From Residues to Revenue: Biogas Plant Installation and Agricultural Outcomes in France

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Abstract

We evaluate the impact of the installation of biogas units in France between 2015 and 2023 using a staggered difference-in-differences design. To address the endogenous location of biogas plants, identification relies on comparisons between treated and not-yet-treated areas within a local geographic window, using estimators robust to treatment effect heterogeneity over time, with no evidence of differential pre-treatment trends. Our preliminary results corroborate findings from the agronomy literature: the introduction of biogas units leads to a reallocation of crops toward short-term sequential and high-methanogenic crops, at the expense of longer-term crops.

These initial findings, combined with the recent authorization[1] granted by the French National Statistical Confidentiality Committee to access detailed administrative data (from January 15th), will allow us to deliver definitive results on other key economic and environmental dimensions of biogas deployment, including farmers' income, fertilizer use, and pesticide use within the circular economy framework. We plan to present the full results at RIEF 2026.

Keywords: Biogas, Circular economy, Crop allocation, Staggered difference-in-differences, Agriculture, Environmental policy

JEL classification: Q18, C23, Q53, Q58

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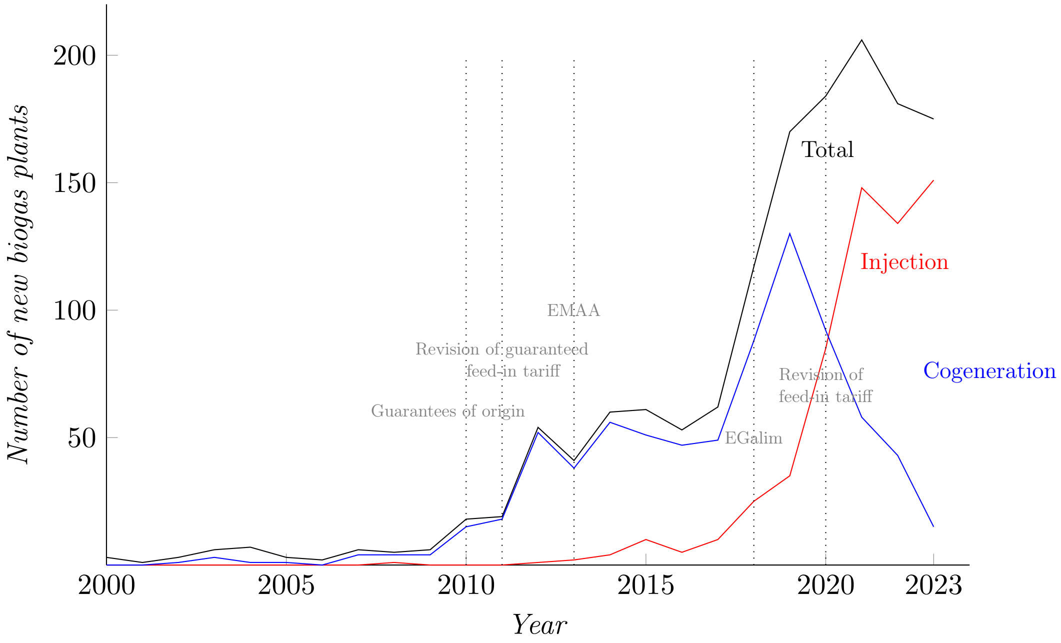
[1] The project received authorization under the name "Développement des unités de méthanisation : analyse quantitative des effets sur les pratiques et les revenus agricoles" and is referenced on the CASD website.

1 Introduction

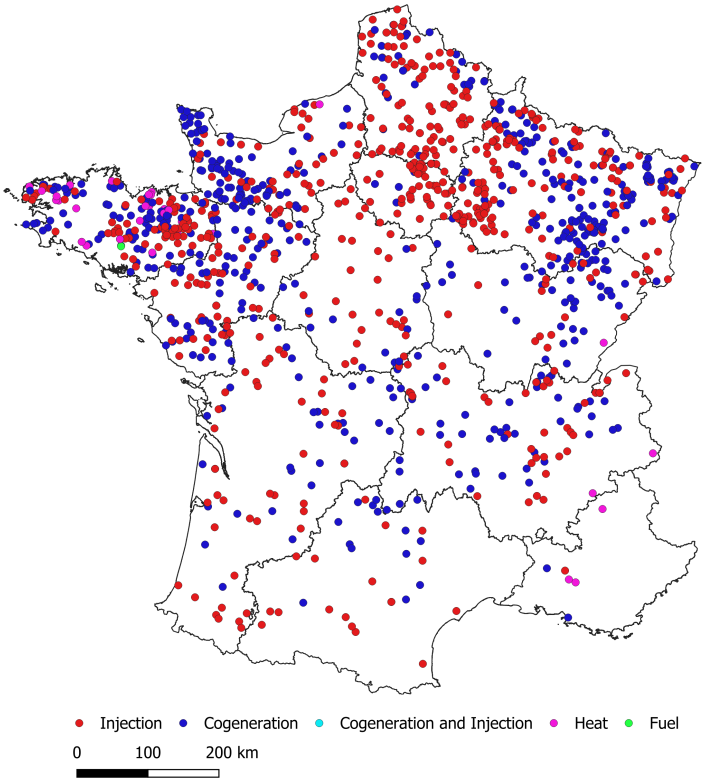
Biogas development is a cornerstone of two key strategies. First, it supports the European Union's and France's ambition to scale up biogas production through anaerobic digestion, aiming to meet climate objectives within the energy mix. Second, it strengthens circular economy practices in the agricultural sector, enhancing resilience to economic and environmental challenges. As a result, the French Ministry of Ecological Transition implemented a mix of policies to strongly incentivize the deployment of biomethane units across France between 2010 and 2023, as illustrated in Figure 1 and Figure 2.

Figure 1: The rise of biogas plants in Metropolitan France, 2000–2023



Note: This figure shows the overall evolution in the number of new biogas plants between 2000 and 2023. The y-axis indicates the annual number of newly established plants. The total includes both injection units – the end-use is the production of gas– (red line), cogeneration units –the end-use is the production of electricity and heat– (blue line) and other type of plants as fuel and heater that account for a small number. Key national policies likely to have influenced plant establishment decisions—such as the introduction of Guarantees of Origin (2010), the revision of feed-in tariffs (2011 and 2020), the *Énergie Méthanisation Autonomie Azote* (EMAA) plan (2013), and the EGalim law (2018)—are marked with vertical dotted lines.
Source: Authors' calculations based on SINOE data (including only plants with a non-missing establishment date).

Figure 2: Geographic distribution of biogas units by type of valorization 2015-2023



To evaluate the causal impact of this blooming trend of biogas development we construct a panel between 2015-2023 combining three core databases : SINOE (biogas installation), RGPD (crop allocation) and CASD (farmers revenue, fertilizer and pesticide expenditures). Using temporal and spatial distribution we build a staggered design with local areas from 1.5km to 15km radius.[2] Our identification strategy hinges on comparing treated areas, where biogas plants are installed, with a control group of not-yet-treated areas. We show that the introduction of such units affects the allocation choice of farmers. First they tend to adopt more sequential cropping strategy by using intermediate crop within the same season to produce more residues to fuel biogas unit. The economic value of such a sequential strategy is explained by the economy of double crops within the same land exceeds traditional rotation. Symmetrically, long-cycle crops are declining because of

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[2] Although public aid programs allow biogas units to source up to 90% of their raw materials within a maximum radius of 40 km (Cour des comptes, 2025), this regulatory limit should be interpreted as an upper limit rather than an economically relevant supply radius. In practice, the marginal cost of transporting agricultural inputs increases rapidly with distance. Economic interactions between plants and farmers are concentrated in a much smaller area. We therefore limit our analysis to a 15 km radius, which corresponds to the area where supply relationships are most likely to be activated and where farmers face credible economic incentives to participate (Commission de Régulation de l’Énergie, 2024).

this sequential strategy. Second it favors the reallocation toward high-methanogenic crops. These findings corroborate results found in agronomy literature.

These preliminary results provide a strong rationale for expanding our analysis using datasets of similar granularity. Building on recent authorization from France's National Statistical Confidentiality Committee to access micro-level data, we will apply the same methodological framework. Circular and environmental economics provide a framework for assessing (i) the economic impact on farmer revenues and (ii) the environmental implications of fertilizer and pesticide expenditures. Results will be available by RIEF 2026.

We contribute to the agronomic literature assessing the impact of biogas units installations on crop allocation. Existing studies consistently show a shift toward short-term, high-yield crops such as maize to supply methanizers, at the expense of long-term crops like rapeseed (Boros, Carozzi, et al., 2025; Boros, Martin, et al., 2025; Britz & Delzeit, 2013; Levavasseur et al., 2023). While previous studies focus on regional analyses of biogas plant owners, our work adopts a national perspective and additionally accounts for potential spillover effects on local agricultural land. Furthermore, we quantify two key aspects: the extent to which nutrient-rich digestate reduces synthetic fertilizer purchases, and how crop reallocation affects pesticide expenditures. This second point is particularly relevant, as pesticide purchases in France are strongly correlated with actual pesticide use (Bareille, Chakir, & Keles, 2024).

Second, our paper contributes to the literature on the social acceptability of biogas units. Existing studies highlight the adverse effects of these facilities, such as reduced nearby property values (Faulques, Bonnet, & Bourdin, 2025; Hoffmann, Gangadhar, & Müsgens, 2025) and decreased household well-being due to negative externalities (Krekel, Rechlitz, Rode, & Zerrahn, 2021). Our analysis assesses the private and environmental benefits that are critical to understanding their overall acceptability. This is especially important in the last decade, where farmers' income and resilience have become a major societal and political concern in France and Europe.

Finally we contribute to the literature assessing the economic impact of biogas units. In this vein, Valve, Lazarevic, and Humalisto (2021) qualitatively assess different types of biogas business models and insist on capturing secondary resources to preserve the circular benefits of such plants. In a recent report, La Cour des comptes (2025) presents evidence of a positive effect of the installation of biogas units on economic performance and resilience of owners and nearby farmers. We extend these results providing quantitative heterogeneous analysis on the type of exploitation and potential agricultural inputs to produce biogas.

The rest of the paper proceeds as follows: we begin by presenting the perspectives and context of biogas in France in section 2. Next, we describe in section 3 the data and key variables used in our analysis. The empirical strategy is outlined in section 4, followed by the presentation of our main results in section 5. Finally, section 6 concludes.

2 Biogas Production in France: Perspectives and Context

2.1 The Role of Biogas Plants in the Energy Transition

A biogas plant is defined as a technical facility that enables the recovery of residual organic matter, such as livestock effluents, crop residues, and biowaste, through anaerobic digestion. This biological process, carried out in an anoxic environment, produces biogas containing methane, a renewable energy source that can be used for combined heat and power generation or upgraded into biomethane for injection into the gas grid.

