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To cite this version:

Florent Levavasseur, Lucie Martin, Léa Boros, Jeanne Cadiou, Marco Carozzi, et al.. Land cover changes with the development of anaerobic digestion for biogas production in France. Global Change Biology - Bioenergy, 2023, 15 (5), pp.630-641. 10.1111/gcbb.13042 . hal-03996734

HAL Id: hal-03996734
https://hal.inrae.fr/hal-03996734v1

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Received: 7 October 2022 | Accepted: 1 February 2023

DOI: 10.1111/gcbb.13042

RESEARCH ARTICLE

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access WILEY

Land cover changes with the development of anaerobic digestion for biogas production in France

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Funding information
C-BASC

Abstract

Anaerobic digestion is developing in various countries worldwide to produce renewable energy. In addition, the resulting digestates provide readily available nutrients when applied to cropping systems as fertilizers. The introduction of a biogas plant on a farm can induce land cover changes, in relation to the production of feedstock for the biogas plant and/or to the modification of the farming system. The aim of this study was therefore to characterize and quantify the land cover changes in farms associated with biogas plants in France. We combined two national spatialized databases: the Land Parcel Identification System (yearly French land cover at the parcel scale with farm identifier per parcel) and the SINOE database (biogas plant location and year of start-up). We showed that, on average, the changes were limited, with an increase in maize areas (+3.4% of the total farm areas) compensated by a decrease in wheat and rapeseed areas (−1.8% and −1.9%, respectively), but with a certain variability. The French regulation and market limiting the use of dedicated energy crops seems to have limited land cover changes in France compared to other countries. However, we elaborated a typology of land cover changes and characterized five clusters of farms across the country. The main one (67% of the farms) corresponded to unchanged land cover after the introduction of a biogas plant. The four other clusters showed contrasting changes, for example, an increase or a decrease in grassland areas, a strong increase in maize areas, or a replacement of winter wheat by winter barley. The diversity and the driving factors behind these changes deserve to be better studied and understood through further farmer surveys.

KEYWORDS

anaerobic digestion, biogas plant, cover crop, energy crop, land cover

Résumé

La méthanisation se développe dans différents pays du monde pour produire de l'énergie renouvelable. Les digestats résultants fournissent des nutriments

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facilement disponibles lorsqu'ils sont valorisés en agriculture. L'introduction d'un méthaniseur dans une exploitation agricole peut induire des changements d'assolement, du fait de la production de matières premières pour la méthanisation et/ou de la modification de son système de production. L'objectif de cette étude était donc de caractériser et de quantifier les changements d'assolement dans les exploitations agricoles associées à des méthaniseurs en France. Nous avons combiné deux bases de données nationales spatialisées: le registre parcellaire graphique (assolement annuel du territoire français à l'échelle de la parcelle avec identifiant d'exploitation par parcelle) et la base de données SINOE (localisation du méthaniseur et année de mise en service). Nous avons montré qu'en moyenne, les changements étaient limités avec une augmentation des surfaces en maïs (+3.4% de la SAU des exploitations) compensée par une diminution des surfaces en blé et colza (−1.8% et −1.9%, respectivement), mais avec une certaine variabilité. La réglementation et le marché français limitant l'utilisation de cultures énergétiques dédiées semblent donc avoir limité les changements d'assolement en France par rapport à d'autres pays. Cependant, nous avons élaboré une typologie des changements d'occupation du sol et caractérisé cinq groupes d'exploitations agricoles à travers le pays. Le principal groupe (67% des fermes) correspond à un assolement inchangé après l'introduction d'un méthaniseur. Les quatre autres groupes ont montré des changements contrastés, par exemple, une augmentation ou une diminution des surfaces en prairies, une forte augmentation des surfaces de maïs, ou un remplacement du blé d'hiver par l'orge d'hiver. La diversité et les déterminants de ces changements méritent d'être mieux étudiés et compris grâce à de nouvelles enquêtes auprès des agriculteurs.

1 | INTRODUCTION

Anaerobic digestion is growing rapidly in various areas worldwide to produce renewable energy. The byproducts resulting from anaerobic digestion, digestates, assume interesting perspectives in crop production, given their ability to provide readily available nutrients when applied as fertilizers. A variety of wastes and byproducts can be digested, for example, livestock solid and liquid manures, wastes from agro-industries, sewage sludge and food wastes. Energy crops (e.g., Herrmann, 2013) or energy cover crops (Launay et al., 2022) can also be used as input biomass. Maize is the main energy crop for biogas production thanks to its high potential of dry matter and biogas yield (Herrmann, 2013). In Germany, the development of anaerobic digestion was mainly based on silage maize as a main crop, which led to an increase in continuous silage maize areas and a decrease in grassland areas (Lüker-Jans et al., 2017; Vergara & Lakes, 2019; Yang et al., 2021). The conversion of grasslands to croplands is known to have adverse environmental impacts, such as soil carbon losses (Tang et al., 2019) or reduced biodiversity (Lark et al., 2020), while the reduced diversity of crop rotations undermines a key feature in agroecology (Wezel et al., 2014). Additionally, the introduction of dedicated energy crops may completely negate the environmental interest of anaerobic digestion due to the indirect land use changes associated with a deviation from food production (Britz & Delzeit, 2013; Styles et al., 2015). This may also impact global agricultural markets in prices and production amounts (Britz & Delzeit, 2013).

