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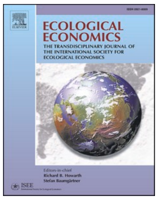

The causal effect of crop diversification obligations on crop diversity: An EU-level analysis

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A R T I C L E I N F O

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A B S T R A C T

The Common Agricultural Policy (CAP) is a cornerstone policy of the European Union, increasingly focused on promoting environmentally sustainable practices. In 2014, the CAP introduced Greening payments and a crop diversification requirement to enhance soil resilience and mitigate ecosystem degradation. Despite its economic significance, the policy's effectiveness across the EU remains largely limited. This study evaluates the impact of the Greening crop diversification requirement on crop diversity itself and on a set of subsequent outcomes, including agricultural land allocation, the economic performance of farms and indirect environmental outcomes. Using farm-level data from the Farm Accountancy Data Network (2012–2017), causal relationships are identified, through a design that combines propensity score matching and difference-in-differences, by comparing farms needing to adapt to the new requirements to those who were already compliant. Additionally, a regression discontinuity design estimates local average treatment effects for 2017, thereby exploiting the diversification requirement's threshold-based design. Both strategies corroborate the conclusion that Greening measures have significantly increased crop diversity across the EU, impacting over the subset of farms that were not already compliant with regulation requirements, primary small- and medium-size crop farms; moreover, results for the remaining farm-level outcomes are consistent with adaptation responses to the new environmental requirements. Overall, the results highlight the policy's effectiveness in promoting sustainable agriculture throughout the EU.

1. Introduction

The Common Agricultural Policy (CAP) is one of the cornerstone policies of the European Union (EU) and has played a pivotal role in sustaining agricultural sectors across member states. In recent years, though, an increasing emphasis has been placed on integrating environmental considerations into the CAP in order to address global concerns about both climate change and sustainability. This shift towards greener policies was marked by the introduction of Greening payments into the CAP policy cycle and began in 2014 (European Union, 2013).

Greening payments represent a significant component of direct payments to farmers and are earmarked for compliance; three specific farming practices were considered beneficial to the environment: maintenance of permanent grassland, crop diversification and allocation of land to ecological focus areas. This study focuses on the Crop Diversification (CD) aspect of the Greening measures that imposes requirements on the minimum number of crops grown by farm holdings, and the maximum proportion of arable land (AL) covered by their main crops. This measure aims to enhance soil and water quality, thereby fostering biodiversity and contributing to climate change mitigation and adaptation efforts, according to a growing body of agronomic literature (see Beillouin et al., 2021, and Tamburini et al., 2020, among others).

Despite the relevant role played by these Greening payments, the empirical evidence about the results of this policy remains limited, and somewhat contradictory. Indeed, there is a lack of comprehensive ex-post evaluations into their effectiveness, particularly from the perspective of the entire EU and some empirical evidence is restricted to analyses that concern single member states (see Sauquet, 2022 and Diop and Védrine, 2025 for CD in France, and Varacca et al., 2022 for ecological focus areas (EFA) in Italy). In addition, a major criticism is that many farms received subsidies for adopting practices that they had already implemented, thereby resulting in a windfall effect (Louhichi et al., 2018; Diop and Védrine, 2025; European Court of Auditors, 2017), but it has also been noted that the policy's primary effects were observed in farms that were already compliant with the CD requirements (Diop and Védrine, 2025). In conclusion, the evaluation of CD policies remains an

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area with several aspects that still require further investigation and clarification.

In order to evaluate the impact of CD obligations, we consider several outcomes: we first examine variables directly related to the implementation of the regulation, including changes in crop diversity, and then land allocation, economic and environmental performance. We use data from the Farm Accountancy Data Network (FADN) (FADN, 2015), an annual survey that provides data on 80,000 farms across EU member states.

Concerning the environmental performance, the impact on direct environmental outcomes, such as biodiversity, soil and water quality, cannot be evaluated because these data are not available at the farm level. To that end, we use the environmental data embedded in the FADN variables, and observe that this information is somewhat indirect, as it characterizes farming practices that influence environmental outcomes. Indirect environmental outcomes, such as the usage intensity of fertilizers or pesticides, are then used because they act as intermediate variables that lie in the causal pathway between the treatment and the outcomes and may even anticipate the effect on environmental outcomes, if any.

