Guilty or scapegoat? Land consolidation and the hedgerow decline

Valentin Cocco[a,b*], Raja Chakir[a] and Lauriane Mouysset[c]

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[a] *University of Paris-Saclay, INRAE, AgroParisTech, Paris Saclay Applied Economics, Palaiseau, France.*

[b] *Centre International de Recherche sur l'Environnement et le Développement, Nogent-sur-Marne, France*

[c] *CNRS, UMR 8568 CIRED, Nogent-sur-Marne, France*

Corresponding author: valentin.cocco@agroparistech.fr

Abstract

Land consolidation is a standard policy instrument to reduce the fragmentation of farmland by spatially redistributing land ownership. While its primary goal is to improve agricultural productivity, evaluation should integrate its potential impact on the landscape, as it may threaten its sustainability. The French consolidation program in the second half of the 20th century is a case in point. Often blamed for the drastic decline in hedgerows observed in the countryside, researchers debate its responsibility. Our study proposes the first causal estimation of its impact on hedgerows by applying a staggered difference-in-difference setting to a longitudinal survey in Lower Normandy, France (1972-2010). The results indicate that consolidated municipalities experienced an additional loss in hedgerow density of 13.55m/ha (standard error: 2.07). Importantly, this loss accounts for only 17% of the total decline, challenging the common narrative that consolidation is the leading cause of the hedgerow decline. Our analyses also reveal heterogeneous impacts over time since consolidation and consolidation period. Our findings call for explicit accountability of land consolidation for landscape damage while placing this policy instrument in a broader context of political, social, and market drivers of landscape dynamics.

Keywords: land property, land consolidation, landscape changes, hedgerows, difference-in-differences

JEL Codes: Q15, Q24

1 Introduction

Productive and sustainable agriculture relies on an efficient allocation of land, a scarce resource. In spatial terms, this allocation problem asks the right level of land fragmentation: to what extent should each land holding be scattered in multiple plots or consolidated into one unique parcel? Many policymakers have estimated land fragmentation to be excessively high in their country. Some would even perceive fragmentation as "the blackest evil" (Farmer, 1960), as it would severely increase the production costs of agriculture and prevent its modernization (King and Burton, 1982). National governments have consequently implemented land consolidation (LC) reforms in varied contexts including Western Europe (Vitikainen, 2004), Central and Eastern Europe (van Dijk, 2007), South and Southern Asia (Niroula and Thapa, 2005), or Eastern Asia (Kawasaki, 2010; Wu et al., 2005).[1] As substitutes to deficient land markets, these policies organize or incentivize land transfers between landowners so that each ends up with the same amount of land but more clustered and contiguous. Many LC programs are still being applied, and other countries consider the opportunity to do so (Veršinskas et al., 2020; Ali et al., 2019). However, the costs and benefits of land fragmentation is both a long-standing and current debate (Bentley, 1987; Knippenberg et al., 2020) and LC can have a substantial public cost (Hiironen and Riekkinen, 2016). *Ex-post* evaluations are therefore precious to develop an evidence-based opinion on the adequacy of LC.

The first LC programs focused on improving the economic performance of farms. The criticisms towards the environmental and social side-effects of LC, as well as the new challenges faced by rural territories, led to broadening the objectives of LC towards sustainable rural development (Veršinskas et al., 2020; Vitikainen, 2004; Zang et al., 2021; Pašakarnis and Maliene, 2010). This enlarged conceptual framework considers outcomes beyond farm productivity for evaluation (Crecente et al., 2002; Hiironen et al., 2010). One critical aspect is landscape changes. Substantial modifications in the landscape composition and structure may follow land transfers. Whether the landscape impacts of LC are positive or negative is a debated question, with presumably complex outcomes affected by the regional conditions and the modalities of consolidation (Janečková Molnárová et al., 2023; Zang et al., 2021). Because agricultural landscapes support many production, regulation and cultural ecosystem services (Duarte et al., 2018), these impacts should matter in the overall assessment of LC.

[1] For example, the first wave of LC programs occurred in Western Europe after the Second World War, targeting agriculture mechanization (Vitikainen, 2004). In Central and Eastern Europe, land consolidation instruments were introduced to compensate for the fragmentation induced by the land reforms that followed the end of the Soviet Union (van Dijk, 2007). China has an ongoing large-scale LC program that started at the end of the 20th century to ensure food security (Zhou et al., 2020).

This paper explores the impact of LC on agricultural landscapes, focusing on the *bocage* landscape in Lower Normandy, France, using a natural experiment approach. Bocages are traditional landscapes characterized by a hedgerow network delimiting parcels. They are commonly observed in Western Europe (e.g., England, Ireland, Western France, Galicia), but hedgerows are typical components of agricultural landscapes on every continent (Baudry et al., 2000).[2] These managed woody linear elements serve various functions, including demarcating property limits, enclosing cattle, providing timber, storing carbon, conserving soil, and contributing to aesthetic value (Montgomery et al., 2020). In France, hedgerows experienced a striking decline in the second half of the 20th century in the context of agricultural intensification and mechanization. The French LC program, implemented during the same period, faced accusations for this decline, though questions about its actual impact have been raised by French geographers (Preux, 2019).

We combine a panel dataset of hedgerows in Lower Normandy (1972-2010) built on the interpretation of aerial photographs in 1175 sampled circles with the census of LC operations to estimate the causal effect of LC on hedgerow density. We use the Callaway and Sant'Anna difference-in-difference estimator (2021) that is robust to treatment effect heterogeneity when treatment assignment is staggered. In our preferred specification, land consolidation leads to a significant average loss in hedgerow density of -13.55m/ha (standard error: 2.07). This decrease accounts for about 17% of the overall hedgerow loss observed for the consolidated municipalities during the study period. Although LC contributed substantially to the hedgerow decline, it does not account for most of it in our study area, challenging common beliefs held by stakeholders.

Our results also suggest heterogeneity in LC effects over time. The earliest treated municipalities experienced a relatively high and persistent loss of hedgerows, while the latest did not show a significant decline. In-between municipalities experienced an intermediate but significant short-term density loss, which became non-significant in the longer term. Heterogeneity over consolidation period is consistent with higher environmental expectations and regulations for LC in France over time. Our analyses do not reveal significant pre-trends and are robust to alternative specifications. In summary, our results bring a nuanced conclusion on the role of LC in the transformation of French bocages. Even if its responsibility is demonstrated, it must be placed in a broader context of policy, market and social drivers of landscape dynamics.

This work relates to three strands of research. First, an abundant literature conducts *ex-post* evaluations of LC effects with a growing interest in environmental outcomes, landscape changes included (Zang et al., 2021; Janečková Molnárová et al., 2023). However, the descriptive settings

[2]The terminology for these features may vary across regions, such as shelterbelts or windbreaks in North America.

often restrain the causal interpretation. Zhang et al. (2014) focus on before-after comparisons of consolidated areas in China so that a counterfactual is missing. In our study area, Preux (2019) studies hedgerow networks and observes no substantial difference between consolidated and non-consolidated municipalities, but they could only access post-consolidation observations for a few municipalities. Conversely, recent econometric studies use natural experiment settings to estimate the effects of the French LC program (Chabe-Ferret and Enrich, 2021; Loumeau, 2022). They consider agronomic, economic, demographic, or political outcomes, not environmental ones. We extend this corpus of literature by proposing the first evaluation of the landscape impacts of LC based on modern causal inference methods.

Second, our study contributes to previous literature on the drivers of landscape changes. Identifying the causal effects of possible drivers is a challenging research avenue because of their intricacy and interactions (Meyfroidt, 2016; Bürgi et al., 2022). For instance, Sklenicka et al. (2014) used a cross-border approach to investigate the influence of the political and socioeconomic conditions on rural landscapes. While highlighting national differences, their setting cannot disentangle their components. Another obstacle is the availability of fine-scale data to describe landscape dynamics beyond extensive transformations, which are much more studied (e.g., deforestation (Busch and Ferretti-Gallon, 2017)). Making good use of a spatially explicit, long-standing panel dataset in a natural experiment setting, we isolate the contribution of a well-defined public policy to a much-discussed landscape change.

Finally, our work connects to land property rights and natural resource management research. Regarding this subject matter, studies tend to focus on the influence of land tenure security on sustainable management (Tseng et al., 2021). Direct measures of environmental outcomes have facilitated estimating the physical impacts of tenure security (Hou et al., 2023). However, the land property regime encompasses other dimensions than security, which may drive land quality as well. Thereby, Li and Zhu (2023) investigate how an extension of land transfer rights altered land erosion. Here, we access the spatial dimension of a land regime, as the French consolidation program made spatial agglomeration of land property a national objective with prescriptive legislation (Sargent, 1952).[3] Our study utilizes this program to display the environmental consequences of a spatial concentration principle, a poorly studied feature in a land property regime.