In France, anaerobic digestion developed later than in Germany, mainly since the 2010s. Very few data exist on the feedstock of biogas plants, although livestock effluents are the main ones (Salmon, 2021) with important regional disparities. The introduction of the main crops in the biogas plant is limited yearly to a maximum of 15% (of the total fresh weight of feedstock) (Code de l'environnement, article D543-292) for biogas plants built after 2017. Additionally, these main crops do not yield subsidies to the plant as livestock effluents do. The exact quantity of the main crops used in biogas plants is, however, uncertain, as is the induced effect on land cover changes (Salmon, 2021). Contrary to the use of main crops, the use of energy cover crops, inserted between two main crops, is not limited in France and offers subsidies to biogas

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plants (despite a regulation rapidly changing). Therefore, energy cover crops are another important feedstock for biogas plants in France (Salmon, 2021). To maximize the introduction of energy cover crops, farmers can modify their crop rotation by favoring main crops with shorter cultivation periods (e.g., maize) to increase the cultivation period of energy cover crops and their biomass production (Carton et al., 2022). Finally, the introduction of a biogas plant in a farm could also lead to changes in its farming system (e.g., intensification of breeding activity) (Carrosio, 2014), possibly leading to further land cover changes. Accordingly, some questions arose about the land cover changes caused by the recent development of anaerobic digestion in France.

In the 2000s, the Land Parcel Identification System (LPIS) was set up in Europe, describing land cover at the parcel scale with a yearly update (Commission Regulation (EC) No 1122/2009, 2009). LPIS has already been used by various authors to study agricultural landscapes and land cover changes (Levavasseur et al., 2016; Zimmermann et al., 2016). Lüker-Jans et al. (2017) successfully used LPIS to study the land cover changes related to the development of anaerobic digestion in Germany. Because of the importance of land cover changes in the environmental assessment of anaerobic digestion and the differences in the management and regulations of anaerobic digestion between Germany and France (dedicated crops versus various feedstocks), there is an interest in using LPIS data to study the land cover changes following the development of anaerobic digestion in France. The objective of this study was to characterize and quantify the land cover changes in farms associated with biogas plants in France. Our hypothesis was that the French regulation restrained these land cover changes and therefore the competition with food production.

2 | MATERIALS AND METHODS

2.1 | Spatialized database used

2.1.1 | French LPIS data

LPIS data are used to manage European agriculture subsidies (Levavasseur et al., 2016). In France, LPIS with farm identifiers is available yearly from 2007, but the data format changed in 2015. From 2007 to 2014, the reference unit was the block (one or several agricultural parcels cultivated by a single farmer), and the land cover was described in a nomenclature of 28 groups of crops (e.g., "maize", which included silage and grain maize, or "barley", which included spring and winter barley). An anonymous farm identifier was given to each block, but the farm identifier changed each year. Since 2015, the reference unit has been the agricultural parcel, and the land cover is described in a nomenclature of more than 300 crops. The anonymous farm identifier remains unchanged every year. Both before and after 2014, the land cover data exhaustively described only the main crops, not the cover crops. For simplification purposes, we included fodder crops (except silage maize) in the temporary grasslands (i.e., grasslands of less than 5 years) because the distinction was not clear in French LPIS data.

2.1.2 | The SINOE database on biogas plants

We used the SINOE database (Ademe, 2022), built by Ademe, the French national agency for the ecological transition, which represented the biogas plants in activity in France. The database was downloaded in July 2022 and contained 1309 biogas plants with their location (latitude and longitude). The available information indicates whether the biogas plants are managed by one or more farms (without providing any details that allow the direct identification of the farm), by agro-industries, waste water treatment plants or others. In our study, we focused on the 895 biogas plants managed by farms and for which it was possible to establish by geospatial methods the relationship between the location of the biogas plant and at least one farm (see Section 2.2). The location of each biogas plant was checked manually with the help of aerial photography and was corrected if needed. The start-up year of each biogas plant was also obtained from the SINOE database. The number of biogas plants strongly increased first in 2012 and then in 2018 (Figure S1). This corresponded to the implementation of various regulations favoring the development of anaerobic digestion, first with cogeneration and then with gas injection (Berthe et al., 2022).

2.2 | Identification of a farm associated with each biogas plant

To identify a farm associated with a biogas plant, we used the farm identifier associated with each parcel of the LPIS data (or with a block for LPIS before 2015). We looked to which farm a specific parcel associated with the biogas plant belonged. This parcel could be (Figure 1):

1. The parcel on which the biogas plant was located in the LPIS data
   a. in the year of the biogas plant start-up, or the following years (and therefore declared as nonagricultural areas in LPIS),

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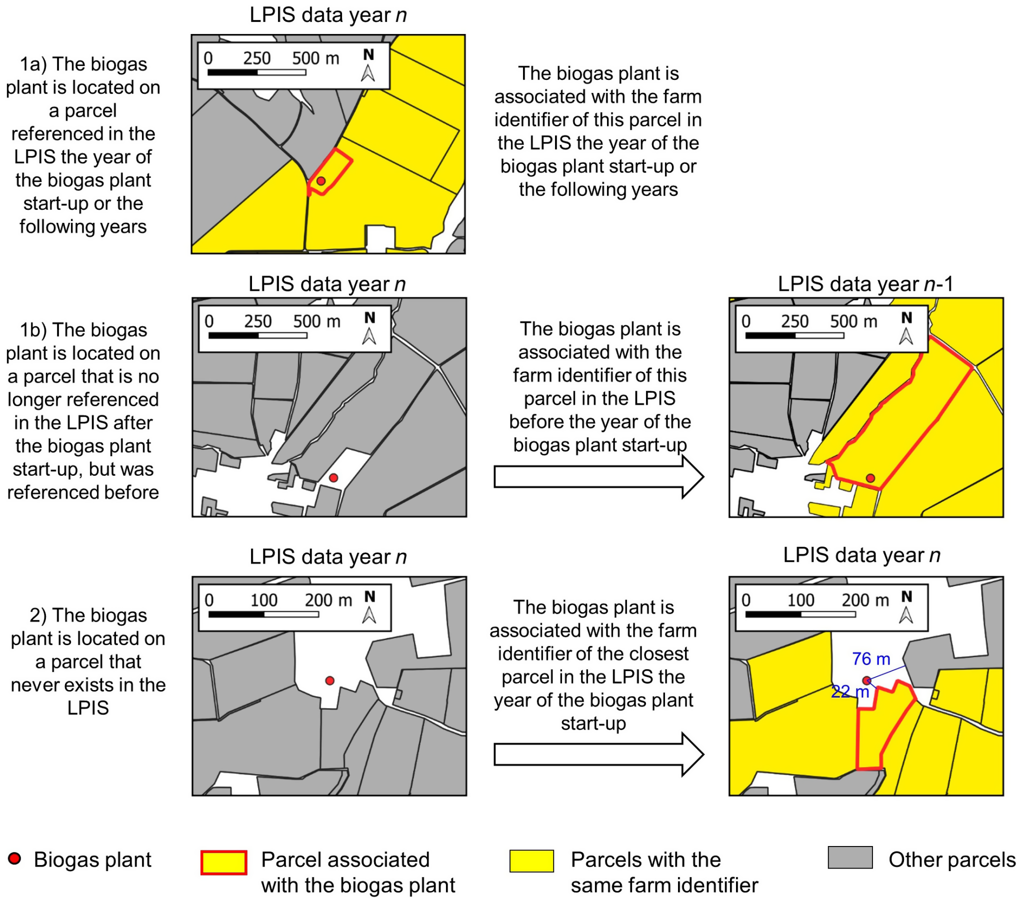