The evaluation study is based on two counterfactual impact evaluation (CIE) approaches. First, we exploit the FADN's time dimension to employ a Propensity Score Matching (PSM) in conjunction with a Difference-in-Differences (DID) method (PSM-DID). In this context, there exists no "pure" control group, given that compliance with CD obligations is mandatory for all farms falling within the regulation criteria. However, we identify the CD regulations' causal impact by comparing farms that were subject to the new requirements and not already complying with these, with those that were already compliant prior to the policy's introduction. Note that this strategy may yield conservative estimates of the impact of CD on regulation-related variables. This is because farms that were already in compliance before 2015 either maintain their number of crops and land allocation over the subsequent years or adjust them in the same direction as non-compliant farms, without the option to change in the opposite direction.

We build treated and control groups of farms, based upon the PSM-DID method, and calculate the cumulative impact of the regulation over three years after the policy's introduction. In the second part of the analysis, we leverage a Regression discontinuity (RD) design to estimate the local average treatment effect (LATE) after the policy intervention, in 2017, thereby capitalising on the policy's threshold-based nature.

The cumulative effects of the PSM-DID showed that treated farms gradually adapted to the policy requirements by both increasing and diversifying the number of crops and this is also confirmed locally by the RD analysis. Three years after its enactment, the regulation has produced an average increase of crops grown by non-already-compliant farms, and a sizeable reduction in the shares of AL dedicated to the main crops. The average farm crop diversity index also increased. Significant impacts also emerge from the RD analysis for farms with an AL size close to the regulation thresholds (i.e., 10 and 30 ha). The results underscore the policy's effectiveness in terms of its intensive margin. It impacted targeted farms, by increasing the number of cultivated crops, thereby decreasing the share of land dedicated to main crops and, consequently, by increasing crop diversification. This study contributes to filling a critical gap in the literature by providing a detailed analysis of the CD policy's impact across 28 EU member states, and by concurring with increasing volumes of evidence about this topic. The study also contrasts prior studies that only focus on single-country case studies and provides mixed evidence types. Findings also have significant implications for future agricultural policies within the EU and offer valuable insights for designing firm-level environmental interventions, given the policy's renewed salience, in the light of its renovation over the 2023–2027 CAP cycle. Our analysis reveals that the Greening architecture has significantly influenced crop diversification practices of farms non-already compliant with regulation requirements, by setting a new standard for sustainable agriculture within the EU. In particular, the estimated impact on regulation-related outcomes are increasing over the period analysed, thereby indicating a progressively adaptive response from non-already-compliant farms.

In the following sections, we outline the methodology and present our findings. Section 2 provides an overview of the policy context, data sources and a discussion of literature review results. Section 3 details the econometric approach, and Section 4 presents the results of our analysis. Finally, Section 5 discusses the policy implications and concludes the study.

2. Institutional background, literature review and data description

The 2013 CAP regulation was officially published in December 2013 and came into effect in January 2014, though not all of its articles took effect immediately. The Greening measures, in particular, became mandatory only from January 2015. This regulatory framework was originally designed to span the period from 2014 to 2020, but was later extended until 2022.

The CD requirement sets targets that are primarily focused on two outcomes: the number of different crops cultivated and the proportion of AL allocated to main crops. The regulation requires farmers cultivating 10 to 30 hectare (ha) of AL to grow at least two crops from diverse species, and the proportion of land covered by the main crop cannot exceed 75 % of AL. Farmers who cultivate over 30 ha of AL are required to grow at least three crops from diverse species, the proportion of land covered by the main crop cannot exceed 75 % of AL and the share occupied by the two main crops cannot exceed 95 % of the total AL.[1] Farms with fewer than 10 ha of AL, those under the Small Farmer Scheme, and Organic farms are exempted from these requirements.

The impact of the Greening Payments on farms' land allocation choices and consequent environmental impacts has attracted the interest of agri-economists ever since the implementation of this reform. The existing studies that contribute to the policy investigation differ in several critical dimensions: territorial approach, choice of instrument, scope and in terms of outcomes and methodology. Two main groups can be identified concerning scope and, consequentially, the methods. Gocht et al. (2017), Louhichi et al. (2018) and Hristov et al. (2020) perform micro-founded ex-ante simulation methods based on sample-based data and use the CAPRI, IFM-CAP and AgriPolis models, respectively, thereby producing a prediction of results at the EU level. The main findings of these simulation exercises can be summarised as follows. The IFM-CAP model estimates that the reallocated area induced by the policy represents only 4.5 % of Utilised Agricultural Area (UAA), even though the proportion of farms and UAA subject to CAP greening represents 55 % of all farms and 86 % of UAA in the EU27. The CAPRI model finds small economic (land use, production, price and income) and environmental (GHG emissions, N surplus, ammonia emissions, soil erosion and biodiversity-friendly practices) impacts.