The remainder of the article is organized as follows: section 2 presents our study area and gives precision on the French LC program before introducing our tested hypotheses. Section 3

[3]The law on consolidation in France gave LC operations the public interest status so that administrative authorities could execute them without the agreement of all landowners or even a majority.

details the data, the sample, and the variables of interest, followed by section 4, which justifies our empirical strategy. Section 5 displays our main results on the impact of LC on hedgerow density with robustness checks and investigates heterogeneity over time and cohorts and underlying mechanisms. Section 6 concludes the article.

2 Background and hypotheses

We focus our study on Lower Normandy, France's densest bocage region. The French LC program was deployed there in the late 20th century. While it concentrated accusations of hedgerow uprooting, French rural geographers have questioned its actual responsibility.

2.1 The Norman bocage

Bocage predominantly characterizes the landscapes of Northwestern France (Flatrès and Flatrès, 1997). Hedgerow plantation there has been a progressive phenomenon (*"embocagement"*), accelerating through the 19th century, so that hedgerow density presumably reached its highest level in the first half of the 20th century (Marguerie et al., 2003; Flatrès, 1979; Bazin and Schmutz, 1994). Three main reasons motivated these plantations. First, they provide material marking of private property in the context of agrarian individualism and equal succession (Bloch, 1930; Bazin and Schmutz, 1994). Second, they support the development of cattle farming by containing livestock in meadows (or protecting field crops from straying livestock) (Baudry et al., 2000). Third, they are "short-rotation linear forests" that supply wood in poorly forested regions (Bazin and Schmutz, 1994). These landscape elements were fully integrated into traditional farming: they protected, produced, and were intensively managed based on peasant knowledge and techniques (Magnin, 2021).

Lower Normandy is home to the Norman bocage, one of the most emblematic of Northwestern France. This administrative French region even shows the highest present density of hedgerows: 80 meters of hedgerow linear per hectare, to compare to the national average density of 28m/ha (ANBDD (2021)).[4] Related to the traditional association between bocage and cattle farming, Lower Normandy has the second highest share of permanent grassland in France (32% of land cover in 2014), even though it had reduced to the benefit of temporary grassland and forage crops (Sieper,

[4]Lower Normandy is actually an *ancient* administrative region. In 2016, French administrative regions merged to reduce their total number from 22 to 13. Lower and Upper Normandy merged into a unique Normandy region. Although the name "Norman bocage" does not explicitly refer to Lower Normandy, Lower Normandy is much richer in hedgerows than Upper Normandy (24m/ha).

1996; Preux, 2019). More broadly, it also has the highest share of farmland (73% of land cover in 2014) and the second smallest share of woodland (15% of land cover) (Fontes-Rousseau and Jean, 2015). This land distribution supports an agricultural sector mainly oriented towards dairy farming and mixed farming. Nevertheless, the regional features hide infraregional heterogeneity. For instance, the plain corridor that crosses Lower Normandy mostly produces field crops, and its landscape is more similar to the open fields of the Parisian basin and Northeastern France (Fig.1; Sieper (1996)).

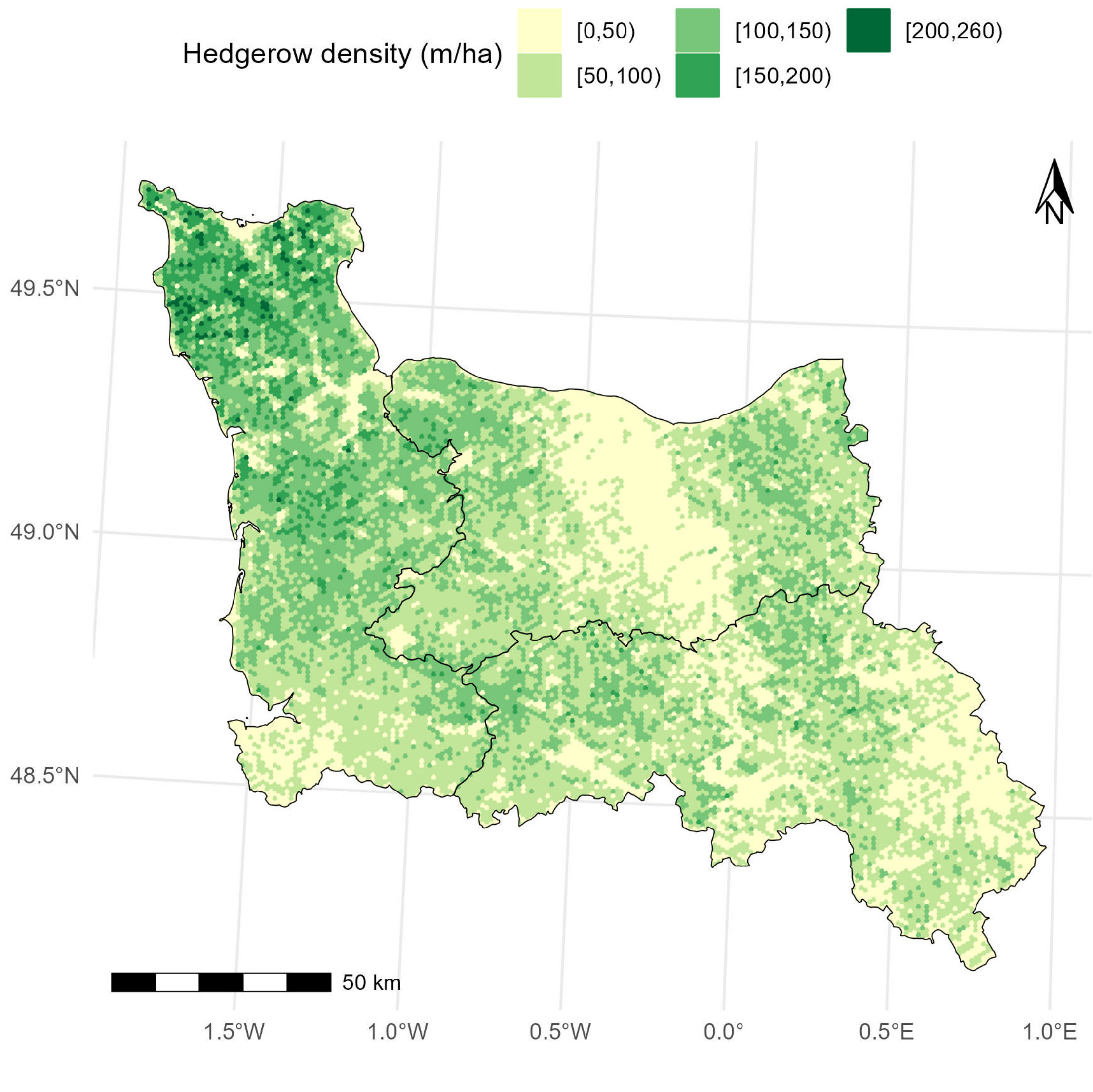

Figure 1: Hedgerow density in Lower Normandy (2009-2013). 1-km hexagonal grid. The black lines represent the borders of the three Lower Normandy departments. Data source: Dispositif de Suivi des Bocages (DSB), IGN, OFB.

2.2 The French land consolidation program

After the end of World War II, the French economy was attempting to recover, including its agriculture, which was producing insufficient amounts to meet the needs of the population or achieve a positive food balance. There was a strong political will to move from traditional peasant agriculture to mechanized, intensive, and market-integrated agriculture (Perichon, 2004). The LC program (*"remembrement"*) was one of the pillars of this project. Farm holdings were too fragmented to make tractor adoption valuable and, more broadly, have a "rational use of land". Previous attempts to reduce fragmentation had shown limited effectiveness and scope. The 1941 law anticipated the modernization of French agriculture to come after the war and set the foundations for a modern, large-scale consolidation, followed by a decree in 1954 that specified the practical modalities (Gatty, 1956; Sargent, 1952). The established protocol navigated between local dialogue and coercion (Gastaldi and Vallery-Radot, 1976):

Landowners, farmers, or State civil servants could suggest initiating an LC operation in a municipality (*"commune"*). An *ad hoc* council of municipality stakeholders would be established and decide on the suitability of such an operation. If the council was favorable, the local State representative ordered an LC operation covering all the farmland of the municipality, even if some landowners or farmers objected. Technical phases and consultation phases alternated until a consolidation project emerged. The proposal had to allocate land so that each owner received a land surface equal to his provision, accounting for the differences in the productive potential of each land type.