FIGURE 1 Principles of the three methods for the identification of the farm associated with a biogas plant with LPIS data. LPIS, Land Parcel Identification System.

b. in the years before biogas plant start-up in the case that the parcel no longer existed in the LPIS after biogas plant start-up.

2. The closest parcel in the LPIS data in the year of biogas plant start-up if no parcel was ever present at the biogas plant location. This last approach is considered more uncertain than the others, since a biogas plant can be built next to a farm not associated with it. Therefore, we applied a circular buffer of 200 m radius around the biogas plant location, and we validated the selected farm only if more than 70% of the area located in this buffer belonged to the same farm. These thresholds (200 m radius, 70%) allowed a good compromise between the number of farms identified and the error rate generated by the identification of farms when this method was applied on the farms identified with the abovementioned methods (Figure S2).

In reality, several farms can manage one biogas plant. However, with our method based on a spatial intersection, we were only able to identify a single farm per biogas plant. We address this limitation in the discussion (Section 4.1).

2.3 | Computation of the land cover changes for the farms associated with biogas plants and in their surroundings

We compared the differences in land cover between two periods considered before and after biogas plant start-up. The period before was defined as the fourth, third and second years before the start-up. We did not consider the year just before the start-up because we noticed that some farms began to modify their land cover the year before, probably to make stocks of energy crops or energy cover crops. The period after was defined as the start-up year and the two subsequent years. Three years for each period were selected as a compromise between the representativeness of land cover data and the number of farms that could be studied (a longer period would imply to remove many farms with a too recent set-up of the biogas plant).

We retrieved the land cover of each farm associated with a biogas plant from LPIS data for both periods, before and after the start-up. To do so and for each farm, we intersected the LPIS data of the years for which we wanted to retrieve land cover with the LPIS data of the year the farm was identified. The farm that intersected

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more than 50% of the farm of the LPIS data the year of farm identification was considered the same farm. If less than 50% of the farm areas were in common between the 2 years, we considered that we could not identify the farm throughout the considered period, and the farm and the biogas plant were removed from our study. Once the farm identified each year of the considered periods, we retrieved its land cover. Finally, we computed the mean land cover of each farm (in % of the total farm area) for the period before and after the start-up of the biogas plant (average over 3 years), as well as Shannon's diversity index.

To account for changes not driven by biogas plants, we compared the land cover in each farm associated with a biogas plant to the land cover in a "control" surrounding area with a similar agricultural activity during the same period. To define the control surrounding areas with a similar agricultural activity, we used the homogenous agricultural areas ("régions agricoles") defined by the French Ministry of Agriculture according to the main agricultural activities, soils, climate and relief. The homogenous agricultural areas considered in our study had a mean area equal to 170×10^3 ha (standard deviation equal to 157×10^3 ha). In the case of a farm belonging to several homogenous agricultural areas, we computed the land cover in the control surrounding area by weighting the land cover in each homogenous agricultural area with the proportion of the farm area located in each homogenous agricultural area. For each biogas plant, we computed the mean land cover in the control surrounding area for the two same periods than for the farm associated with the biogas plant.

Finally, we computed the mean land cover for all the farms associated with biogas plants and for all their control surrounding areas at the French national scale. We also computed it at the NUTS2 scale (the second subdivision of countries according to the European Union nomenclature) to look for spatial heterogeneities.

An analysis of variance (ANOVA) followed by Fisher's least significant difference tests were performed in R 4.1.2 to identify the significant differences ($p\leq0.05$) in crop proportions at the French national scale between all the farms associated with biogas plants and all their control surrounding areas, before and after the biogas plant start-up. ANOVA was also used to test if the changes in crop area proportions after and before biogas plant start-up were significantly different between the farms associated with biogas plants and their control surrounding areas. The effect of farm size (total farm area, computed from LPIS) and biogas plant size (estimated with the yearly maximal amount of feedstock authorized documented in the SINOE database) on the land cover changes were tested with a Kendall rank correlation coefficient (linear model assumptions violated). The effects of NUTS2 unit and of the type of biogas utilization pathway (gas injection or combined heat and power, documented in SINOE) on the land cover changes were tested with a Kruskal-Wallis test.

2.4 | Typology of land cover changes

To identify different patterns in land cover changes among the farms associated with biogas plants, we used *k*-means clustering in R 4.1.2. The number of clusters was defined with the elbow method, which maximized the explained variance as a function of the number of clusters. We used the following descriptive variables for each farm in the clustering: changes in the proportions of wheat, barley, other cereals, maize (grain and silage), rapeseed, permanent grasslands and temporary grasslands between after and before the biogas plant start-up. These crops were selected on the basis of the observed changes at the national scale (see Section 3.2) or because of their high proportion in farm areas.