Biogas plants have the potential to contribute to greenhouse gas emissions reduction, improve energy security, increase the generation of decentralized renewable electricity and heat, and strengthen adherence to the principles of proximity and self-sufficiency in waste treatment, energy production, and resource use. In particular, methane has a global warming potential approximately 25 times higher than that of CO_2, and a substantial share of methane emissions originates from anthropogenic sources such as agriculture and waste management. Capturing methane through biogas production therefore prevents its direct release into the atmosphere, contributing to climate change mitigation (Nevzorova & Karakaya, 2020). As a result, the adoption of biogas plants is expected to play a role in reducing net greenhouse gas emissions.

The development of biogas production is closely linked to broader renewable energy policies. In the context of the European Union's objective of achieving net-zero emissions by 2050, the EU has set a target of sourcing 42.5% of its energy consumption from renewable sources by 2030.[3] France remains below its national renewable energy target (reaching 22.3% in 2023 compared with a 23% target for 2020[4]), partly due to its high reliance on nuclear power and highlights further efforts required in developing this energy source. In this context, biogas remains relatively underexploited

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[3] This trend has been reinforced by the European Commission's objective to double biogas production from agricultural waste under the REPowerEU plan launched in 2022, aimed at reducing energy dependence on Russia.

[4] https://www.statistiques.developpement-durable.gouv.fr/les-energies-renouvelables-en-france-en-2023-dans-le-cadre-du-suivi-de-la-directive-ue-20182001-0

despite its significant technical potential (International Energy Agency, 2025).

2.2 Biogas plants, circular economy, and resilience of the agricultural sector

By using waste as production inputs, biogas plants contribute to waste valorization and offer farmers opportunities for activity diversification (Cour des comptes, 2025). In France, most biogas plants are owned or co-owned by farmers (see Figure 7).[5] Given that agricultural revenues are highly exposed to weather-related shocks—and that these shocks are expected to intensify under climate change—a revenue stream partially based on waste processing rather than solely on crop production may enhance income stability. In addition to energy production, biogas plants generate a co-product known as digestate. Digestate can be used as an organic fertilizer, thereby partially substituting mineral fertilizers and contributing to nutrient recycling.

Waste management is a central determinant of project feasibility and performance. Livestock effluents, intermediate energy crops and crop residues constitute the three main categories of feedstock. Local sourcing of inputs is particularly important and constitutes a mandatory condition for eligibility for public subsidies in France (ADEME, 2013).

Table 1: Source: ADEME's 2050 trend scenario (Faulques, 2024)

	Mobilizable raw material	Primary energy potential (TWh)
Livestock effluents	41%	27%
Intermediate energy crops	32%	34%
Crop residues	10%	16%
Grassland	8%	9%
Energy crops	6%	7%
Household waste	2%	4%
Agri-food industries	1%	3%

Table 1 presents aggregate national trends but masks substantial regional heterogeneity. Livestock-intensive regions such as Bretagne, Normandie, Pays de la Loire, and Hauts-de-France stand out due to their high availability of animal manure, making them particularly suitable for biogas production. In contrast, cereal-producing regions in the North and East rely predominantly on crop residues as feedstock.

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[5] The classification of actors follows the literature Bourdin, Condor, Fournès, & Tessier, 2025; Röder, 2016.

2.3 The expansion of biogas plants in France over the last decade

The rapid expansion of biogas plants in France over the last decade has been strongly supported by national public policies. These policies originate from two main objectives: energy security and climate change mitigation. As shown in Figure 1, two primary policy instruments have driven the diffusion of biogas plants: feed-in tariffs, which secure output prices for producers, and investment subsidies supporting plant construction (notably under the EMAA and EGalim frameworks).

Investment subsidies are administered by ADEME, which also provides technical guidance and project support.[6] These subsidies are notably conditioned on limiting the use of dedicated energy crops[7] and on encouraging local sourcing of feedstock.[8] While most biogas plants were commissioned during the last decade, the recent reduction in financial support helps explain the slowdown observed at the end of the period. However, this overall trend conceals a deliberate policy-driven divergence between technologies: biomethane injection plants have continued to expand, whereas cogeneration units have progressively declined. This divergence reflects a deliberate reorientation of public policy in favour of biomethane injection. Cogeneration units are structurally constrained by a low electrical efficiency (around 35%) meaning that only a limited share of the biogas energy content is converted into electricity, with frequent losses when heat is not fully recovered. In contrast, biomethane injection enables the near-complete valorisation of purified gas through the network, resulting in a substantially higher overall energy efficiency. This technological advantage has been actively reinforced by public action, notably through the introduction of the "right to injection", which eased grid access and increased the connection cost rebate from 40% to 60%. Simultaneously, feed-in tariffs for cogeneration were deliberately tightened from 2020 onwards to curb rising public expenditures and correct profitability levels deemed excessive, while support for injection was selectively revalorised from mid-2023, confirming its clear policy priority (Cour des comptes, 2025).

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[6] Application to methanisation subsidies on the ADEME website (last accessed 22/12/2025).

[7] According to article D.543-292 of the Environmental Code, the share of main crops used for supply is capped at 15% of the total gross tonnage of inputs (*Article D543-292 - Code de l'environnement - Légifrance*, 2022).

[8] Among the eligibility criteria for investment aid awarded by ADEME under the Circular Economy Fund and the Heat Fund in 2024 is the obligation to comply with a restricted supply radius, with at least 90% of inputs coming from an area located within 40 km (Cour des comptes, 2025).

3 Data

3.1 Descriptives

We use three primary datasets covering the period 2015–2023: (i) crop allocation data, (ii) farmers' tax declarations, and (iii) additional control variables.

Crop allocation. The French Land Parcel Identification System (F-LPIS) geographic dataset provides annual plot-level information on agricultural land units benefiting from Common Agricultural Policy (CAP) support, offering near-exhaustive coverage of the French agricultural sector.[9] The parcel-level dataset reports agricultural land use across 372 distinct categories. We follow the *CAP télédéclaration* classification to compute areas devoted to three main categories : permanent crops, permanent pasture and arable land.[10,11] Inside arable land, we derive the "Big Five" which are the five main industrial crops (maize, sunflower, rapeseed, wheat, and barley) (Ministère de l'Agriculture et de l'Alimentation, 2020). Building on this classification, Table 5 to Table 7 report descriptive statistics on the internal composition of arable land, permanent pasture, and permanent crops, expressed as mean shares within each land-use category. Within arable land, cereals dominate (63.95%), followed by herbaceous cover (13.67%) and oilseed crops (8.86%), while all other crop groups individually account for small shares. Permanent pasture is largely composed of grasslands maintained for six years or more (over 80%), with long-rotation grasslands representing most of the remaining area. Permanent crops exhibit more diversity, with orchards and vineyards accounting for the largest shares, alongside non-negligible contributions from perennial biomass and industrial crops. The agricultural characteristics of the buffers are reported in Appendix in Table 4. Agriculture is a component of land use within these areas, with agricultural land accounting for an average of 24.93% of total buffer surface. On average, arable land constitutes the largest share (70.79% or 12474.91 hectares), followed by permanent pasture (27.76% or 4891.33 hectares) and permanent crops (1.45% or 255.41 hectares). The "Big 5" crops (soft wheat, maize, sunflower, barley and rapeseed) make up the largest share of arable land, accounting for 49.48% of the area (without removing

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[9] The main limitation of this dataset is that it does not include crop parcels that are not eligible for CAP aid. However, it still covers approximately 85% of farmers and 98.7% of the utilized agricultural area, and provides yearly plot-level information since 2015 on cultivated crops, farming practices, and farmer identifiers.

[10] Arable land corresponds to cultivated or cultivable land included in a crop rotation (including annual crops, temporary grassland, and fallow land), permanent crops consisting of perennial crops not included in a rotation and remaining in place for at least five years without annual replanting and permanent pasture is grassland dedicated to forage production, which is not plowed or included in a crop rotation for a period of at least five years, and which is used either for mowing or grazing.

[11] In other words, arable land is defined as the total agricultural area minus land allocated to permanent pastures and permanent crops.

overlapping, The Big Five crops account for 72.13% of the arable area, consistent with the related literature.

Farmers' revenues and expenditures. Farmers' revenues are measured using two complementary accounting indicators derived from administrative fiscal data. The Gross Operating Surplus (GOS) captures the economic surplus generated by the farm's productive activity before depreciation, provisions, and financial costs. It is constructed as the difference between operating revenues (including crop and livestock sales, processed products, subsidies, inventory variations, and other operating products) and operating expenses (intermediate inputs, external services, labor costs, taxes, and social contributions). This indicator reflects the farm's capacity to generate value independently of investment and financing decisions. The Current Income Before Tax (CIBT) extends this measure by incorporating depreciation, provisions, and financial results, thereby capturing the final disposable income available to the farmer. Both indicators are expressed in euros at the farm-year level and, in robustness checks, normalized by total utilized agricultural area to account for differences in farm size.[12] Expenditures related to fertilizer consumption are measured through annual fertilizer and soil amendment consumption, proxied by monetary purchases reported in the fiscal accounts. This monetary indicator enables the identification of both a potential reduction in fertilizer consumption due to digestate substitution from biogas units and a possible rebound effect driven by crop reallocation toward biomass-intensive crops.[13] Descriptives will be avaiable at the RIEF 2026.

Control variables. To mitigate potential confounding effects, we complement the main dataset with a set of control variables capturing climatic conditions, urbanization and circular economy characteristics. Climatic conditions are accounted for using weather variables derived from the TerraClimate dataset.[14] These controls include seasonal temperature indicators, average minimum and maximum temperatures during winter (December of year $t-1$ to February of year t) and summer (June–August of year t), as well as annual average precipitation and downward shortwave radiation. All climatic variables are computed as buffer-level averages in order to capture local climatic shocks

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[12] The GOS and CIBT are constructed from the "Bénéfices Agricoles" (BA) fiscal files provided by the French administration (DGFiP) for the period 2015–2023. The GOS is reconstructed from detailed accounting lines of the BA form by summing operating products (i.e. crop and livestock sales, processed products, subsidies, inventory changes) and subtracting operating charges (i.e. intermediate consumption, labor remuneration, taxes, and social contributions), excluding depreciation and provisions. The CIBT corresponds to the sum of operating and financial results and includes depreciation and financial costs, thus reflecting the income effectively available to the farmer.

[13] Fertilizer consumption is measured using the French authority's (DGFiP) agricultural income (BA) tax records. We calculate annual fertilizer consumption at the farm level using the accounting item "purchases of inputs: fertilizers and soil amendments" expressed in euros. In order to estimate actual fertilizer consumption, we combine annual purchases with changes in input stocks where available, so that consumption is measured as purchases net of stock changes. Where stock information is incomplete, expenditure is used as an indicator of consumption.