In addition to land transfers, the council planned landscaping works (*"travaux connexes"*) to support agricultural development. These works included the creation of new paths for heavy machinery, the drainage of wetlands, and the elimination of natural obstacles, notably hedgerows. Once the council validated the consolidation project, a decree stated that land transfers were effective and development works had to start. Until 1983, the State was the project owner of consolidation operations and paid for all the costs of the operation *per se*. It also subsidized the development works up to 60% of the total cost (landowners covering the rest). The 1983 law on decentralization made the department (*"département"*), an administrative-territorial unit,[5] take responsibility for project administration and financing. The State continued to control for legality and to advise local stakeholders (Peignot et al., 1999).

[5] Three departments constitute Normandy.

The deployment of LC in France was gradual (Philippe and Polombo, 2009). The first operations started at the end of the 1940s, and the last were in the 2000s, for about 18000 operations in total. Regional participation was highly heterogeneous. The field-crop-oriented Parisian basin and Northeastern France went for consolidation first in the 1950s-1960s. LC progressively extended, mainly to the rest of the northern half of France. As for Lower Normandy, whereas the grain-growing plain corridor and southeastern regional border consolidated as early as the Parisian basin, the rest of the region engaged lately and incompletely: LC events peaked at the end of the 1980s, and only 41.7% of its municipalities got consolidated (Fig.2, Fig.A.1).

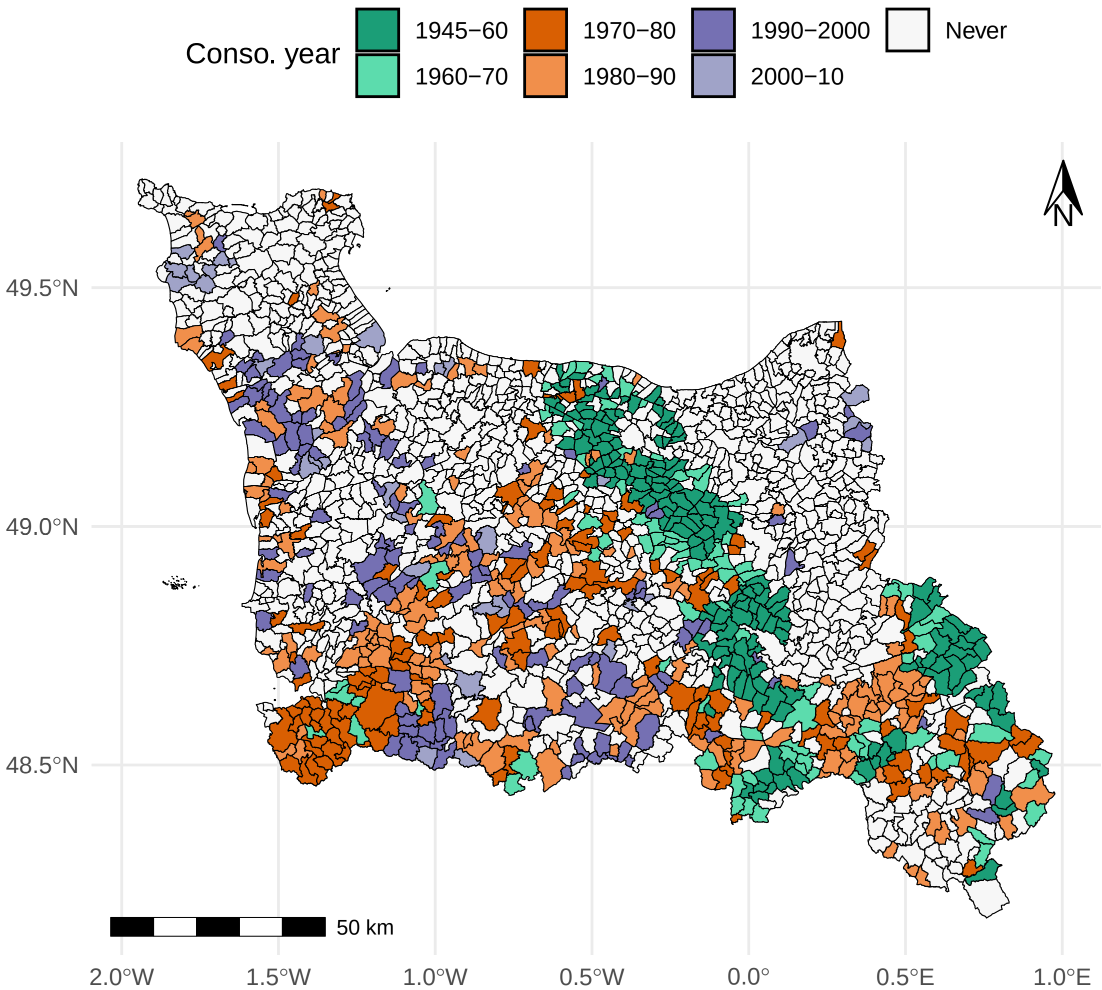

Figure 2: Map of consolidation operations in Lower-Normandy. Data source: Philippe and Polombo (2009).

2.3 The debated role of LC on the hedgerow decline

During the 20th century, the French countryside lost about 70% of its initial 2 million kilometers of hedgerows (Pointereau, 2001). LC is often held responsible for this. "Blank slate" operations could uproot tens of kilometers of hedgerows with bulldozers within a few weeks and abruptly transform the landscape (Flatrès, 1979; Preux, 2019). The accusations sometimes mixed with social conflicts due to unfair land redistribution and forced modernization. Overall, LC concentrated criticism of excessive agricultural intensification, symbolized by a "national monument to nature and the victims of land consolidation" erected in Geffosses, a village of Lower Normandy (Preux, 2019).

Nonetheless, French rural geographers have qualified the actual contribution of LC to *"débocagement"*. Flatrès (1979) argues that the State administrations were aware of the environmental risks and took good care to prevent unnecessary removals. Although some uprooting was inevitable to agricultural modernization, the concerted approach led to a "controlled and rational clearing" (Renard, 1973). Not only would LC limit uprooted hedgerows, but it would also determine conservation priorities to maintain a well-connected and functional network (Flatrès and Flatrès, 1997). In that sense, it may have even been beneficial to the bocage, as, in its absence, farmers would have removed more hedgerows in a disorderly way (Guellec, 1971). To quote Renard in Missonnier (1976):

"It is wrong to believe and repeat that official land consolidation is the main cause of débocagement. First, because some clearing is observed after consolidation, on hedges retained by the land surveyor. Second, in all regions, individual clearing is considerable, although difficult to assess. [...] From this point of view, there is no doubt that a well-done consolidation would preserve the bocage more than anarchic individual clearings."[6]

One may answer back that the consolidation operation induced the clearing activity observed afterward. But the safety-net conjecture may be all the more accurate over time, as the environmental expectations grew, with legislative translations (Husson and Marochini, 1997). For instance, the 1975 and 1976 laws made mandatory the attendance of an expert environmentalist to the consolidation council as well as an *ex ante* environmental impact assessment (Baudry and Burel, 1984).

[6] "Il est faux de croire et de répéter que le remembrement officiel soit le grand responsable du débocagement. D'une part, parce que des arasements sont constatés après le remembrement, sur des haies conservées par le géomètre. D'autre part, dans toutes les régions, l'arasement individuel est considérable bien qu'il soit difficile à apprécier. [...] De ce point de vue, il ne fait pas de doute qu'un remembrement bien fait préserverait sans doute plus le bocage que des arasements individuels anarchiques."

From that perspective, LC could be more of a scapegoat, hiding the actual causes of the hedgerow downfall (Preux, 2019).

However, quantitative elements to corroborate these assumptions are missing. To our knowledge, the only exception is Preux (2019), who observes no substantial difference between consolidated and non-consolidated municipalities, but only had recent post-consolidation data on a small territory.

2.4 Hypotheses

Based on the above discussion, we formalize competing hypotheses on the impact of LC on the Norman bocage.

- **The ripper.** The consolidation framework led to land transfers, changes in agricultural practices, and hedgerow removal that would not have occurred otherwise. In its absence, total costs for spontaneous consolidation and individual development works were too high. The organized negotiation framework and public financing made them feasible. In that case, we expect the causal effect of a consolidation operation on the hedgerow density to be negative. We also distinguish between LC's direct and indirect effects on hedgerow density. Direct effects are the hedgerows removed during development works and subsidized by the official operation. Indirect effects are subsequent uprooting by farmers throughout the intensification trajectory triggered by LC.