3 | RESULTS

3.1 | Farms associated with biogas plants

Over the 895 biogas plants associated with one or several farms, we removed four plants because their exact location could not be validated (uncertainty in latitude and/or longitude). We removed three duplicated plants. We removed four plants because the start-up year could not be found in the SINOE database. We removed 469 plants because they started too early (before 2011) or too late (after 2018) with regard to available LPIS data. We removed seven plants because the identification of the associated farm over years could not be ensured (major changes in farm areas over years). We removed five plants because of issues in the LPIS data. We removed 11 plants because the closest farm did not respect the threshold of 70% of farm area in the surrounding 200 m (see third identification method, Section 2.2). We also excluded 13 farms with a total area of less than 40 ha, as they presumably corresponded to unrepresentative fractions of the land cover of the actual farms, which were represented by several administrative farms in the LPIS data. Finally, 379 biogas plants were associated with a farm for all the years examined.

The mean area of the farms associated with the biogas plants was equal to 245 ha. This area was more than double the average area of the farms in the control surroundings, which was 100 ha. It was also higher than the mean area of all French farms and of French cereal or

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dairy cattle farms (69, 96 and 106 ha in 2020, respectively) (Barry & Polvêche, 2021).

3.2 | Land cover changes at the national scale

At the national scale before the biogas plant start-ups, the main significant difference between farms associated with biogas plants and their control surrounding area was a higher proportion of maize area (21% and 15%, respectively) (Figure 2; Table S1). After the biogas plant start-up, a significant increase in maize area proportions (+3.4% of the total farm areas), a non-significant decrease in wheat area (−1.9% of the total farm areas) and a significant decrease in rapeseed area (−1.8% of the total farm areas) proportions were observed in the farms associated with biogas plants, whereas these proportions remained almost stable in the control surrounding areas (0.0%, +0.1% and −0.2% for maize, wheat and rapeseed, respectively). The mean proportion of grassland area, considering both permanent and temporary grasslands together, remained unchanged after the biogas plant start-up both in the farms associated with biogas plants and their surrounding areas. However, we observed both in farms associated with biogas plants and in the surrounding areas an increase in permanent grasslands (+1.2% and +2.3%, respectively) compensated by a decrease in temporary grasslands (−1.2% and −2.3%, respectively). No significant changes in the barley area proportion were observed (Table S1). Finally, in addition to these changes in crop proportions, only a very small decrease in Shannon's diversity index was observed in the land cover of the farms associated with a biogas plant (1.49 and 1.46, before and after biogas plant start-up, respectively).

In addition to the mean changes described above, we observed variability depending on the considered farm associated with a biogas plant (Figure 3). The changes in the proportions of maize therefore ranged from −31% to +47% of the total farm areas but more than 70% of the farms showed an increase in maize proportions. Despite the limited mean change in the proportion of permanent grasslands for all farms, their proportion varied from −37% to +37% depending on the farms. The changes were, however, limited between −5% and +7% for three quarters of the farms in most cases. For maize, permanent grassland, wheat, rapeseed and temporary grassland, the changes were significantly different between the farms associated with biogas plants and the control surrounding areas (Figure 3). No significant effects of the farm size on these changes were detected for maize, wheat and barley, while a slight and significant correlation existed for permanent

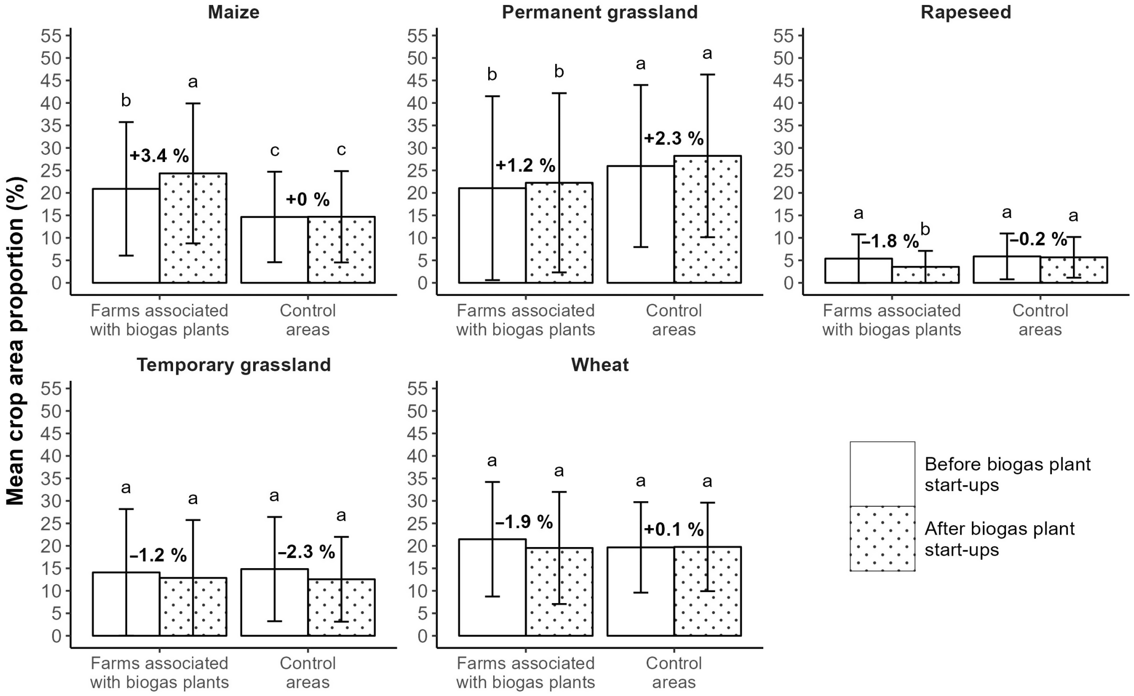

FIGURE 2 Mean crop area proportions of the farms associated with biogas plants and of their surrounding control areas, before and after biogas plant start-ups at the France scale. The area proportions referred to the proportion of farm areas or to the proportion of the surrounding control areas. The figures above the bars indicate the differences between the crop proportions after and before biogas plant start-ups. Error bars represent the standard deviation. Statistically significant differences among treatments are represented by letters ($p \leq 0.05$).