[14] `https://www.climatologylab.org/terraclimate.html`

that may affect crop yields and relative profitability. We control for total agricultural area because areas with larger agricultural surfaces are more likely to host biogas plants and to supply biomass, which may jointly affect treatment exposure and cropping patterns. Controlling for total agricultural area therefore reduces bias arising from spatial heterogeneity in productive capacity across buffers.[15] Urbanization effects are captured through a set of spatial indicators reflecting land-use pressure and competing non-agricultural uses. We include an urban area dummy equal to one if the municipality hosting a biogas unit belongs to an urban unit as defined by INSEE and zero otherwise.[16] Coastal proximity is captured by a dummy defined at the canton level, equal to one if at least one municipality within the canton has a coastal border.[17] Population density, measured as the number of inhabitants per square kilometre at the municipal level, is included as a continuous proxy for urban pressure.[18] To account for circular economy characteristics, we include two additional controls reflecting local biomass availability and competing uses. Livestock density is measured as the ratio of livestock units to utilised agricultural area within each buffer and captures both the availability of animal waste for biogas production and the orientation of local farming systems. We also control for agri-food industry density, defined as the number of agro-industrial establishments with high biogas potential per unit of utilised agricultural area, which reflects local competition for methanisable biomass as well as agriculture–industry linkages.[19]. All variables are harmonised at the buffer level surrounding each biogas unit using standard spatial aggregation procedures to ensure comparability across territories.[20]

3.2 Composition and Cohorts

Our empirical strategy is based on a spatial analysis. We draw 10 equal bands to form a 15-kilometer radius around each forthcoming biogas plant (see Figure 3). Agricultural lands are observed within these local areas over the 2015–2023 period, corresponding to the years when most biogas units were installed (see Figure 1 and Table 2). These buffers are spread across metropolitan

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[15] No statistically significant effect was observed on total agricultural land area either before or after the opening of a biogas plant. This suggests that the treatment affects crop allocation rather than total agricultural land area.

[16] An urban unit is defined by INSEE as a municipality or group of municipalities with a continuously built-up area (no break exceeding 200 meters between buildings) and at least 2,000 inhabitants. Data source: `https://www.data.gouv.fr/datasets/communes-et-villes-de-france-en-csv-excel-json-parquet-et-feather`.

[17] Following Letort and Temesgen (2013), a canton is classified as coastal if at least one of its municipalities belongs to the "Communes de la loi Littoral". Data source: `https://www.data.gouv.fr/datasets/communes-de-la-loi-littoral-au-code-officiel-geographique-cog-2020-2022`.

[18] Population data are provided by INSEE: `https://www.insee.fr/fr/statistiques/3698339`.

[19] Including circular economy controls allows us to account for local availability of organic resources and competing uses of biomass, which may jointly affect both biogas location and farmers' land-use decisions.

[20] Further methodological details are reported in Appendix B.

France (see Figure 2). An important implication of this strategy is that some biogas plants may overlap the same agricultural parcel over time. To preserve the non-contamination assumption required in a staggered DiD framework, we exclude from the treatment group agricultural parcels that have already been exposed to another plant. We acknowledge that this restriction may mechanically attenuate the estimated treatment effects.

Figure 3: Spatial analysis of agricultural allocation around a biogas unit (3 selected bands)

Note: The figure illustrates the extraction of agricultural parcels (2022) from the F-LPIS within three bands buffer zones around a biogas unit opened in 2022 in the Centre-Val-de-Loire region, capturing local agricultural activity at different distances. For readability, the figure focuses on three distance bands, the full analysis relies on a 15 km radius divided into successive 1.5 km bands.
Source: Authors' calculations based on F-LPIS data.

Table 2 reports the number of biogas units installed each year, along with their cumulative total. First, Table 2 shows that the data include a substantial number of both pre- and post-treatment observations for most cohorts. Second, it documents a sharp increase in installations beginning in 2018, culminating in a peak of 169 new units in 2021.

Table 2: Summary statistics on the number of biogas units per opening year

Group	Number of biogas units open	Cumulative	Observations
2015 cohort	61	61	5490
2016 cohort	53	114	4698
2017 cohort	62	176	5220
2018 cohort	117	293	9531
2019 cohort	158	451	11403
2020 cohort	154	605	9945
2021 cohort	169	774	10161
2022 cohort	130	904	7596
2023 cohort	113	1017	6777

Note: Each buffer consists of 10 concentric bands of 1.5 km, forming a 15 km radius, and is tracked over 9 years. As a result, for the 2015 cohort, the sample includes $61 \times 10 \times 9 = 5{,}490$ *observations.*

Table 3 reports the average of the variables representing presence of livestocks, agro-industries, urban area and population. Cohort refers to all biogas installations in a particular year. Note that all observations are treated within the period of observation and we are left with no never-treated. Table 3 also show no structural change in the cohort evolution regarding important covariates.

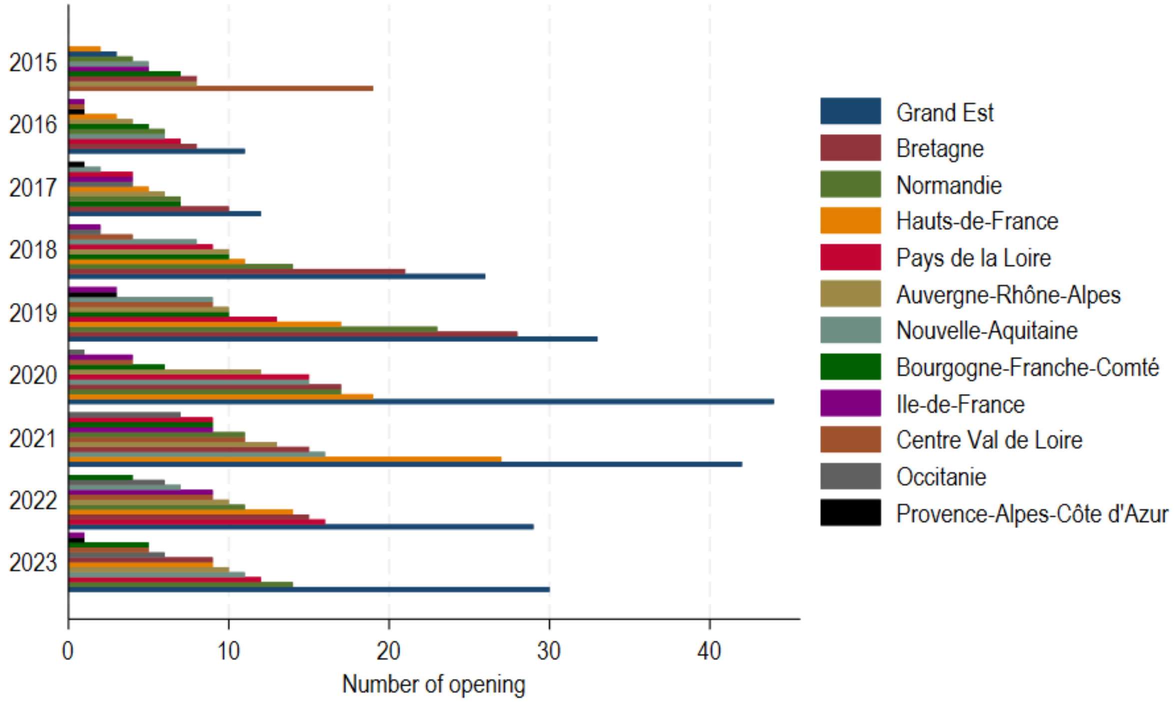
Table 3: observation=bandes

Group	Livestock	Agro-industries	Urban area	Population	Observations
2015 cohort	1.66	0.50	0.28	90.23	5490
2016 cohort	1.85	0.53	0.23	163.18	4698
2017 cohort	1.58	0.99	0.24	140.65	5220
2018 cohort	1.62	0.81	0.24	92.91	9531
2019 cohort	1.74	0.63	0.21	158.61	11403
2020 cohort	1.54	1.39	0.28	172.18	9945
2021 cohort	1.12	0.88	0.30	154.96	10161
2022 cohort	1.24	1.32	0.29	108.73	7596
2023 cohort	1.17	0.47	0.36	211.79	6777

Note: see Table 13 for variables definition.

In Figure 4, we show the distribution of openings across France's 12 regions. Grand Est, Bretagne, Normandie, and Hauts-de-France consistently contribute the most each year, compared to regions like Provence-Alpes-Côte d'Azur. No significant structural changes appear across treatment years.

Figure 4: Number of biogas plants per opening year (cohort) and per region



An additional dimension, not shown in Table 3 or Figure 4, is the heterogeneity in plant capacity. The French model features two deployment strategies: regions with many small biogas units and others with fewer, larger units. This variation motivates further exploration of heterogeneous treatment effects that will be discussed in a later section.

4 Empirical Strategy

Our objective is to estimate the causal effect of the installation of biogas units on crop allocation, farmers' income, and fertilizer and pesticide expenditures. A central challenge in this setting is that the location of biogas units is not random: areas hosting such installations may already differ from others due to pre-existing characteristics, including climate conditions, cropping patterns, livestock endowment or land suitability. We address this concern using a difference-in-differences design that exploits variation in the timing of biogas unit installation across areas.

We exploit the staggered roll-out of biogas units across geographic areas, defined as buffers with radiuses ranging from 1.5 to 15 kilometers around each installation. Because treatment adoption is staggered over time, standard two-way fixed effects (TWFE) estimators may produce biased estimates in the presence of heterogeneous treatment effects (Callaway & Sant'Anna, 2021; De Chaisemartin & d'Haultfoeuille, 2020; de Chaisemartin & D'Haultfœuille, 2023). Instead, we adopt a local projections difference-in-differences (LP-DiD) approach following Dube, Girardi, Jorda, and Taylor (2025), which is well suited to dynamic treatment settings with staggered adoption. We use the LP-DiD framework to identify dynamic causal effects by comparing newly treated areas to a time-varying set of areas that have not yet been treated.

We estimate the effect of biogas unit installation on a set of outcomes using the following specification:

$$Y_{j,t+k} - Y_{j,t-1} = \beta^k \, \Delta\text{biogas}_{j,t} + \mathbf{X}_{j,t} \cdot \delta^k + \eta^k_{c_j,t} + \varepsilon^k_{j,t}, \tag{1}$$

where $Y_{j,t+k} - Y_{j,t-1}$ denotes the change in (i) crop allocation, (ii) farmers' income, or (iii) farmers' expenditures in area j between year $t+k$ and the reference year $t-1$. Our panel spans nine years, allowing us to estimate dynamic treatment effects up to seven years after treatment, i.e. $k \in \{1, \dots, 7\}$.[21] Differencing the outcome variable helps eliminate slow-moving confounders such as historical land use, long-term subsidy schemes, or persistent local policies.