- **The safeguard.** LC rationalized hedgerow removal at the municipality level, balancing the need for farmers to regroup their holding with the public cost of development works and the social demand for a preserved bocage. Otherwise, uncoordinated farmers would have pulled up more hedgerows to support mechanization at the individual level. Hence, we expect LC to have a positive impact on hedgerow density.

- **The neutral.** The two above mechanisms can coexist and compensate for each other. They can also make no difference compared to the absence of consolidation: farmers do not need LC to initiate hedgerow uprooting, and subsidizing development works only engender dead-weight effects. In any case, we expect a null effect of LC on hedgerow density.

3 Data

A longitudinal survey produced by the public administration describes the temporal evolution of the hedgerow network in Lower Normandy. We combine these panel data with a census of land consolidation operations at the municipality level. We compute covariates from additional data sources to control for potential confounding factors linked to environmental, administrative, and agricultural conditions.

3.1 Data sources

Hedgerows. We use the panel dataset produced by DREAL Normandie, the administration representative of the national Ministry of Ecology at the regional level. Their sample is composed of 1175 circles covering the entire region. Within each circle, hedgerows are mapped as linear objects based on human photointerpretation of aerial photographs. Circles are 300m-radius (28.3ha) and grouped by lots of four so that adjacent circles of the same lot are 2km apart and adjacent lots are 7.9km apart (Fig. A.2, Fig. A.3). DREAL Normandie chose this 2-level systematic sampling plan to ensure the representativeness of the whole region and compute aggregated statistics at the subregional level with reasonable precision and limited monitoring costs (Vadaine, 2002).[7] Data are available for all 1175 circles for four time periods: 1972, 1984, 1997/98, 2009/10. Aerial photography campaigns took place between May and August, were black and white for 1972, 1984, and 1997/8, colored for 2009/10.

Consolidation operations. Philippe and Polombo (2009) collected the consolidation operations carried out in France since 1944 from the archives of the Ministry of Agriculture. State administrations at the department level sent a paper table to the Ministry each year listing LC operations in their territory. The Ministry converted them into a computer file around 2000, which Philippe and Polombo have supplemented with operations after 2005 when they were no longer centralized. The file specifies, for each consolidation event, its municipality (*commune*) and its start and end dates.

Municipality map. We use the vectorial map of the French municipalities produced by OpenStreetMap from municipalities' land registers. The administrative division is that of March 6, 2014, which is the cleaned version with high-resolution municipality boundaries (5m-simplification) closest to our last observation (2010).

[7] For instance, based on 137 circles, they assess the 1998 hedgerow density of Pays d'Auge, about a tenth of Lower Normandy, with a relative precision of more or less 8.5% (at a 95% confidence level). The producers used lot grouping because it limits the number of aerial photographs needed in comparison to a single-level sampling.

Sources for covariates. The following datasets provide data we use to compute covariates or select our sample. The national agricultural census informs on the crop surfaces and the farm characteristics (size, work intensity) at the municipality level for 1970, 1979, 1988, 2000, and 2010. The agricultural region zoning regroups French municipalities into 432 regions based on dominant agricultural vocations. Its first version dates from 1956 and has only been through minor changes afterward due to modifications in the administrative division. BDTOPO (IGN) provides vectorial maps of wood cover for years 2001/2, 2009/10 and 2012 with a lower threshold of 0.05ha. The High-Resolution Layer on sealing rate (Copernicus) is a raster layer with a 20mx20m (0.04ha) resolution; the value of each pixel estimates the soil sealing rate. The raster layers on soil physical and chemical properties produced by the European Soil Data Centre (ESDAC) inform about grain texture (clay, silt, sand rates) and chemical composition (phosphorus rate, nitrogen rate, carbon-nitrogen ratio) at 500mx500m (5ha) resolution. The Official Geographic Code (INSEE) reports the events relative to administrative division since 1943. In particular, municipalities could merge into one bigger municipality.

3.2 Sample and variables

Sampling circles in the hedgerow dataset can overlap neighbored municipalities. They may especially cover consolidated and non consolidated municipalities. To ensure homogeneity of treatment status within each unit, we intersect circles with the municipality map to get mono-municipality "chunks". From 1175 circles, we get 1763 chunks. These chunks form our individual units for which we compute the variables described Table 1. The following rules select from the raw sample the chunks we eventually use in our empirical analysis:

1. Chunks whose municipality consolidated before 1972, our first observation period, are removed because no pre-treatment observation is available. Almost all of these chunks belong to the field crop areas of the plain corridor and the southeastern regional border (Fig.2).

2. A few municipalities experience several successive LC operations. We remove them from our sample so that treatment assignment follows a binary absorbing state.

3. We exclude municipalities that merge after consolidation, as we cannot distinguish between consolidated and non-consolidated parts of the resulting municipality.

4. The bordering chunks outside of Lower Normandy are removed because they are too few to respect the overlap assumption when controlling for the department.

5. Chunks with a soil sealing rate above 60% are removed, because highly sealed areas cannot support bocage landscapes. In the absence of older data, our reference year is 2012, assuming that consolidation did not affect having a very high sealing rate at that time.

6. Similarly, chunks with a woodland rate above 60% are removed. Because we have 3 observation periods at chunk level for this land use (2001/2, 2009/10, 2012), we take the maximum woodland share observed across the three time periods. Here again, we assume that consolidation has no influence on the probability of a chunk to be mainly woody.

7. Chunks with missing values for one or several variables are removed. Most of the missing values come from agricultural census data under statistic secret: an observation is unavailable when two or fewer farmers contribute to it, or one farmer represents 85% of it. This rule may reduce the representativeness of our sample by excluding municipalities with few farmers or highly concentrated farmland.

8. After applying previous rules, we only keep the largest chunk of each circle to limit chunk size heterogeneity and spatial autocorrelation issues. If the biggest chunk is under 5ha, it is also removed because the smallest chunks show high variance and extreme values (Fig.A.4).

This set of rules reduces our sample size from 1763 to 895 chunks, "1-chunk-per-circle" being the most exclusive rule. Table 2 details the contribution of each rule to the sample size.

3.3 Descriptive statistics

Table 3 presents descriptive statistics conditioned on treatment groups and the results of distribution independence tests. Regarding initial hedgerow density, the independence test detects significant differences in distributions between groups, but the large standard errors reflects extensive overlapping. Grouped means show that consolidated municipalities do not systematically have a lower or higher hedgerow density compared to non-consolidated ones: the average initial hedgerow density of the never-consolidated group (147 m/ha) lies between the one of the first treated group (140 m/ha) and the second treated group (156 m/ha). However, within consolidated chunks, the higher the initial density, the later the treatment date. The last treated group notably stands out from the others with an initial density of 182m/ha (although it is also substantially smaller with 34 chunks).

By contrast, we observe strong homogeneity within treated groups regarding the average change in hedgerow density between 1972 and 2010, around -80m/ha, with relatively high standard devia-

Table 1: Description of selected variables. TV: time-varying, TI: time-invariant.

Variable	**TV / TI**	**Description**
		Outcome
Hedgerow density (m/ha)	TV	Total length of hedgerow linear within a chunk divided by chunk's surface
		Treatment variable
Consolidation period (categorical)	TI	Treatment group based on the start date of development works. Dates are grouped into intervals marked out by observation years. For example, a chunk whose municipality began development works in 1986 belongs to the "1984-1998" treatment group.
		Covariates / Sample selection variables
Chunk area (ha)	TI	Total surface of the chunk unit
Administrative department (categorical)	TI	Department of chunk's municipality. Lower-Normandy has 3 departments.
Grassland area share (%)	TV	Grassland surface of municipality's farmers over municipality surface.
Farmsize (ha)	TV	Mean farmsize of municipality's farmers.
Clay rate (%)	TI	Mean clay rate at chunk level. Zonal statistics weighted by pixel surface covered by chunk.
Phosphorus rate (%)	TI	Mean phosphorus rate at chunk level. Zonal statistics weighted by pixel surface covered by chunk.
Soil sealing rate	TI	Mean sealing rate at chunk level. Zonal statistics weighted by pixel surface covered by chunk.
Woodland share (%)	TV	Share of chunk area covered by woodland.

Table 2: Sample size depending on selection rules. See subsection 3.2 for detailed rule description.