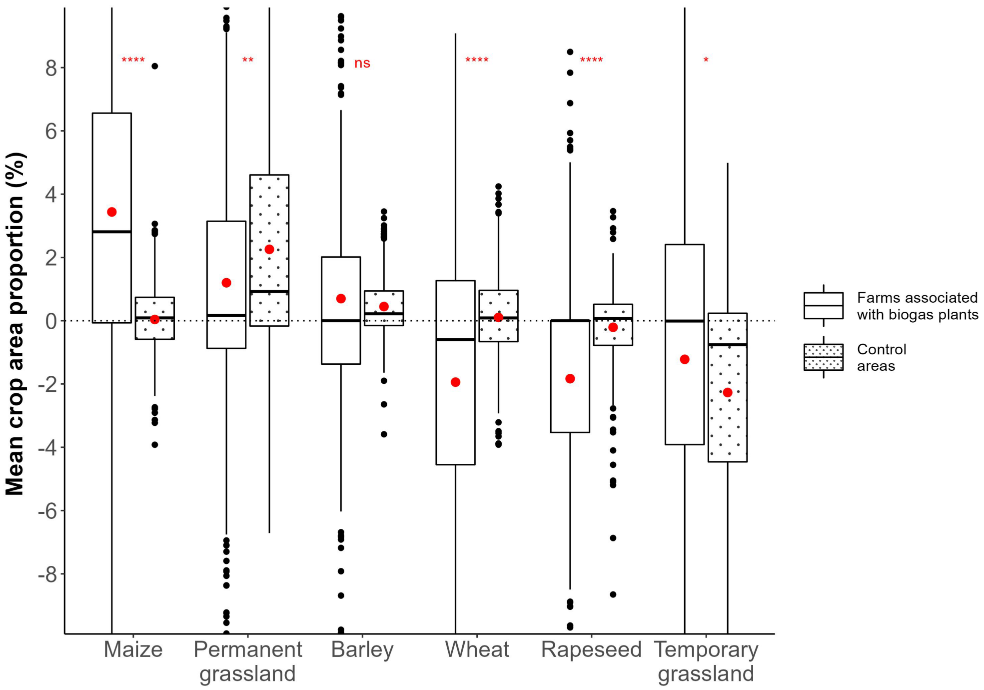

FIGURE 3 Distribution of the difference in crop area proportions per farm associated with a biogas plant after and before biogas plant start-up at the France scale and per control surrounding area. The red points indicate the mean changes. Very few data were higher than 10% or lower than −10%, and the *y*-axis was cut to –10% and +10% to improve visibility. ns: non-significant difference between farms associated with biogas plants and control surrounding areas, *: significant difference ($p \leq 0.05$), **: significant difference ($p \leq 0.01$), ****: significant difference ($p \leq 0.0001$).

grassland, temporary grasslands and rapeseed (equal to −0.08, 0.08 and −0.14, respectively). No significant effects of the biogas plant size on the changes in the proportion of maize, wheat and barley were detected, while a slight and significant correlation existed for permanent grassland, temporary grasslands and rapeseed (equal to −0.09, 0.07 and −0.15, respectively). The biogas plants with gas injection were significantly ($p < 0.05$) associated with a higher increase in the barley proportion and with a higher decrease in the rapeseed proportion (results not shown).

3.3 | Variability of land cover changes at the NUTS2 scale

In addition to the changes at the national scale, some differences emerged between the NUTS2 units (Figure 4). For example, the difference in permanent grassland changes in farms associated with biogas plants compared to those in their control surrounding areas was negative in western and central France (e.g., −2% of total farm areas in Brittany and −8% in Limousin), indicating a slower increase or a stronger decrease in permanent grassland area proportions in farms associated with biogas plants compared to control areas. This difference was almost null or even positive in northern and southwestern France (e.g., +0.4% in Nord-Pas-de-Calais and +2% in Aquitaine), indicating a stable or slight increase in permanent grassland area proportions on the farm with biogas plants compared to control areas. The positive differences for maize and the negative difference for wheat were more homogenously spread over French territory. The Kruskal–Wallis tests indicated a significant effect ($p < 0.05$) of the NUTS2 unit on the changes in permanent grassland, temporary grassland and rapeseed.

3.4 | Typology of land cover changes

We selected five clusters of land cover changes for *k*-means clustering. These five clusters explained 45% of the variance of the dataset (Figure 5). The first cluster included 14 farms (4% of the studied farms) in which the proportion of temporary grassland area increased (+21% of total farm areas), compensated by a decrease in winter wheat, maize, rapeseed, permanent grassland and barley area proportions (−8%, −4%, −4%, −4% and −3%, respectively). The overall proportion of grassland area (temporary and permanent) in this cluster increased (+17%). The second cluster included most of the studied farms (247, 67% of the farms) in which almost no land cover changes occurred. The third cluster included 48 farms (13% of the