$\Delta\text{biogas}_{j,t}$ is an indicator equal to one if a biogas unit is installed in area j between years $t-1$ and t. A key advantage of the LP-DiD approach is that it explicitly excludes observations that may be contaminated by earlier treatments. In our setting, each horizon-specific regression includes only newly treated areas ($\Delta\text{biogas}_{j,t} = 1$) and a comparison group consisting of areas that have not yet been treated at horizon k ($\text{biogas}_{j,t+k} = 0$).[22] The coefficient β^k therefore captures the effect of installation of a biogas plant on changes in the outcome variables at horizon k. All specifications include region-by-year fixed effects, $\eta^k_{c_j,t}$, which absorb time-varying regional policies, subsidy programs, and other common shocks. The vector $\mathbf{X}_{j,t}$ includes time-varying controls such as temperatures, solar exposure and precipitations. Standard errors are clustered at the area level to account for serial correlation.

We estimate equation Equation 1 using ordinary least squares (OLS). A variance decomposition of the outcome variables indicates that most of the variation arises from within-area changes over time, supporting the relevance of identification based on within-area variation in the LP-DiD framework.[23]

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[21] For crop allocation outcomes, the treatment is lagged by one year to account for potential anticipation effects, which restricts the horizon to $k \in \{1, \dots, 6\}$.

[22] We also run the estimations following Callaway and Sant'Anna (2021) and de Chaisemartin and D'Haultfœuille (2023) and we find similar results.

[23] We also explored specifications using a never-treated comparison group selected via random sampling; however,

5 Results

In this section, we first estimate the effects of biogas plant openings on changes crops allocation, farmers revenue, farmers fertilizer and pesticide expenditures.

5.1 Dynamic Effects on Crop Allocation

The staggered DiD model yields several insights into the impact of biogas unit implementation on crop allocation in surrounding areas (treated group) relative to areas without such units (control group) at horizon k. In all subsequent graphs, the parallel trends assumption holds, reinforcing the validity of our empirical setting.

5.1.1 From Long-Term to Sequential Crops

Exposure of agricultural land to a biogas unit leads to a reallocation of crops, with farmers adopting a sequential cropping strategy. This strategy involves planting a main crop followed by an intermediate crop (IC) within the same season to maximize opportunities in the biogas production. To facilitate this system, farmers shift their crop choices toward short-cycle crops, which offer two advantages: use as dedicated energy crops, compatibility with winter or summer ICs. By selecting short-cycle main crops, farmers can plant an IC, a practice not feasible with long-cycle crops.

This strategy is illustrated in Figure 5.[24] Panel (a) shows that, for silage maize, post-treatment coefficients turn positive shortly after plant commissioning, with a steady increase over time. Estimated effects for silage maize range from +3.89% to +7.62%. The pooled average treatment effect indicates a significant increase of +4.3% in the share of silage maize (see Table 8), consistent with findings in the agronomy literature (+3.14% in Levavasseur et al., 2023). These relatively modest increases can be explained by French regulatory constraints, which cap the share of energy crops at 15%. Panels (b) and (c) display similar dynamic patterns. The increase in sorghum and winter rye likely reflects their role as summer and winter intermediary crops (ICs), respectively, which are explicitly recommended by the public agency in charge of biogas-related subsidies. Following the installation of a biogas plant, sorghum exhibits a pronounced and sustained increase, with estimated gains ranging from +13.59% to +33.22%.[25; 26] The pooled average treatment effects confirm mod-

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preliminary results suggest that such specifications are more likely to violate the parallel trends assumption.

[24] See Appendix A, Figure 9.

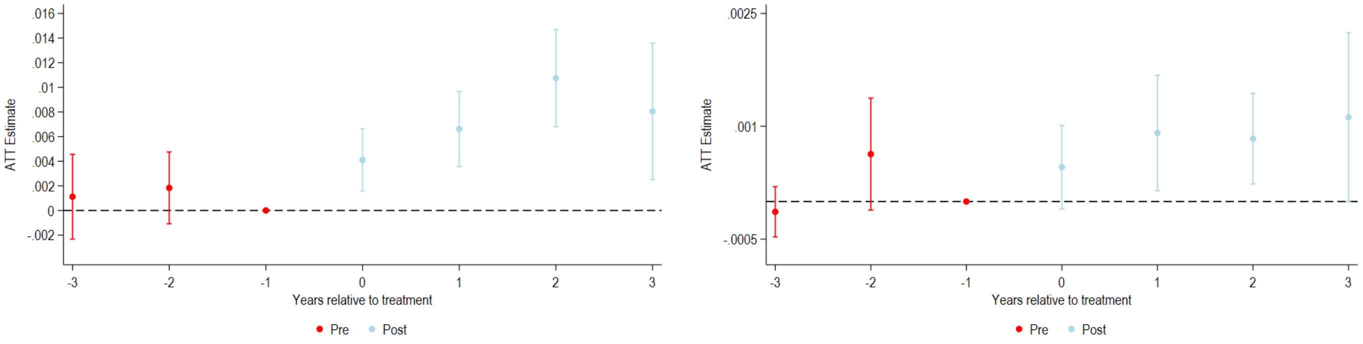
[25] Winter rye shows a persistent and statistically significant increase over time within a 6 km radius, with estimated effects ranging from +31.85% to +74.31%.

[26] This corresponds to an increase of 0.063 percentage points in sorghum and 0.05 percentage points in winter rye.

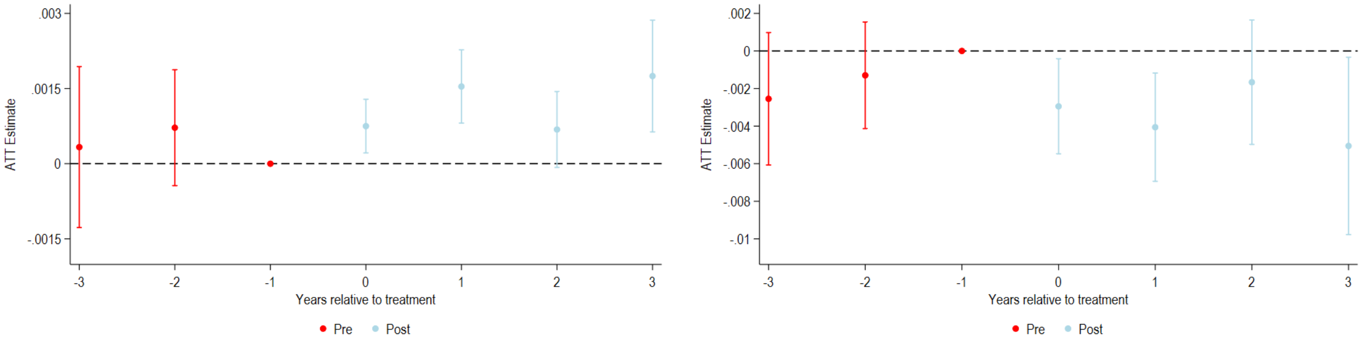
erate but statistically significant increases of $+27.31\%$ for sorghum and $+18.84\%$ for winter rye (see Table 8).

Figure 5: Dynamic Effects of Biogas Unit Openings on Crop Allocation

(a) Silage Maize (b) Sorghum



(c) Winter Rye, within 6 kilometers (d) Winter Rapeseed



Notes: This figure plots the estimates β_k and 95% confidence intervals (robust to clustering at the area j) from the event-study specification Equation 1, exploring the dynamic effects of biogas plant installation on crop allocation. The outcome variables are: % of silage maize (panel a), % of Sorghum (panel b), % of Winter Rye within a radius of 6km (panel c), % of winter rapeseed (panel d). The x-axis denotes the number of years relative to the year preceding installation ($t = 0$). The omitted reference period is $t = -1$, corresponding to the period immediately preceding plant commissioning. The specification includes buffer and year fixed effects, as well as baseline controls: temperatures, solar exposure and precipitations. The pre-treatment period is shown in red, and the post-treatment period in blue.

Conversely, long-cycle crops, particularly winter rapeseed, is incompatible with the integration of an energy crop, as the economic value of a double crop exceeds that of traditional rotation. Figure 5 reveals a persistent decline in winter rapeseed after plant opening, with estimated losses ranging from -4.42% to -7.58%.

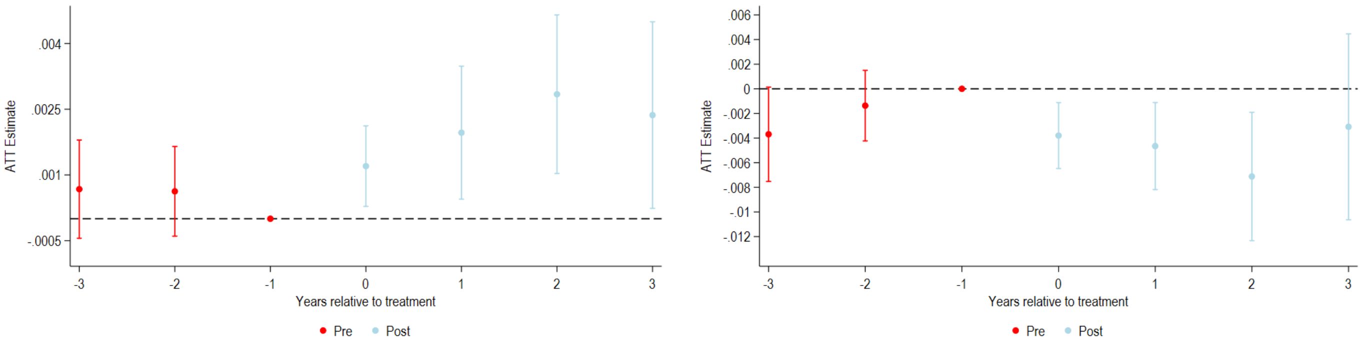
Overall, Figure 5 presents consistent evidence of a shift toward sequential cropping. Short-cycle crops (silage maize, sorghum and winter rye) facilitate the organization of double cropping without compromising subsequent operations in the following season, enhancing their attractiveness in the biogas plant's supply area. Symmetrically, long-cycle winter crops (winter rapeseed) is declining because their extended soil occupation prevents the establishment of a summer IC. The observed trend reflects a coherent restructuring of the cropping system, with farmers adjusting cycle lengths to increase opportunities for intercalating an IC. These findings align with the agronomic literature (Boros, Carozzi, et al., 2025).

5.1.2 Reallocation from Low to High-Methanogenic Temporary Grasslands

Certain grassland types exhibit particularly high productivity, both in terms of usable biomass and primary energy yield (see Table 1), which translates into a high methanogenic potential and makes them especially attractive feedstocks for biogas units. Accordingly, in Figure 6, for mixtures dominated by legumes and forage crops, post-treatment coefficients turn positive from $t+1$ and rise steadily up to $t+3$, indicating a sustained upward trajectory, with estimated effects ranging from +8.22% to +16.19%.