Sampling rules	N_{chunks}
No rule	1763
All rules	895
All but...	
... 'consolidation-after-1972' rule	1040
... '1-consolidation-only' rule	897
... 'no-municipality-merging' rule	895
... 'Lower-Normandy-only' rule	900
... 'no-sealing' rule	899
... 'no-woodland' rule	959
... 'no-missing-value' rule	912
... '1-chunk-per-circle' rule	1290

Table 3: Descriptive statistics per treatment group. Mean (standard deviation) for continuous variables, counts (share) for categorical variables. Last column reports p-values of Kruskal-Wallis independence test for continuous variables and Chi-square test for categorical variables. "H." stands for hedgerow.

	Never	1972-84	1984-98	1998-2010	p-value
Number of chunks	572	110	179	34	
Chunk area (ha)	24.8 (5.4)	25.6 (5.0)	25.4 (5.0)	25.7 (3.9)	0.346
Number of clusters	416	76	117	17	
H. density 1972 (m/ha)	147.4 (64.8)	140.4 (58.4)	156.2 (58.5)	181.6 (50.4)	0.001
H. density 2010 (m/ha)	87.2 (46.8)	60.3 (33.1)	76.3 (34.6)	101.9 (39.8)	< 0.001
H. change 1972-2010 (m/ha)	-60.2 (43.1)	-80.0 (44.5)	-79.9 (43.4)	-79.7 (47.1)	< 0.001
Grassland share 1970 (%)	67.5 (18.2)	61.3 (15.3)	68.8 (14.8)	73.2 (7.8)	< 0.001
Average farm size 1970 (ha)	21.1 (9.0)	18.0 (7.5)	16.8 (6.5)	17.9 (6.0)	< 0.001
Clay rate (%)	21.1 (4.4)	20.1 (2.9)	19.7 (3.2)	19.8 (2.9)	< 0.001
Phosphorus rate (%)	45.3 (5.7)	45.9 (5.5)	46.3 (5.3)	45.7 (4.9)	0.209
Administrative department					< 0.001
n°14	206 (36%)	29 (26%)	23 (13%)	11 (32%)	
n°50	208 (36%)	37 (34%)	94 (53%)	20 (59%)	
n°61	158 (28%)	44 (40%)	62 (35%)	3 (9%)	

tion ($\sim$ 45 for all three groups), to compare to the average loss for never consolidated chunks, -60 m/ha (s.d. 43). While we will control for potential confounders with distinct distributions between treatment groups like farm size, this suggests a negative impact of LC on hedgerow density.

Figure 3 brings graphical insights into the trend deviation caused by consolidation. During their respective treatment interval, consolidated groups show visibly sharper declines in hedgerow density than the never-consolidated group. On the other hand, the trend difference appears relatively low for pre-treatment periods, in favor of the parallel trends assumption, and for long-term post-treatment periods, suggesting persistent impact.

4 Empirical framework

We benefit from a natural experiment setup to evaluate the impact of LC on hedgerow density with a difference-in-differences strategy. Our preferred specification employs the estimator proposed by Callaway and Sant'Anna (2021) to account for treatment effect heterogeneity under staggered treatment. The nonparametric doubly-robust estimator conditions the parallel trends hypothesis on time-invariant covariates.

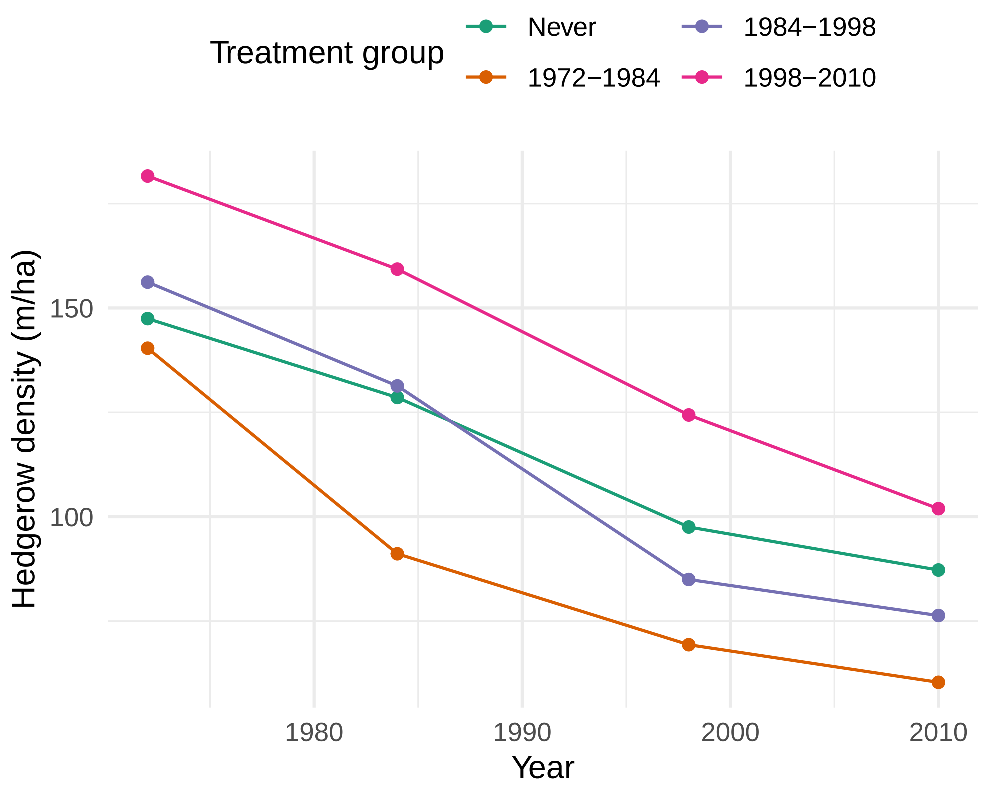

Figure 3: Average hedgerow density over time per treatment group. Weights are proportional to chunks' surface.

4.1 Estimation strategy

Following Rubin causal modeling framework, we aim to estimate the Average Treatment effect on the Treated (ATT):

$$ATT = \mathbb{E}[\ Y_{i,t}(1) - Y_{i,t}(0) \mid D_i = 1, t \geq g_i\ ] \tag{1}$$

$Y_{i,t}(1)$, $Y_{i,t}(0)$ being the potential consolidated and non-consolidated hedgerow densities of chunk i at time t, D_i a dummy for belonging to consolidated chunks, g_i the individual treatment period. The global ATT can break down into sub-sample ATTs accounting for treatment effect heterogeneity over time of treatment g (cohort) and time since treatment l:

$$ATT_{g,t} = \mathbb{E}[\ Y_{i,t}(1) - Y_{i,t}(0) \mid g_i = g\ ] \tag{2}$$

$$ATT_g = \mathbb{E}[\ Y_{i,t}(1) - Y_{i,t}(0) \mid g_i = g, t \geq g_i\ ] \tag{3}$$

$$ATT_l = \mathbb{E}[\ Y_{i,t}(1) - Y_{i,t}(0) \mid D_i = 1, t - g_i = l\ ] \tag{4}$$

Taking advantage of our panel dataset and our natural experiment setting with a binary treatment, our estimation strategy relies on difference-in-differences. More specifically, we use the Callaway and Sant'Anna (CS) estimator (2021). First, group-time ATTs are estimated separately following the standard non-parametric difference-in-differences estimator:

$$ATT_{g,t} = \mathbb{E}[\ Y_{i,t} - Y_{i,g-1} \mid g_i = g\ ] - \mathbb{E}[\ Y_{i,t} - Y_{i,g-1} \mid D_i = 0\ ] \tag{5}$$

Potential confounders on outcome trends can be accounted for with regression adjustment, inverse probability weighting, or a doubly-robust estimator (Sant'Anna and Zhao, 2020). Weighted means of group-time ATTs return aggregated ATTs:

$$ATT_g = \sum_t \frac{1}{T_g} ATT_{g,t} \tag{6}$$

$$ATT_l = \sum_g \frac{N_g}{N_{D=1}} ATT_{g,g+l} \tag{7}$$

$$ATT = \sum_g \frac{N_g}{N_{D=1}} ATT_g \tag{8}$$

with T_g the number of post-treatment periods of cohort g, N_g its number of individuals g, $N_{D=1}$ the total number of treated individuals.

Several reasons motivate our choice to use the CS estimator compared to other difference-in-differences estimators:

1. When treatment adoption is staggered with heterogeneity of treatment effects over time or cohort, the common two-way-fixed-effect estimator (TWFE) may suffer from negative weights or contamination issues (Goodman-Bacon, 2021; Sun and Abraham, 2021). As one may expect changes in the impact of consolidation over time (see section 2), we turn towards recent heterogeneity-robust difference-in-differences estimators.