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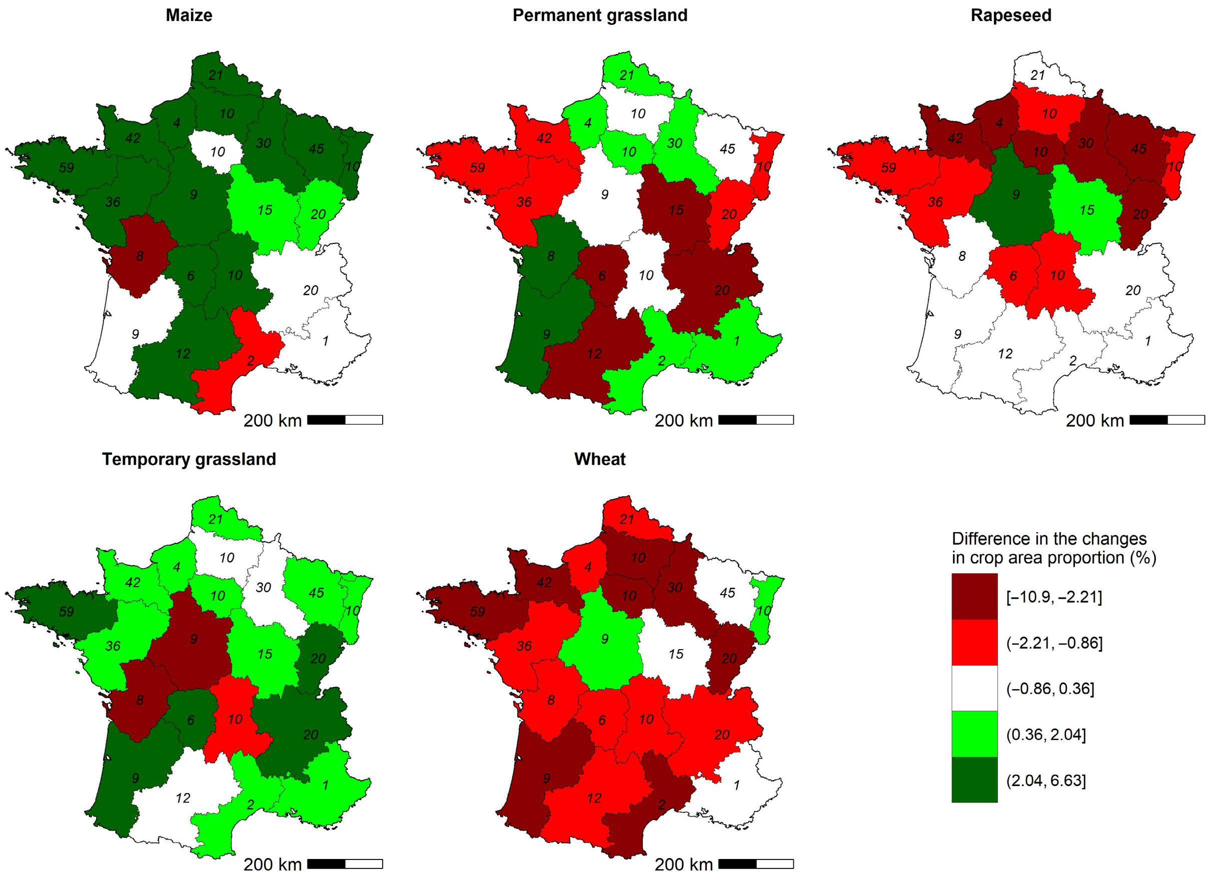

FIGURE 4 Differences between the changes in crop area proportions in farms associated or not with a biogas plant at the NUTS2 scale. Figures inside each NUTS2 unit indicate the number of biogas plants in the NUTS2 unit. The lower and upper limits of the intervals of the color bar corresponded to the minimum, 20th, 40th, 60th and 80th centiles and the maximum of the changes in crop area proportion (all plotted crops together).

farms) in which the proportions of maize and permanent grassland areas increased (+6% and +10%, respectively), compensated by a decrease in temporary grassland area proportion (−17%). The overall proportion of grassland area (temporary and permanent) decreased (−7%). The fourth cluster included 68 farms (18%) in which the maize area proportion increased (+12%), mainly compensated by a decrease in wheat and rapeseed area proportions (−8% and −6%, respectively). Finally, the fifth cluster included only two farms (less than 1% of the farms), with specific and strong land cover changes: a strong increase in barley area proportion (+50%) compensated by a strong decrease in winter wheat area proportion (−42%) and a decrease in rapeseed area proportion (−12%). The geographical distribution of these clusters did not indicate any strong specificity at the NUTS2 scale (results not shown).

The clustering of land cover changes could include some changes not specifically related to the biogas plant but connected with the surrounding control areas. However, when we performed clustering on the differences in land cover changes between the farms associated with a biogas plant and the corresponding surrounding control areas, we obtained almost the same clustering (results not shown). Additionally, a specific clustering of land cover changes observed in the surrounding control areas yielded different clusters with smaller changes (Figure S3), indicating the peculiarity of land cover changes observed in farms associated with biogas plants.

4 | DISCUSSION

4.1 | Interest in national databases to study land cover changes associated with biogas plants

A recent report of the French Senate pointed out the lack of information about land cover changes caused by the development of anaerobic digestion in France (Salmon, 2021). We therefore combined land cover data (LPIS) with data about the location of biogas plants to provide a comprehensive picture of these land cover changes at the national scale. Interest in the use of LPIS data to track land cover changes over time has been highlighted in various