In this context, the decline of temporary grasslands relative to other mixtures with grasses reflects the fact that this residual group consists of non-specialized mixtures (neither grasses nor fodder) that are less efficient energetically. As shown in Figure 6, the category other mixtures with grasses shows a downward trend: coefficients remain close to zero before treatment, then turn negative from $t+1$ and remain so until $t+2$, suggesting a contraction of this area, with estimated effects ranging from -3.44% to -6.44%.

Figure 6: Dynamic Effects of Biogas Unit Openings on Grassland Choice



(a) Temporary Grasslands : Legume-forage mixtures

(b) Temporary Grasslands : other mixtures with grasses

Notes: This figure plots the estimates β_k and 95% confidence intervals (robust to clustering at the area j) from the event-study specification Equation 1, exploring the dynamic effects of biogas plant installation on crop allocation. The outcome variables are: % of Temporary Grasslands : Legume-forage mixtures (panel a), Temporary Grasslands : other mixtures with grasses (panel b). The x-axis denotes the number of years relative to the year preceding installation ($t = 0$). The omitted reference period is $t = -1$, corresponding to the period immediately preceding plant commissioning. The specification includes buffer and year fixed effects, as well as baseline controls: temperatures, solar exposure and precipitations. The pre-treatment period is shown in red, and the post-treatment period in blue.

5.2 Dynamic Effects on Farmers Revenue

The previous section shows strong support to the use of a staggered DiD approach with external validity among agronomic literature. We want to pursue, in this section by assessing the effect of biogas installation on (i) owner revenue and its potential spillover on (ii) contingent agricultural lands. With CASD data, we are able to identify if the farmer owns a biogas unit and we are able to reconstruct the same geographical granularity.

We will also perform an analysis by heterogeneity, given the main inputs of the farm as discussed in section 2.

-We plan to present the full results at RIEF 2026-

5.3 Dynamic Effects on Farmers Fertilizer and Pesticide Expenditures

Again, we want to explore another channel as biogas units modify crop allocation and also generate digestate (see section 2). We expect to have some result when farmers rely on livestock as it is waste which is not the case for crop residue that could have been used for fallow as natural fertilizer.

As it modifies crop allocation, it might also impact the use of pesticide. While we have data on pesticide expenditures, it is important to note that Bareille et al. (2024) underline that the purchase of pesticide is strongly correlated with the use of pesticide in the case of France.

-We plan to present the full results at RIEF 2026-

6 Conclusion

Understanding how residue valorization reshapes agricultural economies is critical. This paper examines the causal impact of biogas installations on crop allocation, farmer revenues, and expenditures on fertilizers and pesticides, using a panel dataset of over 1,000 units in France from 2015 to 2023. Our findings provide robust evidence that biogas units drive a shift toward sequential cropping to maximize residue production, alongside a reallocation toward crops with high methanogenic potential.

Future work will investigate the economic returns for biogas unit owners and potential spillover effects on neighboring farms, particularly in relation to unit capacity. We will also assess whether the use of organic inputs—such as livestock effluents or crop residues—reduces mineral fertilizer dependence. Finally, we plan to explore how crop reallocation affects pesticide expenditures.

Looking ahead, further research could extend this analysis to a comprehensive cost-benefit framework, offering deeper insights into the policy efficiency of biogas deployment regarding resilience of farmers and carbon mitigation efficiency.

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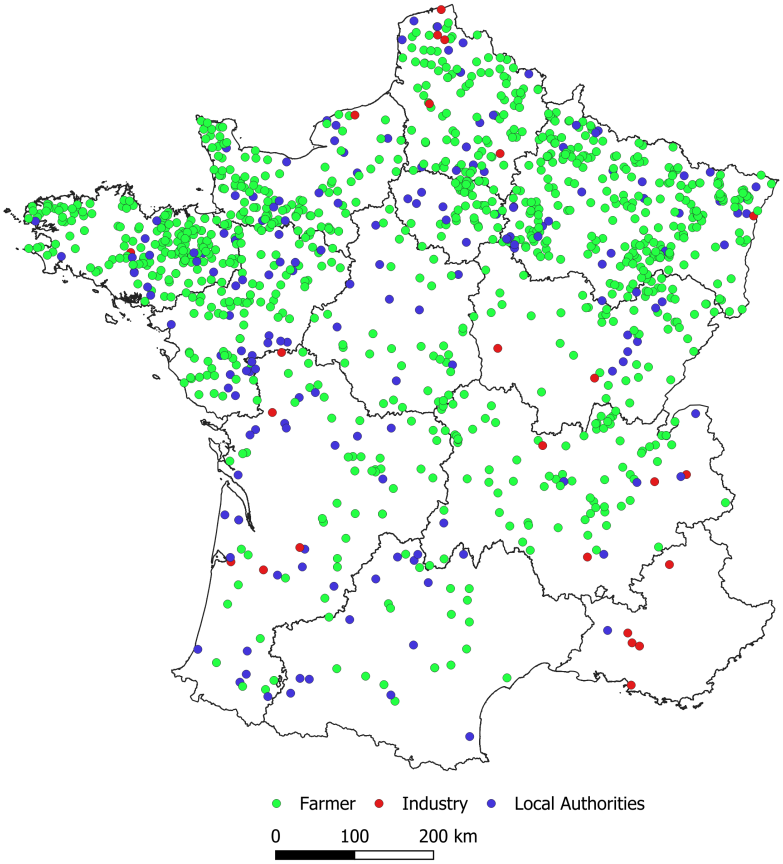
A Additional tables and figures

Figure 7: Geographic distribution of biogas units by type of actors



Source: Authors' calculations based on SINOE data.

Table 4: Summary statistics of all variables for biogas sites (all sample, Buffer) - Period: 2015–2023

Variables	**Unit**	**Level**	**Mean**	**Median**	**Std. Dev.**	**Min.**	**Max.**	**Source**
Agricultural Area								
Total agricultural land	ha	Buffer	17 621.65	12 837.10	15 748.72	0.00	59 319.73	RPG
Arable land	ha	Buffer	12 474.91	7 925.43	12 754.15	0.00	59 183.49	RPG
Permanent crops	ha	Buffer	255.41	27.10	1 085.11	0.00	17 134.93	RPG
Permanent pastures	ha	Buffer	4 891.33	2 270.51	6 455.34	0.00	48 810.83	RPG
Arable land description								
Big 5	ha	Buffer	8 719.88	5 028.76	9 400.89	0.00	44 377.16	RPG
Silage maize	ha	Buffer	1 071.40	327.19	1 829.81	0.00	14 555.97	RPG
Grain maize	ha	Buffer	1 171.28	385.28	2 102.02	0.00	25 445.01	RPG
Sunflower	ha	Buffer	294.47	11.44	801.59	0.00	9 881.53	RPG
Winter Rapeseed	ha	Buffer	1 000.07	317.73	1 572.48	0.00	11 443.21	RPG
Spring Rapeseed	ha	Buffer	1.61	0.00	5.90	0.00	92.58	RPG
Winter Barley	ha	Buffer	956.54	492.79	1 221.38	0.00	8 649.98	RPG
Spring Barley	ha	Buffer	438.19	59.41	1 189.48	0.00	18 245.60	RPG
Winter Soft Wheat	ha	Buffer	3 771.46	1 882.59	4 663.29	0.00	27 503.75	RPG
Spring Soft Wheat	ha	Buffer	14.87	2.98	34.51	0.00	1 235.35	RPG
Temporary grassland	ha	Buffer	1 404.01	452.61	2 400.16	0.00	26 337.58	RPG
Legume-forage mixtures	ha	Buffer	133.43	33.78	267.99	0.00	3 195.14	RPG
Other mixtures with grasses	ha	Buffer	1 074.27	316.40	1 989.00	0.00	26 060.35	RPG
Ryegrass	ha	Buffer	175.08	18.29	492.90	0.00	7 194.12	RPG
Agricultural Factors								
Climate index								
Winter temperature (min)	°C	Buffer	2.52	2.49	1.72	−3.59	7.09	TerraClimate
Winter temperature (max)	°C	Buffer	8.57	8.52	1.70	2.87	15.27	TerraClimate
Summer temperature (min)	°C	Buffer	14.07	13.98	1.16	9.83	21.21	TerraClimate
Summer temperature (max)	°C	Buffer	24.82	24.94	1.93	19.77	32.34	TerraClimate
Downward Shortwave Radiation (average)	W/m^2	Buffer	141.81	141.10	10.89	116.56	182.85	TerraClimate
Precipitation (average)	mm	Buffer	66.99	64.72	13.33	24.39	131.26	TerraClimate
Non-Agricultural Factors								
Urban area	yes=1/no=0	Municipality	0.26	0.00	0.44	0.00	1.00	INSEE
Costal proximity	yes=1/no=0	Canton	0.15	0.00	0.35	0.00	1.00	INSEE
Population density	inhab./km^2	Municipality	142.51	53.17	442.15	2.50	8 017.08	INSEE
Circular Economy Factors								
Livestock density	UGB/ha	Buffer	1.48	1.25	1.16	0.03	6.09	Agreste
Agro-industries density	Number/ha	Buffer	0.97	0.08	4.62	0.00	73.78	SIRENE

Notes: Number of observations: 7,587, with 843 biogas units. In the case of overlapping buffer zones, each agricultural parcel is classified as treated from the date of the first biogas unit installation affecting that parcel. Subsequent biogas unit openings whose buffer zones overlap with already treated parcels are not considered, in order to avoid double counting of treatment exposure.