2. Among them, we distinguish imputation estimators (Borusyak et al., 2024; Gardner, 2022; Wooldridge, 2021) and aggregation estimators (Sun and Abraham, 2021; Callaway and Sant'Anna, 2021; de Chaisemartin and D'Haultfœuille, 2020). While Borusyak et al. (2024) show their estimator to be BLUE for independent and identically distributed errors, Harmon

(2022) shows that agglomeration estimators are more efficient when serial correlation is high. Here, hedgerow mapping at a given period is built from the hedgerow mapping the period just before, so, regarding measurement error, a random walk seems more plausible than idiosyncratic error. More broadly, we expect inertia in hedgerow dynamics so that persistent shocks dominate transitory ones.

3. Another helpful property of aggregation estimators is that we conveniently access group-time ATTs (compared to imputation estimators that directly return time-since-treatment ATTs). As we only have three treatment groups with reasonable sample size (except for the last one), it is worth analyzing treatment effect heterogeneity at the group-time level.

4. While the other agglomeration estimators include covariates linearly, CS incorporates a doubly-robust control for covariates, combining the strengths of outcome regression and propensity score modeling. This is particularly interesting because our outcome is non-negative, and a linear outcome regression may not adequately describe the relationship between covariates and a limited dependent variable.

5. Finally, CS also proposes simultaneous estimation of confidence bands to overcome multiple-testing problems, which is especially valuable when computing many group-time ATTs.

Regarding inference, the bootstrap-based estimator proposed by Callaway and Sant'Anna (2021) computes standard errors clustered at the municipality level, i.e., at treatment level, to allow for dependence of error terms within (Abadie et al., 2023). Table 3 checks for group size at the cluster level because the standard error estimator is asymptotically valid. The number of clusters in each treatment group is relatively high except for the last one, so the interpretation of confidence bands for the latter is strongly limited. We also weight chunks according to their area to correct for heteroskedasticity (Solon et al., 2015).

4.2 Identification strategy

Causal identification of treatment effect in our difference-in-differences framework leans on three assumptions: parallel trends, absence of anticipation, and absence of spillover (SUTVA).

The parallel trend assumption questions the relationship between participation in consolidation and potential trends of the hedgerow network. French rural geography gives qualitative insights into the criteria influencing LC participation. At the national scale, there is a clear regional prioritization based on the preponderant production systems and their expected trajectories (Philippe and Polombo, 2009). However, at the regional scale, LC participation seems much more multifactorial. Guellec (1971) discusses for their study area how LC's spatial distribution correlates with production orientations, pedoclimatic conditions, urban proximity, or farmers' age structure. State administrations could also push for consolidation in municipalities estimated to show higher agricultural retardation (Flatrès and Flatrès, 1997; Husson and Marochini, 1997). Nevertheless, the driver reported most frequently is the presence of pro-consolidation local stakeholders with political influence (Flatrès and Flatrès, 1997; Renard, 1973; Preux, 2019; Guellec, 1971). For instance, Renard (1973) reports situations where the administration is overwhelmed by consolidation requests, so priority order results from insistent requests by local public figures and diffusion effects.

While some of these factors may be quasi-independent to hedgerow dynamics, others can correlate so that, if they affect the consolidation decision in Lower Normandy, parallel trends cannot hold. Therefore, we relax general parallel trends into a conditional parallel trend hypothesis by including covariates that proxy potential confounders. We compute a large set of variables from the data sources introduced earlier. To achieve the overlap assumption and to limit sample size reduction due to missing values, we only keep a few of them that target distinct sources of confounding. Selection variable is heuristic: we pick variables that are relatively well correlated to time variations of our dependent variable and are poorly correlated with each other. The five time-invariant covariates selected are department (reflecting, among other things, territorial political and administrative characteristics), 1970 grassland share (orientation of agricultural production), 1970 farm size (work intensity), clay rate (soil texture), phosphorus rate (soil chemistry). All are significantly correlated with hedgerow density variation and show significantly different distributions among treatment groups except phosphorus rate (Table 3, Fig. A.5).

Another source of variation in parallel trends assumption is the group used to build the counterfactual. Here, only never-treated observations compose the control group in ATT estimations (an alternative option includes the not-yet-treated observations). This choice reduces the scope of the parallel trend hypothesis without affecting the efficiency of our estimation because our never-treated group is much bigger than the other groups. Finally, pre-treatment observations in the second and third treated groups allow us to test for pre-trends and investigate the plausibility of our hypothesis (Roth, 2024). Alternatively, we can use these pre-trends to dimension the violation of parallel trends and assess the results' sensitivity to such deviation (Rambachan and Roth, 2023).

Regarding the absence of anticipation, the wide time range between two observation periods (12 to 14 years) dilutes the risk of an upcoming LC event influencing a pre-treatment value. Nevertheless, chunks whose consolidation happens shortly after the last pre-treatment observation may be sensitive to this. Once an LC procedure starts, farmers may wait until its end (less than three years later on average) for the beginning of subsidized development works to uproot hedgerows they would have removed sooner otherwise. As a robustness check, we run an alternative estimation where treatment groups depend on the starting date of the LC operation *per se* rather than the start of development works.

Hedgerow uprooting in consolidated municipalities may induce similar uprooting in neighbored municipalities, violating the stable unit treatment value assumption (SUTVA). Farm holdings are often spread over several municipalities. Suppose consolidation was associated with changes in agricultural practices at the farm level facilitated by hedgerow removal (e.g., procurement of a larger machine). In that case, farmers may also remove hedgerows in non-consolidated parts of their farms. Farmers without parcels in consolidated municipalities could also imitate their neighbors as they witness the economic benefits. As an *ex-post* check, we test for spatial autocorrelation in estimation residuals when we use a TWFE estimator. As an *ex-ante check*, we run a TWFE specification incorporating a dummy for being neighbored by a consolidated municipality.

5 Results

5.1 Main results

Table 4 presents the global ATT estimated with the CS estimator and four different sets of covariates. Our preferred specification (n°4) shows a highly significant negative impact of LC on hedgerow density of -13.55m/ha (std. err.: 2.37). The joint test for pre-trends shows no significant deviation from parallel trends (p-value = 0.32) in favor of the plausibility of conditional parallel trends. Specifications n°1-3 are variants with no or a subset of covariates. They also have highly significant negative ATTs, with point estimates between -13.19 and -17.71 m/ha. However, pre-tests reveal significant pre-trend deviations for specifications n°1 and 2, hampering the plausibility of unconditional parallel trends or conditioned on the administrative department only.

Table 5 decomposes the ATT of specification n°4 into group ATTs (ATT_g) and reveals heterogeneity of consolidation impact over groups. Only the first two groups have a significant ATT, with substantial differences in their point estimates. Chunks consolidated first (1972-1984) experienced a relatively high loss of -22.3m/ha (std. err. = 3.7), against -8.6m/ha (std. err. = 2.9) for the chunks consolidated during 1984-1998. Their confidence bands overlap at the 95% level but not at 90%, so we have some evidence that the consolidation impact is significantly lower for the second group. Regarding units consolidated during 1998-2010, although the point estimate is comparable

Table 4: Average treatment effect on treated population for different set of covariates. Estimated with the Callaway and Sant'Anna estimator. Doubly-robust control with covariates: departement and four continuous variables (grassland, farmsize, clay rate, phosphorus rate). Sample weighting with chunk area. Bootstrap standard errors clustered at the municipality level. *, **, ***: significance at the 10, 5 and 1 percent levels.

	(1)	(2)	(3)	(4)
ATT (m/ha)	-17.71 (2.63) ***	-16.49 (2.24) ***	-13.19 (2.18) ***	-13.55 (2.07) ***
Joint pre-test p-value	0.006 ***	0.08 *	0.17	0.315
Department covariate	No	Yes	No	Yes
Continuous covariates	No	No	Yes	Yes
N	895	895	895	895

to the others (-11.2m/ha), the large standard error (5.7) does not allow us to conclude a significant impact. A plausible explanation for this result is the small sample size of the last group (34 units).

Table 5 also reformulates level ATTs as a percentage of the total loss of hedgerow density observed between 1972 and 2010. It appears that LC accounts for 16.7% of the observed loss of density in the total treated population, more than a fourth in the first treated group (27.2%), and about a tenth in the second treated group (10.7%). It thus only explains a limited part of the total decline in the study period.

Table 5: Aggregated ATTs at the group and global levels. Estimated with the Callaway and Sant'Anna estimator. Doubly-robust control with covariates: departement, grassland, farmsize, clay rate, phosphorus rate. Sample weighting with chunk area. Simultaneous bootstrap standard errors clustered at municipality level. *, **, ***: significance at the 10, 5 and 1 percent levels. The last column relates ATT to the average total decline observed for the 1972-2010 period.