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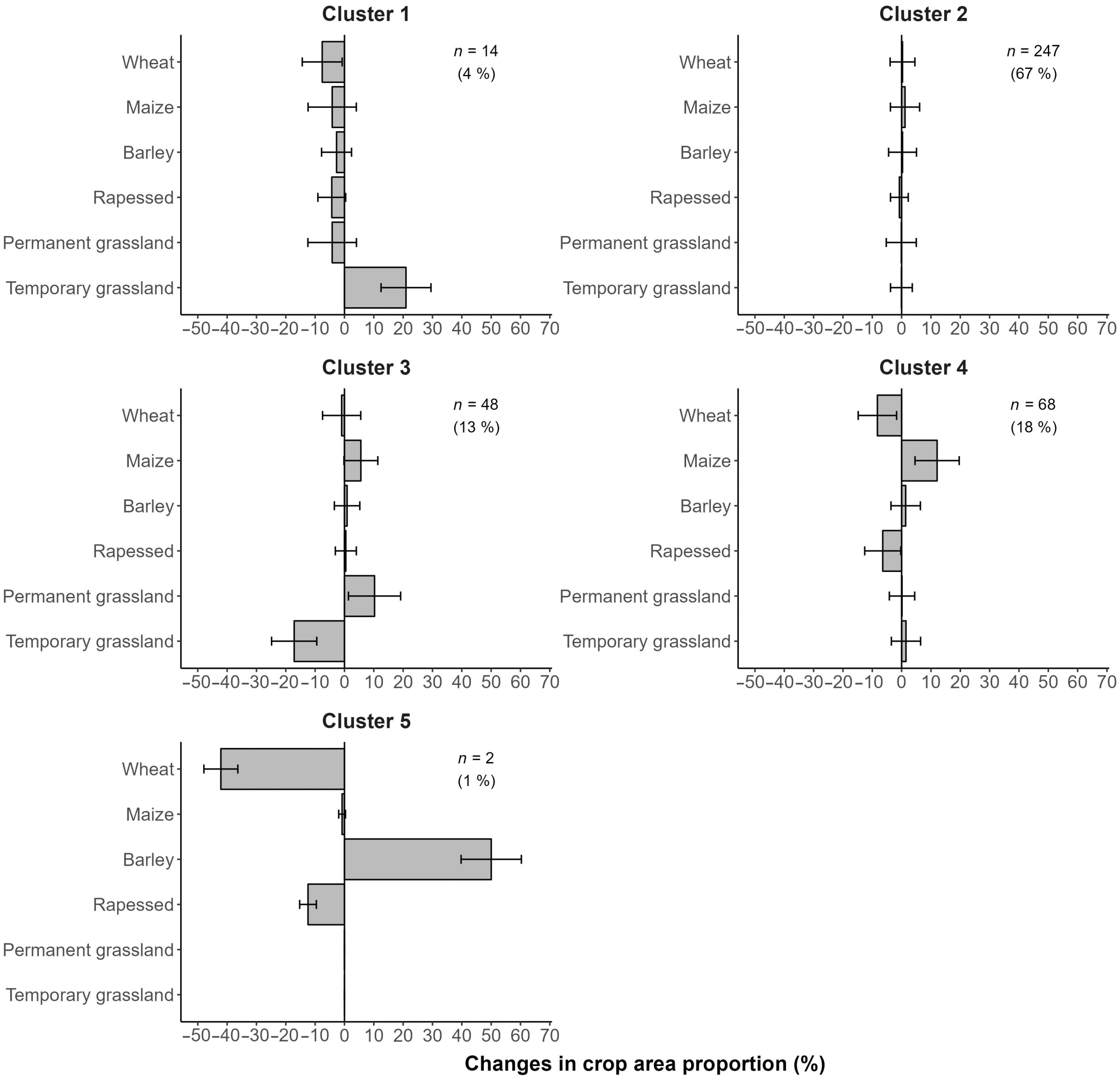

FIGURE 5 Results of the *k*-means clustering of crop area proportion changes in farms associated with biogas plants. For each cluster and each crop, the mean change in crop area proportion (% of the total farm areas) after biogas plant start-up is plotted. Error bars represent the standard deviation.

contexts by several authors (Levavasseur et al., 2016; Zimmermann et al., 2016). Lüker-Jans et al. (2017) used LPIS to track land cover changes caused by the development of anaerobic digestion in Germany at the municipality scale. However, in comparison to their study, we identified the farm areas associated with biogas plants. This allowed us to focus on the changes observed in these farms, regardless of whether these effects were significant at a larger scale. Despite the interest in using the LPIS to characterize land cover, Kerselaers and Levin (2019) highlighted some limits of using these data to track changes in agricultural areas in Flanders and Denmark (e.g., some agricultural land disappearing in the LPIS). However, we did not observe a significant and persistent disappearance of agricultural areas in French LPIS data, except for actual losses of agricultural areas, as pointed out by Levavasseur et al. (2016). On average, the area of the farms associated with biogas plants was constant after biogas plant start-up (mean and standard deviation of relative farm area changes equal to 3% and 18%, respectively). Despite this apparent stability of farm areas, it could be interesting to use LPIS data to track the farm area dynamics following the biogas plant start-up, with the method proposed by Barbottin et al. (2018).

A limitation of our method was to study the land cover changes for a single farm associated with each biogas plant, whereas several farms could be associated with a single biogas plant. No simple method appeared to be able

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to overcome this issue. Farm surveys would be necessary to identify all the farms associated with the biogas plants and to assess the consistency of land cover changes with already studied farms. Some uncertainties also existed in the identification of the farms associated with the biogas plants, for example, if the parcel used to identify the farm changed from the owner just before the biogas plant start-up and when the parcel disappeared from the LPIS (see Section 2.2).

Our method also relied on the comparison between the land cover changes in the farms associated with biogas plants and their surrounding agricultural areas considered as controls This notion of the surrounding area is only meaningful in the case of limited development of anaerobic digestion in homogenous agricultural areas, which we used as surrounding control areas. We considered this to be the case in France, given that the area of farms identified as associated with biogas plants represented only 0.6% on average of homogenous agricultural areas (from 0.0% to 3.8%), but effectively with only a single farm per biogas plant identified. The limited land cover changes observed in these control areas reinforced this idea. If the development of anaerobic digestion occurs in the coming years as it is planned in France, an alternative method would be necessary, as proposed, for example, by Lüker-Jans et al. (2017) (correlation analysis at a larger scale between biogas plant density and land cover changes).