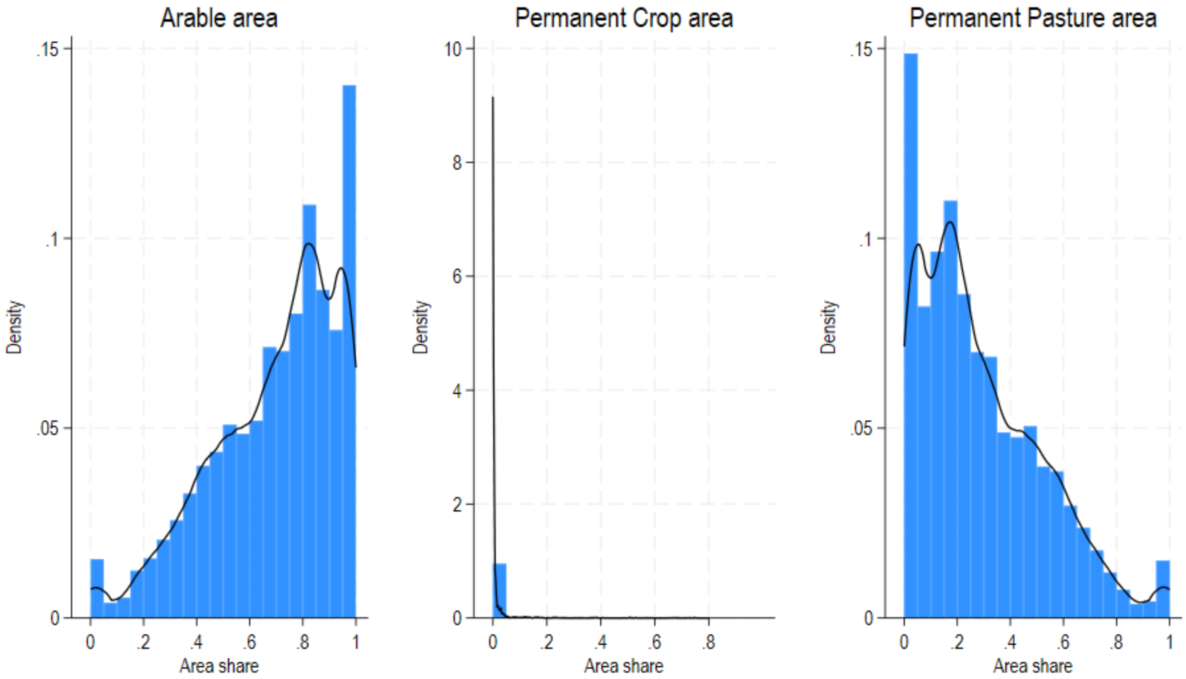


Figure 8: Distribution agricultural data

Table 5: Classification of arable land crops

Categories	**Crops**	**Crop share (mean, %)**
Cereal	Winter oats, Spring oats, Other spring cereal of the genus *Zea*, Other pseudo-cereal (quinoa, canary grass, chia…), Other winter and spring cereals (*Avena*, *Hordeum*, *Secale*, *Panicum*, *Sorghum*), Wheat (durum, soft, winter, spring), Spelt, Maize (grain, sweet, silage), Millet, Rice, Barley, Buckwheat, Rye, Triticale, Cereal mixtures.	63.95%
Oilseed crops	Camelina, Rapeseed (winter / spring), Non-textile flax, Mustard, Poppy (opium poppy), Sunflower, Turnip rape (winter / summer), Niger seed, Sesame, Other oilseed crops (*Brassica napus*, *B. rapa*, *Helianthus*), Oilseed mixtures.	8.86%
Protein crops	Faba bean (winter / spring), Sweet lupin (winter / spring), Chickpea, Protein pea (winter / spring), Soybean, Pea / lupin / faba bean mixtures, Dehydrated legumes (sainfoin, clover, alfalfa, vetch, sweet clover), Late sowings (after 31/05).	2.38%
Fibre	Hemp, Non-compliant hemp, Fibre flax.	0.61%
Fallow	Arable land fallow, Fallow <5 years, Fallow 6 years declared EFA.	1.63%
Legume	Peanut, Lentil, Fenugreek, Cowpea, Dolichos, Sweet pea, Birdsfoot trefoil, Minette, Non-forage legume mixtures + cereals / oilseeds.	0.13%
Forage legume	Forage faba bean, Jarosse, Forage lupin, Alfalfa, Sweet clover, Forage pea, Sainfoin, Serradella, Clover, Vetch, Multi-species mixtures, Establishments 2015–2018.	2.86%
Forage	Forage beet, Forage carrot, Forage cabbage, Forage lentil, Forage turnip, Forage radish, Annual forage crops, Miscellaneous mixtures.	0.37%
Herbaceous cover (Temporary grassland)	Legume + grass mixtures (<5 years), Pure grasses (fescue, cocksfoot, ryegrass, timothy…), Watercress, Brome, Phacelia, X-Felium.	13.67%
Vegetable	Garlic, Beetroot, Carrot, Cabbage, Celery, Cucumber, Zucchini, Spinach, Strawberry, Melon, Watermelon, Turnip, Parsnip, Onion/shallot, Leek, Squash, Potato, Beans, Peas, Tomato, Artichoke, Diversified market gardening.	5.44%
Aromatic	Parsley, Non-perennial aromatic plants, Medicinal plants, Dill, Basil, Chamomile, Caraway, Chervil, Chives, Coriander, Cumin, Tarragon, Fennel, Lemon balm, Mint, St. John's wort, Rosemary, Savory, Sage, Thyme, Valerian, Nettle, Marjoram, Cornflower, Bedstraw, Pansy, Primrose, Rosemary, Savory, Sage, Thyme, Valerian, Veronica, Other perfume plants, Nettle, Black psyllium of Provence, Marjoram/Oregano, Daisy.	0.11%

Table 6: Classification of permanent pasture

Permanent Pasture	**Share (mean, %)**
Grassland of 6 years or more	82.59%
Grassland with predominant grass and woody forage resources present	1.17%
Pastoral area – Predominant woody forage resources	0.53%
Long-rotation grassland (6 years or more) predominant	14.01%
Grazed woodland	0.47%
Reed bed	0.01%
Fallow of 6 years or more	1.21%
Chestnut grove maintained by pigs or small ruminants	0.0000425%
Oak grove maintained by pigs or small ruminants	0.000426%
Reed bed (reed harvesting)	0.000671%
Pastoral area or rangeland not used in the current year	0.0025%

Table 7: Classification of permanent crops

Permanent Crops	**Permanent crops share (mean, %)**
Citrus	0.20%
Avocado	0.00%
Carob	0.07%
Cherry	0.08%
Chestnut	1.17%
Hazelnut	1.28%
Walnut, including coconut	3.08%
Olive	0.03%
Small berry fruit excluding strawberry	2.86%
Pistachio	0%
Peach, nectarine, flat peach	0.029%
Pear	0.13%
Plum	0.32%
Other orchard	38.61%
Vine: wine grapes in production	13.21%
Vine: table grapes	0.29%
Vine: wine grapes not in production	0.47%
Vineyard restructuring	0.08%
Other ornamental plants	3.97%
Lavender and lavandin	0.42%
Perennial aromatic plant	0.08%
Perennial perfume plants	0.03%
Perennial medicinal plants	0.09%
Hop	0.28%
Short-rotation coppice	4.19%
Truffle orchard	1.75%
Nursery $>$ 1 year	7.73%
Nursery $<$ 1 year	0.05%
Other perennial vegetable or fruit	5.53%
High-biomass perennial crop (TA)	2.46%
Miscanthus (TA)	10.57%
Other perennial crop	0.96%

Table 8: Average treatment effect (group aggregation) by crop

Crop	**ATT**	**Standard error**	**Mean Y**
Silage maize	0.0046**	0.0023	0.1056
Winter rapeseed	-0.0028	0.0018	0.0667
Spring rapeseed	-0.00005	0.00005	0.0002
Winter barley	0.0031	0.0019	0.0723
Spring barley	-0.0014	0.0012	0.0292
Winter Soft Wheat	0.0004	0.0028	0.2663
Spring Soft Wheat	-0.0002	0.0003	0.0013
Sorghum	0.0006*	0.0003	0.0034
Winter rye	0.0006*	0.0003	0.0021
Temporary grassland			
Mix. predominant legume and forage	0.0016**	0.0007	0.0146
Temporary grassland + other mix.	0.0012	0.0029	0.1105
Permanent pasture			
Grassland	0.0027	0.0053	0.7939
Long-rotation grassland	0.0026	0.0043	0.383

Note: *** p<0.01, ** p<0.05, * p<0.10. . Standard errors are clustered at the band-buffer level.

Table 9: Average treatment effect (group aggregation) by crop, within 12 kilometers

Crop	**ATT**	**Standard error**	**Mean Y**
Silage maize	0.0049*	0.0029	0.1069
Winter rapeseed	-0.0045**	0.0022	0.0658
Spring rapeseed	-0.00007	0.00005	0.0002
Winter barley	0.0030	0.0022	0.0724
Spring barley	-0.0014	0.0014	0.0286
Winter Soft Wheat	0.0004	0.0034	0.2654
Spring Soft Wheat	-0.0006***	0.0002	0.0013
Sorghum	0.0006*	0.0004	0.0035
Winter rye	0.0008*	0.0004	0.0021
Temporary grassland			
Mix. predominant legume and forage	0.0014	0.0008	0.0147
Temporary grassland + other mix.	0.0029	0.0037	0.1121
Permanent pasture			
Grassland	0.0038	0.0064	0.7929
Long-rotation grassland	0.0036	0.0054	0.1391

Note: *** p<0.01, ** p<0.05, * p<0.10. . Standard errores are clustered at the band-buffer level.

Table 10: Average treatment effect (group aggregation) by crop, within 7.5 kilometers

Crop	**ATT**	**Standard error**	**Mean Y**
Silage maize	0.0054	0.0046	0.1087
Winter rapeseed	-0.0062*	0.0032	0.0646
Spring rapeseed	-0.00009	0.00008	0.0002
Winter barley	0.0026	0.0029	0.0723
Spring barley	-0.0022	0.0019	0.0276
Winter Soft Wheat	0.0008	0.0050	0.2637
Spring Soft Wheat	-0.0007**	0.0003	0.0012
Sorghum	0.0006	0.0004	0.0037
Winter rye	0.0011***	0.0003	0.0022
Temporary grassland			
Mix. predominant legume and forage	0.0019*	0.0011	0.0149
Temporary grassland + other mix.	0.0096	0.0056	0.1134
Permanent pasture			
Grassland	0.0102	0.0090	0.7900
Long-rotation grassland	0.0059	0.0070	0.1398

Note: *** p<0.01, ** p<0.05, * p<0.10. . Standard errores are clustered at the band-buffer level.