Group	N	ATT (m/ha)	ATT (%)
Global	323	-13.5 (2.3) ***	16.7
1972-1984	110	-22.3 (3.7) ***	27.2
1984-1998	179	-8.6 (2.9) ***	10.7
1998-2010	34	-11.2 (5.7)	13.9

Figure 4 displays the impact of consolidation over time for each treatment group ($ATT_{g,t}$). Consistent with the joint pre-test, the confidence bands overlap zero for all three pre-treatment estimations. Consolidation in the first group causes a persistent, significant impact. Point estimates suggest the impact decrease over time since consolidation. In other words, non-consolidated units would slowly "catch up" for the hedgerow uprooting. Nonetheless, the overlapping confidence bands prevent more than careful conjectures. As for the second treated group, ATT appears to be significant only in the short term. In 2010, the point estimate was smaller, which may reflect a "catching up" phenomenon, although large standard errors limit interpretation here again. Finally, we retrieve the zero-overlapping confidence band mentioned earlier regarding the last treated group.

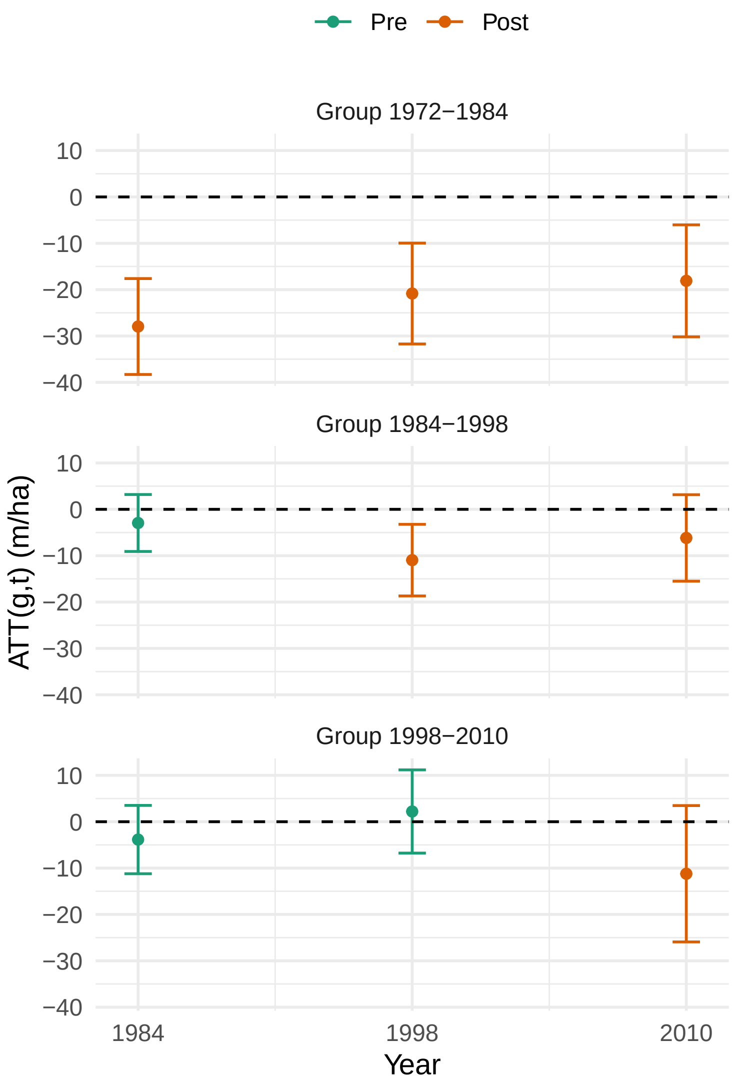

Figure 4: ATT(g,t). Estimation of group-time ATTs with the Callaway and Sant'Anna estimator. Doubly-robust control with covariates: department, grassland share, farm size, clay rate, phosphorus rate. 95% bootstrap-estimated simultaneous confidence bands. Sample weighting with chunk area. N=895.

5.2 Robustness checks

Work in progress. Robustness checks to conduct:

- Sensitivity analysis for the restriction on possible violations of parallel trends, following Rambachan and Roth (2023).
- Robustness to variations in estimation options with the Callaway and Sant'Anna estimator: control group (nevertreated / not-yet-treated), sampling weights (with / without), method

for controlling for covariates (outcome regression / inverse probability weighting / doubly robust).

- Robustness to the choice of difference-in-difference estimator: two-way-fixed-effect, Sun and Abraham (2021), Borusyak et al. (2024), Gardner (2022).

- Robustness to sampling rules. Selection rules introduced in 3.2 may alter the representativeness of our sample in the Norman bocage. We check for the robustness of our results when using more or less exclusive rules.

- Robustness to treatment definition: starting date of development works / starting date of consolidation operation.

- Robustness to possible spatial spillover: *ex post* - spatial autocorrelation in the TWFE residuals, *ex ante* - adding a spatial spillover dummy in the TWFE specification.

5.3 Treatment heterogeneity

Work in progress. We explored treatment effect heterogeneity over time with the Callaway and Sant'Anna estimator. Estimations of Quantile Treatment effects on the Treated (QTT) with dedicated estimators (quantile difference-in-differences, change-in-changes) will underscore possible variations of the consolidation impact depending on the initial hedgerow density.

5.4 Mechanisms

Work in progress. Our specification identifies aggregated impacts on hedgerow density. However, it cannot disentangle the direct effect of subsidized hedgerow uprooting from the indirect effect of non-subsidized uprooting following changes in farming practices motivated by consolidation. As a first exploration, we envision investigating more finely heterogeneity over time since treatment to separate quasi-immediate impact (direct effect) from short-term impact (indirect effect).

Moreover, the consolidation census also informs the number of landowners involved in LC operations. We could use this variable to explore how much the coordination of many economic agents played a part in landscape changes.

5.5 Other landscape indicators

Work in progress. We focused on the hedgerow density, but the network's spatial configuration can differ for a given density. Spatial configuration may notably affect the network's ecological functions (biodiversity corridor) or ecosystem services (windbreak, soil erosion regulation). Because LC coordinates hedgerow uprooting at the municipality level, it may not impact network configuration, even though it reduces its density. We can test this hypothesis from the spatially explicit hedgerow data by computing indices reflecting network connectivity (density of intersections) or fragmentation (density of dead-ends).

6 Conclusion

We investigated how land consolidation affects landscape dynamics in the case of the French consolidation program and the Norman hedgerow network from 1972 to 2010. Our difference-in-differences framework with a heterogeneity-robust estimator revealed nuanced results on the contribution of LC to the historical hedgerow decline. On the one hand, we found a highly significant negative impact of LC operations on hedgerow density. It is incorrect to defend that consolidation played a protective role in maintaining the hedgerow network at that time. On the other hand, this causal effect only accounts for about 17% of the total decline observed for our study period. We also found this that this effect decreased with consolidation time, suggesting that later operations integrated higher environmental expectations or norms. This work shows that LC cannot be held solely responsible for the decline and refutes the rhetoric that uses LC as a convenient scapegoat to focus blame.

While the present paper provides relevant insights into our understanding of the impacts of LC on bocage landscapes, it is important to recognize certain limitations associated with the study. One notable constraint we encountered was the limited availability of data, which may have restricted the strength of our results. The number of periods prevented us from conducting more tests on pre-trends to increase our confidence in the plausibility of conditional parallel trends. The number of observation units favored large standard errors in our analysis of treatment effect heterogeneity. Manual photo interpretation is a tedious task that shapes the sampling plan. Automated methods of hedgerow identification, such as remote sensing or image segmentation, could help expand the spatial coverage and temporal depth of our dataset. Machine learning algorithms can be particularly beneficial, using already available data as training or validation sets.

Another threat to internal validity is the assumption of no global spillover. We test for local spillovers in alternative specifications (work in progress). Identification in this framework still requires that at least some units are not directly or indirectly affected by consolidation operations. This condition would be incorrect if consolidation were to change Norman agriculture systemically, forcing non-consolidated farms to follow up. In this case, our specification with local spillover would underestimate treatment effects, so our estimate should be considered a lower bound instead.

