation. *Energy Sustain Soc* 5:4. <https://doi.org/10.1186/s13705-015-0034-z>
- Stinner PW, Deuker A, Schmalfuß T et al (2018) Perennial and intercrop legumes as energy crops for biogas production. In: Meena RS, Das A, Yadav GS, Lal R (eds) *Legumes for soil health and sustainable management*. Springer, Singapore, pp 139–171. https://doi.org/10.1007/978-981-13-0253-4_5
- Szerencsits M, Weinberger C, Kuderna M et al (2015) Biogas from cover crops and field residues: effects on soil, water, climate and ecological footprint. *Int J Environ Ecol Eng* 9:4. <https://doi.org/10.5281/zenodo.1126493>
- Toffolini Q, Jeuffroy M-H, Mischler P et al (2017) Farmers' use of fundamental knowledge to re-design their cropping systems: situated contextualisation processes. *NJAS Wagening J Life Sci* 80:37–47. <https://doi.org/10.1016/j.njas.2016.11.004>
- van Midden C, Harris J, Shaw L et al (2023) The impact of anaerobic digestate on soil life: a review. *Appl Soil Ecol* 191:105066. <https://doi.org/10.1016/j.apsoil.2023.105066>
- Vaneekhaute C, Styles D, Prade T et al (2018) Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: a multi-dimensional sustainability assessment. *Resour Conserv Recycl* 136:110–117. <https://doi.org/10.1016/j.resconrec.2018.03.027>
- Vergara F, Lakes T (2019) Maizification of the landscape for biogas production? *Humboldt-Univ Zu Berl*. <https://doi.org/10.18452/20977>
- Wangel J (2011) Exploring social structures and agency in backcasting studies for sustainable development. *Technol Forecast Soc Change* 78:872–882. <https://doi.org/10.1016/j.techfore.2011.03.007>
- Zahm F, Ugaglia AA, Barbier J-M, Boureau H (2018) Evaluating sustainability of farms: introducing a new conceptual framework based on three dimensions and five key properties relating to the sustainability of agriculture. The IDEA method version 4. 13th Eur IFSA Symp "Farming Syst Facing Uncertainties Enhancing Oppor 20. <https://hal.science/hal-01851634/>. Accessed 18 Sept 2023

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