TWFE model by crops categories

Table 11: Basic model TWFE regression

Dependent var.:	Arable land (Big 5 crop share)							
	Silage maize	Spring Soft Wheat	Winter Soft Wheat	Winter Rapeseed	Spring Rapeseed	Spring Barley	Winter Barley	Sunflower
Treatment	0.0082016***	-0.000212*	-0.0000146	-0.0019199**	0.0000881	-0.0005707	-0.0009748	0.0010763***
	(0.0008425)	(0.0001111)	(0.0011228)	(0.0008207)	(0.0000616)	(0.0005230)	(0.0007262)	(0.0003427)
Precipitation	0.0001724***	0.00000825	-0.0001776***	-0.0004476***	0.000000815	0.0001406***	-0.0000894**	0.0000240
	(0.0000624)	(0.00000577)	(0.0000677)	(0.0000454)	(0.00000555)	(0.0000278)	(0.0000413)	(0.0000243)
Down. Shortwave Radiation	-0.0013894***	0.0000109	-0.0016712***	-0.0019860***	-0.0000179***	0.0010557***	-0.0010687***	0.0005805***
	(0.0001511)	(0.0000166)	(0.0001786)	(0.0001222)	(0.00000456)	(0.0000753)	(0.0001154)	(0.0000732)
Max. temp. (summer)	-0.0013833	0.0005101**	-0.0019188	0.0074684***	-0.00000703	-0.0022601**	0.0035571**	-0.0065526***
	(0.0020364)	(0.0001972)	(0.0025751)	(0.0016001)	(0.0000579)	(0.0008944)	(0.0016444)	(0.0007861)
Max. temp. (winter)	0.0116521***	-0.0008960**	-0.0051563	-0.0440178***	-0.0003149***	0.0051813***	-0.0069604***	0.0033266***
	(0.0025660)	(0.0003659)	(0.0034965)	(0.0023432)	(0.0001063)	(0.0011927)	(0.0022594)	(0.0008663)
Min. temp. (summer)	0.0093205***	-0.0004072**	0.0040717	-0.0083712***	-0.0001661*	0.0022666***	0.0012342	0.0040914***
	(0.0020531)	(0.0002051)	(0.0025596)	(0.0015637)	(0.0000895)	(0.0008645)	(0.0016932)	(0.0008432)
Min. temp. (winter)	0.0074827***	0.0005433*	-0.0010804	0.0317908***	0.0001890	-0.0062301***	0.0067539***	0.0025863***
	(0.0024054)	(0.0003178)	(0.0033162)	(0.0022141)	(0.0001212)	(0.0011225)	(0.0021112)	(0.0007799)
Population density	0.0000495***	-0.00000751**	-0.0000812***	0.0000700***	0.0000000308	-0.0000515	-0.0000134	-0.0000138**
	(0.0000117)	(0.00000361)	(0.0000249)	(0.0000176)	(0.000000238)	(0.0000440)	(0.0000271)	(0.00000643)
Fixed effects								
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Band buffer FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region × Year FE	No	No	No	No	No	No	No	No
Observations	58,554	58,554	58,554	58,554	58,554	58,554	58,554	58,554
R^2 (within)	0.0108	0.0011	0.0024	0.0133	0.0007	0.0037	0.0019	0.0099
Mean Y	0.1056	0.0013	0.2663	0.0667	0.0002	0.0292	0.0723	0.0183
Clusters	6,506	6,506	6,506	6,506	6,506	6,506	6,506	6,506

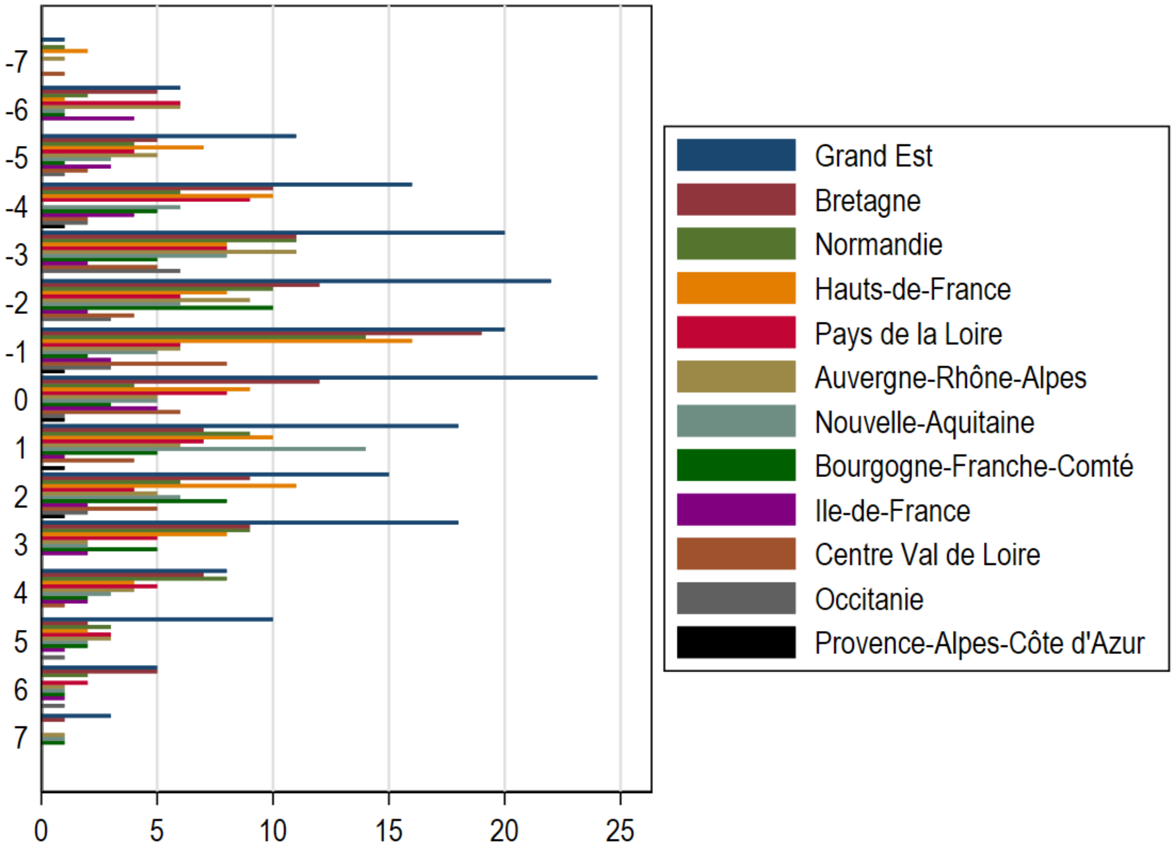
${}^{*}p < 0.10$, ${}^{**}p < 0.05$, ${}^{***}p < 0.01$. All regressions are TWFE specifications including the set of controls shown in the table. Standard errors (SE) are cluster-robust at the band-buffer level.

Table 12: Basic model TWFE regression

Dependent var.:	Arable land (crop share)				Permanent pastures (crop share)	Permanent crops (crop share)
	Winter Rye	PTR	MLG	Sorghum		
Treatment	0.0001039	0.0045386***	-0.0005642	0.0003753*	-0.0004043	0.0001355
	(0.0001229)	(0.0012495)	(0.0004336)	(0.0002013)	(0.0010030)	(0.0001547)
Precipitation	0.0000212*	0.0004049***	-0.0000872***	-0.00000855	-0.0004324***	-0.0000194
	(0.0000112)	(0.0000759)	(0.0000254)	(0.0000191)	(0.0000614)	(0.0000138)
Downward Shortwave Radiation	0.0000246	0.0038819***	-0.0005347***	-0.0000414	-0.0036498***	-0.0001389***
	(0.0000219)	(0.0002304)	(0.0000717)	(0.0000331)	(0.0001857)	(0.0000403)
Max. temp. (summer)	-0.0011458***	0.0204835***	-0.0172434***	-0.0021022***	-0.0059504**	-0.0011588***
	(0.0002692)	(0.0034804)	(0.0013007)	(0.0004151)	(0.0027923)	(0.0004184)
Max. temp. (winter)	0.0002239	0.0367077***	-0.0062040***	0.0024394***	-0.0568475***	0.0013374**
	(0.0003549)	(0.0034837)	(0.0011734)	(0.0006692)	(0.0033087)	(0.0005456)
Min. temp. (summer)	0.0013291***	-0.0161785***	0.0155847***	0.0025377***	-0.0004153	0.0014309***
	(0.0002935)	(0.0034150)	(0.0013289)	(0.0004030)	(0.0027424)	(0.0004850)
Min. temp. (winter)	-0.0000901	-0.0323847***	0.0049097***	-0.0008683	0.0438929***	-0.0010703**
	(0.0003089)	(0.0029815)	(0.0009626)	(0.0007010)	(0.0030727)	(0.0005418)
Population density	-0.00000133	0.0001413***	-0.0000252***	-0.00000273	0.0000438	-0.000000144
	(0.00000147)	(0.0000192)	(0.00000577)	(0.00000234)	(0.0000381)	(0.00000594)
Fixed effects						
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Band buffer FE	Yes	Yes	Yes	Yes	Yes	Yes
Region × Year FE	No	No	No	No	No	No
Observations	58,554	58,554	58,554	58,554	58,554	58,554
R^2 (within)	0.0004	0.0196	0.0124	0.0017	0.0219	0.0021
Mean Y	0.0021	0.0224	0.0146	0.0034	0.2869	0.0179
Clusters	6,506	6,506	6,506	6,506	6,506	6,506

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$. All regressions are TWFE with clustered SE at the band buffer level. PTR: Temporary grassland ($\leq$5 years) + other mixtures with grasses, MLG: Mixture of predominant legumes and forage grasses ($\leq$5 years).

Figure 9: Event-time



B Data

This data appendix first presents the list of data sources used in the analysis. We then detail the construction of our main variables, focusing on crop allcoation and income.

B.1 Data sources

We collect data from 9 different sources : SINOE, F-LPIS, BA: Agricultural profits - standard and simplified regime, General Agricultural Census, TerraClimate, INSEE (urban area), INSEE (costal proximity), INSEE (population density) and SIRENE.

Table 13: Descriptions and sources of variables

Variable	**Definition and measure**	**Source**
Biogas units (identifiers)	Administrative and geographical information on biogas units.	SINOE
Arable crops	Share of total agricultural land allocated to arable land within each biogas buffer. Arable land includes cultivated or cultivable land under crop rotation (annual crops, temporary grassland, and fallow land). Measured in hectares and expressed as a share of total agricultural area.	F-LPIS
Permanent crops	Share of total agricultural land allocated to permanent crops within each biogas buffer. Permanent crops are perennial crops not included in crop rotations and remaining in place for at least five years (i.e., orchards, vineyards, perennial energy crops). Measured in hectares and expressed as a share of total agricultural area.	F-LPIS
Permanent pastures	Share of total agricultural land allocated to permanent pastures within each biogas buffer. Permanent pastures are grasslands used for grazing or mowing that are not plowed or rotated for at least five years. Measured in hectares and expressed as a share of total agricultural area.	F-LPIS
Winter temperature	Average minimum and maximum temperatures during winter, defined as December of year $t-1$ to February of year t, aggregated at the buffer level.	TerraClimate
Summer temperature	Average minimum and maximum temperatures during summer, defined as June to August of year t, aggregated at the buffer level.	TerraClimate
Downward Shortwave Radiation	Annual average downward shortwave radiation (W/m^2), aggregated at the buffer level to capture solar exposure affecting crop growth and yields.	TerraClimate
Precipitation	Annual average total precipitation (mm), aggregated at the buffer level to capture local climatic conditions affecting agricultural productivity.	TerraClimate
Urban area	Binary variable equal to one if the municipality hosting the biogas unit belongs to an urban unit as defined by INSEE (continuous built-up area with at least 2,000 inhabitants) and zero otherwise.	INSEE
Costal proximity	Binary variable equal to one if the canton is classified as coastal, meaning that at least one municipality within the canton has a coastal border and zero otherwise.	INSEE
Population density	Number of inhabitants per square kilometer, measured at the municipal level and used as a proxy for urban pressure on agricultural land.	INSEE
Livestock density	Ratio of livestock units (UGB, Unité Gros Bétail)[27] to utilised agricultural area (SAU, in hectare) within each buffer, measuring the intensity of livestock farming and availability of animal waste for biogas production.	Agreste
Agro-industries density	Number of agri-food industrial establishments with high biogas potential per unit of utilised agricultural area, capturing local competition for methanisable biomass.	SIRENE

B.2 Creation of variables

B.2.1 Main variables

Crop share

Our objective is to capture the reallocation between crops. Our raw data comes from *F-LPIS* (see `https://geoservices.ign.fr/rpg`). *F-LPIS* is a geographic reference tool for the parcels of land belonging to farmers who have submitted a declaration in order to obtain aid under the Common Agricultural Policy. The procedure we use is as follows:

1. We retain only files from regions in mainland France (excluding Corse) for the period from 2015 to 2023.

2. Agricultural parcels (surface in hectare) are identified using a spatial intersection between the agricultural parcel layer and the multi-ring buffer zones constructed around the biogas units. This produces a file of geolocated agricultural parcels for each year and each region, assigned to a specific band-buffer around the biogas units.