Beyond these limitations, this paper calls for more environmental evaluations of LC reforms using robust causal inference methods to draw general conclusions about the environmental performance of LC. While contemporary reforms often claim to integrate environmental concerns into their goals and designs, the reality of this claim remains to be formally tested. Conversely, our results pointed out the limited liability of consolidation in the hedgerow decline. What are the other responsible factors? One may look further at the drivers motivating farmers to keep or remove their hedgerows, be it input and output markets, public policies, or social interactions. Addressing these questions will not only enhance our comprehension of the complexities surrounding hedgerow dynamics but also offer valuable contributions to the broader discourse on sustainable land management. These inquiries, which go beyond the current scope of our study, should be considered as avenues for future research endeavors seeking to provide a more comprehensive and nuanced understanding of how human societies interact with their environment.

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A Supplementary figures

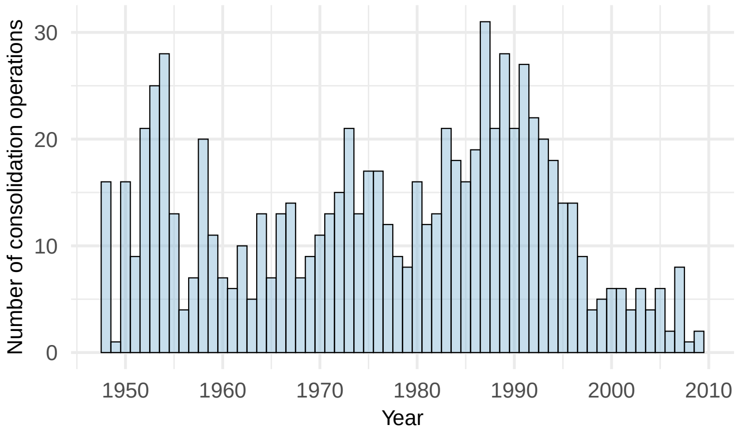

Figure A.1: Consolidation operations in Lower Normandy over time. Data source: Philippe and Polombo (2009)

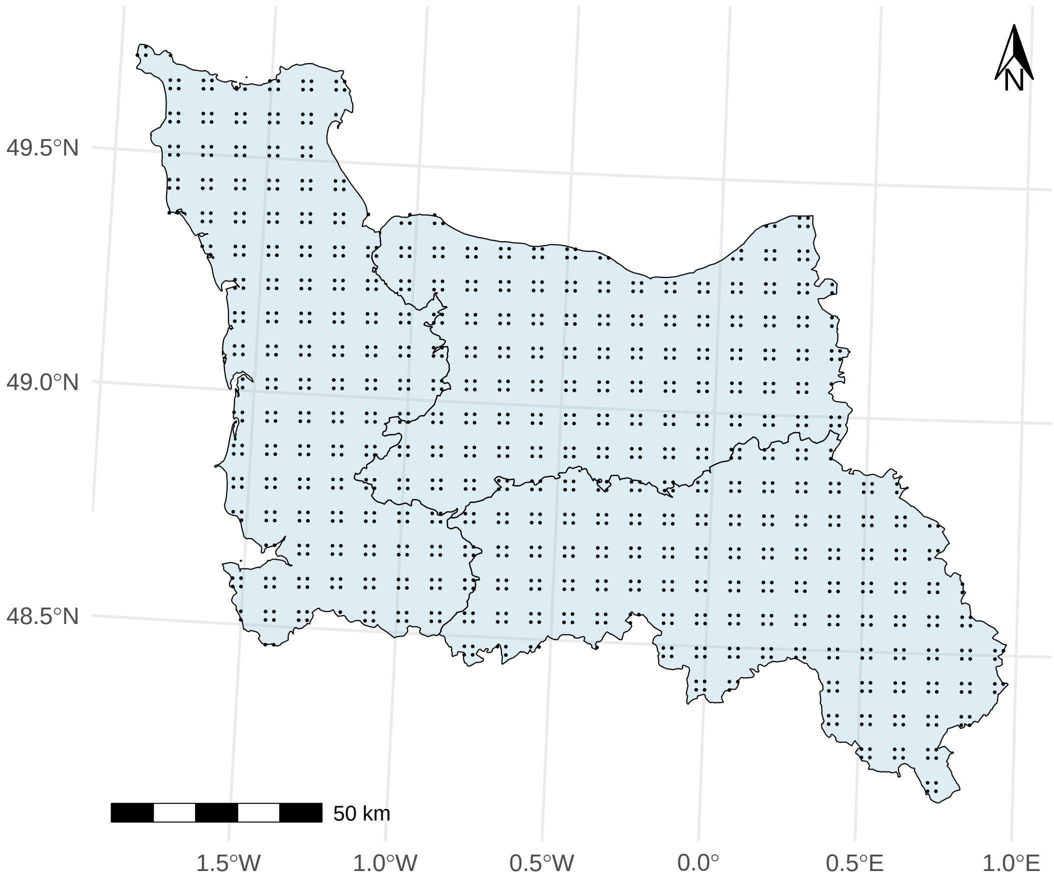

Figure A.2: Hedgerow sampling plan. 1175 circles are grouped by lot of four. Neighbored lots are 7.9km apart (from their center), neighbored circles (within a lot) are 2km apart.

Figure A.3: Photointerpretation of the hedgerow network. Within each 300m-radius circle of this lot of four, hedgerows are mapped from the aerial photograph.

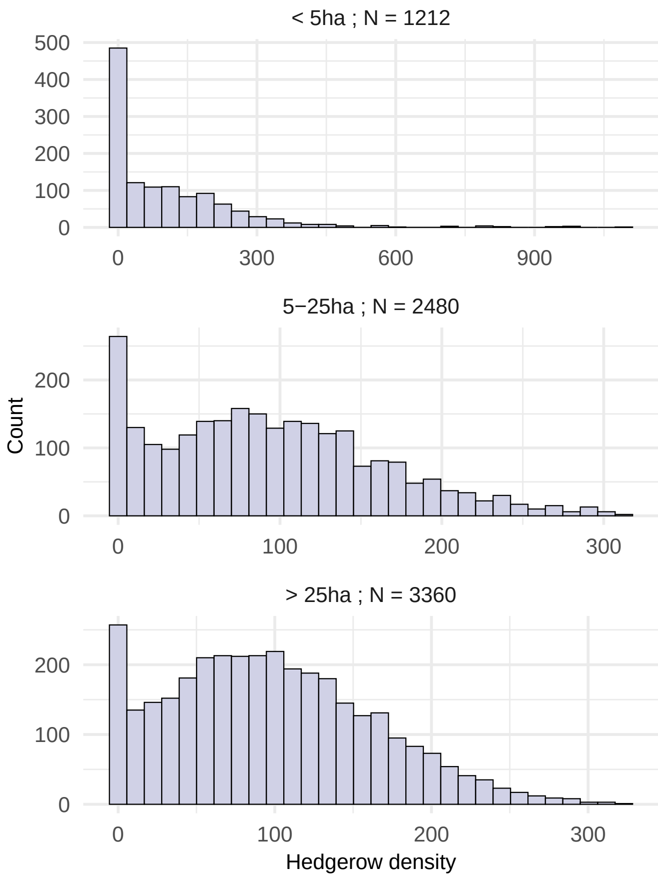

Figure A.4: Distribution of hedgerow density for different chunk size classes.

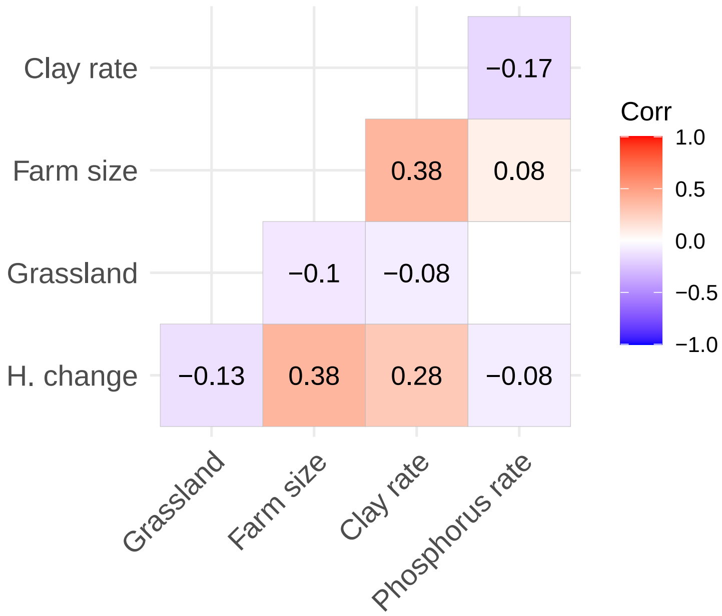

Figure A.5: Correlation plot with Pearson coefficients. H. change: variation of hedgerow density between 1972 and 2010. Blank cells are non-significant correlation tests (at the 95% confidence level).