4.2 | Limited land cover changes at a national scale

Our results indicated some specific changes in the land cover of farms associated with biogas plants in comparison to their surroundings. At a national scale, the increase in maize areas in these farms seemed however limited (+3.4% of the total farm areas) in comparison to the increase in maize areas observed at the Hesse Länder scale in Germany by Lüker-Jans et al. (2017) (+2.8% of the Länder area, involving a much higher increase at the scale of the farms associated with biogas plants). However, at a national scale, no decrease in permanent grasslands was observed, again in contrast to the results of Lüker-Jans et al. (2017) in Germany. The land cover changes also seemed limited to what was observed in Italy, the second largest European biogas producer, where energy crops used a total of 3% of the national UAA in 2015 (Bozzetto et al., 2017). Land cover changes in Italy are now estimated to be contained due to the reductions of the feed-in tariffs that took place from 2013 (Bartoli et al., 2016). Additionally, we showed that most of the farms (67%) showed an absence of land cover changes following the biogas plant start-up (in terms of main crops). Our results therefore contrasted with the results obtained in Germany and Italy. This could be related to the maximal amount of dedicated energy crops allowed in the feedstock of biogas plants in France (15%), as well as the lower subsidies for the digestion of dedicated energy crops, which limited the expansion of maize areas and the conversion of grasslands. The limited changes observed in land cover could ensure a better environmental balance of anaerobic digestion and a limited impact on the agricultural market in comparison to the German situation (Britz & Delzeit, 2013). However, the development of energy cover crops, inserted between two main crops, did not directly appear in our study focused on main crops, whereas they can impact the yield of the following crop (Launay et al., 2022) and therefore compete with food production. Additionally, a change in crop use, which does not necessarily translate into a change in land cover (e.g., silage maize used for biogas instead as feed), can still mean productive changes at the farm level in other activities such as livestock production.

4.3 | A diversity of land cover changes calling for further investigation

Although the land cover changes were limited at the national scale, we observed some types of farms and some areas in France for which the differences in land cover changes between the farms associated with biogas plants and their surroundings were stronger (Figures 4 and 5; Figure S3). Despite the regulated limited use of dedicated energy cover crops, it is documented that some farms used them, which could explain a part of the increase in maize areas (Clusters 3 and 4, Figure 5). The non-limited use of energy cover crops cultivated during winter and before summer crops (i.e., mainly maize for food/feed) could also indirectly promote the expansion of maize areas, as documented in the farmer surveys realized by Carton et al. (2022). The introduction of summer energy cover crops (i.e., mainly silage maize for biogas production) could also promote the expansion of winter crop areas with an earlier harvest, as was observed for Cluster 5 with a replacement of winter wheat by winter barley, again as documented in the farmer surveys realized by Carton et al. (2022). Finally, concerning the dynamics of grasslands, we observed two contrasting trends beyond the apparent stability at the national scale. The proportion of permanent grasslands decreased in some farms (Cluster 3, Figure 5), partly replaced by maize. This could possibly be the effect of the use of energy crops, as in Germany (Lüker-Jans et al., 2017; Vergara & Lakes, 2019). In contrast, some farms increased their proportion in grasslands (Cluster 1), possibly because a biogas plant could help to economically

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sustain the breeding activity in a farm and thus the associated grasslands (Demartini et al., 2016).

The variability of land cover changes between farms and NUTS2 units calls for further studies focusing on the understanding of these changes, relative to the agricultural and economic context of each biogas plant and farm, the use of energy crops or cover crops, and others. It would especially be interesting to have a holistic look at the overall transformation of farm activities in relation to the transformation of the crop rotation. The first attempts we made to explain these changes with available variables in LPIS or SINOE (farm size, biogas plant size, biogas utilization pathway) did not yield very promising results. Regarding the farm size, this could be explained by the usual association of several farms of varying size with a single biogas plant and by the diversity of biogas production models in France, which potentially lead to various land cover changes (Berthe et al., 2022). The land cover changes should be studied depending on the type of farming system (arable crops, mixed crop-livestock, etc.). However, LPIS data did not identify the farming system, even if some authors attempted to define it from the proportion of each crop per farm (Piet & Cariou, 2014). The possibility to use ancillary data to refine this analysis should be considered in future studies.

Finally, we focused on two periods before and after the biogas plant start-ups to describe land cover changes. However, the changes described just after the biogas plant start-up could be only transient because farmers progressively adapted to this new activity. We clearly distinguished in the LPIS data some additional changes in land cover more than 3 years after the start-up for some farms (individual results not shown for privacy concerns). This result also calls for further investigation to understand the adaptation of farmers to the introduction of a biogas plant.

5 | CONCLUSION

We showed that the land cover changes induced by the development of anaerobic digestion in France existed but were limited on average. The French regulation and market limiting the use of dedicated energy crops therefore seems to have limited the land cover changes in France in comparison to other countries. This could ensure a better environmental balance of anaerobic digestion regarding this issue. However, a diversity of land cover changes existed between farms and among different areas in France. This diversity calls for further investigation to understand the drivers of these land cover changes. We also recommend checking whether the numerous new biogas plants not included in this study will follow the same trends.

ACKNOWLEDGMENTS

We would like to thank the reviewers for taking the necessary time and effort to review the manuscript, which helped us to improve the quality of the manuscript. We thank C-BASC for partial funding of this work.

FUNDING INFORMATION

This work was partly funded by the Center for Interdisciplinary Studies on Biodiversity, Agroecology, Society and Climate (C-BASC).

CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or nonfinancial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available: (i) in the SINOE database for biogas plant location: https://eci-sig.ademe.fr/adws/app/bb11ce07-5cc9-11eb-a8fe-7dd6c4f9bb1d/index.html; (ii) on the Open platform for French public data for the LPIS data (LPIS version without farm identifier, the version with farm identifier has restricted access for privacy concerns): https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-culturaux-et-leur-groupe-de-cultures-majoritaire/; (iii) on the Agreste website for "régions agricoles" (RA) limits: https://agreste.agriculture.gouv.fr/agreste-web/methodon/Z.1/!searchurl/listeTypeMethodon/.

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How to cite this article: Levavasseur, F., Martin, L., Boros, L., Cadiou, J., Carozzi, M., Martin, P., & Houot, S. (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

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