3. We reshape the database by crops. Each observation represents a band of the buffer zone with the different crops linked to the individual characteristics of the biogaz unit and a year.

4. We calculate the share of crops by dividing the area in hectare of each crop by the total area of the band (i.e. which is the sum of total area of each crops). Since the absence of a crop within a given band-year corresponds to a genuine zero allocation of land, we code such observations as zeros. This partial rebalancing avoids conditioning the analysis on ex post crop presence and ensures a consistent interpretation of changes in land allocation over time.

Following these steps, we construct our main outcomes variable measured at the crop share × band-year level. The closer the indicator is to 1, the stronger the presence of that crop.

B.2.2 Control variables

Weather data

We use data from the TerraClimate dataset[28], developed by Abatzoglou, Dobrowski, Parks, and Hegewisch (2018), which provides monthly climate variables at 4 km spatial resolution for the period 1958–2023. Their methodology combines fine-scale climatological baselines from WorldClim with time-varying anomalies from CRU TS4.0 and the Japanese 55-year Reanalysis (JRA55), yielding a high-resolution climate dataset with broad temporal coverage. We control within the buffer for temperature patterns during summer (June–August) as well as during the previous winter (December–February), which is a critical season for crop survival and establishment. These seasonal temperature controls account for interannual climatic shocks that affect crop yields and relative profitability, thereby influencing farmers' crop share decisions. We calculate minimum and maximum temperatures for winter (December of year t-1 to February of year t) and for summer (June to August of year t) for each biogas unit buffer by taking the average of all pixels over the considered months within each buffer and each year. We use as controls annual downward shortwave radiation and total precipitation by calculating the annual average of all pixels within each buffer and each year. The procedure we use is as follows:

1. We import yearly raster files corresponding to the study period into QGIS from the TerraClimate dataset.
2. For each biogas plant, raster layers are clipped using the spatial extent of the corresponding buffer.
3. Zonal statistics are computed for each buffer and each year by aggregating pixel-level values within the buffer boundaries (mean).
4. The resulting zonal statistics are exported as `.csv` files and merged with the master dataset.

Urban Area

Urbanization is likely to influence agricultural land allocation through land pressure and competing land uses. We therefore control for whether a municipality hosting a biogas unit belongs to an urban unit based on the definition of the National Institute of Statistics and Economic Studies (INSEE). An urban unit is defined as a municipality or group of municipalities with a continuously built-up

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[28] https://www.climatologylab.org/terraclimate.html

area (no break of more than 200 meters between two buildings) and at least 2,000 inhabitants. We construct a binary variable equal to one if the municipality with a biogas unit belongs to an urban unit, and zero otherwise.[29] This file is merged with the master dataset[30] based on the INSEE code, which serves as the common merging key.

Costal proximity

We control coastal location to account for land uses pressures.[31] Following (Letort & Temesgen, 2013), coastal proximity is constructed from the "*Communes de la loi Littoral*" database[32], which identifies municipalities located along to the coast. A canton is considered as coastal if at least one of its munucipalities has a coastal border. The resulting variable is merged with the master dataset using the municipal identifier (i.e. code INSEE) as the common identifier.

Population density

The final control variable to capture the competition-related effects of urbanization is population density. Following (Letort & Temesgen, 2013), population density is measured as the number of inhabitants per square kilometer. We construct yhis variable by merging the master dataset with INSEE file using the municipal identifier (i.e. code INSEE).[33]. Municipal surface areas are obtained from the dataset used to build *urban area* variable, allowing us to compute the population density.

Livestock density

Our objective is to capture the livetsock intensity surronding biogas units, this component affects both the likelihood of biogas plant siting (through the availability of animal waste) and the orientation of local cropping systems toward livestock production. Our raw data come from the 2010 Agricultural Census, we divide livestock units by utilised agricultural area (in hectares) allowing buffer comparabl and capturing the pressure of animal production on land resources.[34] The procedure we use is as follows:

1. At the municipal level i, we calculate the ratio of livestock Units to utilised agricultural area (SAU) as $d_i = \frac{UGB_i}{SAU_i}$.

2. Since buffers of 15 kilometers radius overlap multiple municipalities, we perform a spatial

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[29] Dataset available online : Communes et villes de France en CSV, Excel, Json, Parquet et Feather.

[30] The file contains information on biogas units and agricultural parcels.

[31] These pressures (as residential and industrial development) increase competition for land and can influence farmers' crop choices, thereby affecting the distribution of agricultural land among different crops

[32] Available online at Communes de la loi littoral au Code Officiel Géographique

[33] Available dataset online : See *Recensements de la population 1876-2023*

[34] 2010 Agricultural Census. The analysis will be updated using the 2020 Agricultural Census accessed via the CASD data.

intersection between municipalities with d_i and buffer biogas units. This operation decomposes space into spatial fragments indexed by (i, j), each fragment belonging simultaneously to municipality i and buffer j.

3. Let A_{ij} denote the agricultural surface (in hecatre) of the intersection between municpality i and buffer j. For each fragment, we compute the level of livestock as $Q_{ij} = d_i \times A_{ij}$ to convert municipal into fragment livestock quantity.

4. At the end, we obtain the livestock density at the buffer level by aggregating framgment livestock quantities as $d_j = \frac{\sum_i Q_{ij}}{\sum_i A_{ij}} = \frac{\sum_i d_i \times A_{ij}}{\sum_i A_{ij}}$.

By appling the areal-weighting interpolation approach of Goodchild and Lam (1980), we construct a measure of livestock density at the buffer level. Higher values of this indicator reflect a stronger orientation toward livestock farming in the vicinity of the biogas unit

Agro-industries density

Industries generate waste that can be valorized in the methanization process, which can affect the localization of biogas units. Our raw data come from the SIRENE database, and we select, from the categories listed in the ADEME (2013) report, only agro-industries that generate industrial methanogenic waste potential (classified as Category 2 and 3 under EU Regulation No. 1069/2009). We construct a density of agri-food industries, defined as the number of agri-food establishments per unit of Utilised Agricultural Area. This normalization measures the pressure exerted by agro-industrial activities on the local agricultural production base. It captures the intensity of agriculture–industry interactions and ensures comparability between territories that differ in size and land structure. The procedure is as follows:

1. We extract from the SIRENE database only agro-industrial establishments using their NAF codes (reported in Table Table 14), which provide establishment-level information with precise spatial localization.

2. Following the areal interpolation approach of Goodchild and Lam (1980) and the same steps used to construct the livestock density control variable, we replace livestock units (UGB) by the number of agro-industrial establishments to compute agro-industry density at the buffer level.

We obtain a measure of local agro-industrial pressure that controls for the availability of industrial organic waste and for spatial attractiveness to biogas plant siting, thereby reducing potential location-driven confounding in the estimation of crop reallocation effects.

Table 14: Agro-industries classification

NAF Code	**Activity**	**Type of waste**
10.11Z	Processing and preserving of meat	Animal by-products (cat. 1,2,3), manure-related matter, fats
10.12Z	Processing and preserving of poultry meat	Animal by-products (cat. 1,2,3), manure-related matter, fats
10.13A	Production of meat and poultry meat products	Cutting fats, meat waste
10.20Z	Processing and preserving of fish, crustaceans and molluscs	Fish waste
10.31Z	Processing and preserving of potatoes	Potato peels and potato waste
10.32Z	Manufacture of fruit and vegetable juice	Fruit and vegetable waste
10.39A	Other processing and preserving of vegetables	Vegetable waste, sorting rejects
10.39B	Processing and preserving of fruit	Fruit waste, sorting rejects
10.41A–B	Manufacture of oils and fats	Oil cakes, grain sorting residues, filtration residues
10.42Z	Manufacture of margarine and similar edible fats	Fat residues
10.51A	Operation of dairies and cheese making (fresh products)	Whey, milk, fresh cheese waste
10.51B	Manufacture of butter	Dairy by-products
10.51C	Manufacture of cheese	Cheese waste
10.51D	Manufacture of other dairy products	Dairy by-products
10.52Z	Manufacture of ice cream	Sweet dairy waste
10.61A–B	Manufacture of grain mill products	Cereal dust, wheat distillers grains
10.62Z	Manufacture of starches and starch products	Starch processing residues
10.71A	Manufacture of bread and fresh pastry goods	Cooked dough, flour, non-compliant bread
10.72Z	Manufacture of rusks and biscuits; preserved pastry goods	Sweet processing waste
10.73Z	Manufacture of pasta products	Pasta waste
10.81Z	Manufacture of sugar	Beet pulp, molasses, sugar factory waste
10.82Z	Manufacture of cocoa, chocolate and confectionery	Cocoa and confectionery waste
10.85Z	Manufacture of prepared meals	Fruit and vegetable waste
10.86Z	Manufacture of homogenised food and dietetic food	Mixed agri-food waste
10.89Z	Manufacture of other food products n.e.c.	Mixed agri-food waste
10.91Z	Manufacture of prepared feeds for farm animals	Meat waste
10.92Z	Manufacture of pet food	Meat waste
11.01Z	Distilling, rectifying and blending of spirits	Distillation residues
11.02A–B	Wine production and sparkling wine	Grape pomace
11.03Z	Manufacture of cider and other fruit wines	Apple and fruit pomace
11.04Z	Manufacture of other non-distilled fermented beverages	Fermentation residues
11.05Z	Manufacture of beer	Brewers' spent grain (barley)
11.06Z	Manufacture of malt	Malt spent grains, malt germs