A second set of contributions is based on ex-post evaluation exercises from observable data. Bertoni et al. (2021) and Varacca et al. (2022) use a sample of Italian farms, whereas Sauquet (2022) and Diop and Védrine (2025) explore the French case. In particular, Bertoni et al. (2021) investigate the impact of Greening on land use changes for farms that were not initially compliant with the crop diversification rules. They find evidence of a shift in farmland use in this group of farms, thereby suggesting that Greening rules induced farmland conversion in farms with a lower degree of crop diversification. This evidence was then used to estimate the Greening impact on land allocation measures by using machine learning techniques. Sauquet (2022) exploits the 30 ha threshold by means of an RD and a DID analysis. Using administrative

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[1] This general rule is adapted for farms for which the production of grasses or other herbaceous forage of land lying fallow are a significant part of the arable crops.

data, he quantifies the CD's impact in France and finds that farms greater than 30-ha significantly increased both compliance with the measure and the number of crops grown on their lands. He also stresses that farms respond differently to the greening reform, depending on their size. In particular, farms larger than 30 ha increased the farmland used for their third and fourth largest crops. Diop and Védrine (2025) used a Difference-in-Discontinuity design on a sample of French farms and found that farms around 10 ha experienced significant land reallocation and an increase in crop diversity, while farms around 30 ha increased their overall number of crops. Finally, Varacca et al. (2022) uses data from Italian FADN and evaluates the local impact of the EFA measure on the farms' crop mixes through an RD regression that exploited the farm size threshold for the EFA's exemption requirement. They found that farms opted for the least costly adaptation of land use by increasing the share of leguminous crops and by estimating a proxy for the biodiversity impacts.

The present study evolves alongside the strand of ex-post evaluation literature and proposes an ex-post evaluation of the CD policy throughout the whole EU territory.

The analysis is based on the European FADN, which is a survey carried out each year and that is harmonised at the EU level, with a sample of 80,000 farms across member states, representing the population of commercial farms exceeding a minimum economic size, about 4.8 million in 2018. The FADN is the richest dataset on farm activities at the EU level: it collects data about types of farming, economic activity, land use, crop and livestock products, inputs, CAP subsidies, and much more. This notwithstanding, some caveats still must be borne in mind for this study's purposes.

First, the crops reported by the FADN are necessary fewer than the species specified by the Regulation. This discrepancy could potentially lead to an underestimation of the number of crops species, and the changes made thereto. Likewise, the proportion of land dedicated to the main crop(s) may be overestimated because of this limitation.

Second, the FADN's environmental content of variables is mainly of the indirect type. Indeed, environmental outcomes (emissions, soil and water quality) are not quantified at the farm level. Still, variables relating to farms' activity, such as the number and the density of livestock, or to the quantity of fertilizers and pesticides purchased may be monitored in FADN as descriptors and drivers of direct environmental outcomes. For instance, using high quantities of fertilizers may lead to a large nitrogen surplus, and correspondingly large flows of nitrogen emissions and pollution. Similar transmission mechanisms apply to the use of pesticides and energy. In summary, higher expenditures on inputs are expected to result in more pollution and higher environmental damage. From this point on, we will refer to FADN variables relating to environmental aspects as indirect environmental outcomes, contrasting them to the direct environmental outcomes, such as biodiversity, soil and water quality, GHG emissions. Approximating direct environmental outcomes by farms' input usage has already been exploited by some CIE empirical research (Cisilino et al., 2019; Uehleke et al., 2022, among others) and was supported theoretically by the agricultural literature, as recently summarised by Rega et al. (2021).

3. Causal identification strategy

The introduction of the CD obligation has both a time dimension and a farm-size dimension characterising it. There is therefore scope for two different causal identification strategies for its evaluation. In the first strategy, we capitalise on the temporal variation in treatment and assess the impact of CD through a DID approach, combined with the PSM method for further refinement. The PSM-DID strategy is both capable of addressing observable sources of before-policy heterogeneity, and of controlling for the influence of unobservable, albeit temporally invariant, factors (Smith and Todd, 2005). The second strategy focuses on the size thresholds triggering CD obligations, set at 10 and 30 ha of AL. Indeed, within the framework of local randomisation, the probability of receiving treatment—conditional on AL—discontinuously jumps at the cut-off, rendering treatment assignment independent of potential confounders. The underlying principle is that farms close to both sides of the threshold are sufficiently similar so as to provide a valid counterfactual. Hence, we implement a RD design to evaluate the effect of the policy, as a complement to the PSM-DID approach. Neither of the two strategies is preferable on its own, and their results are not directly comparable, but their combination can provide complementary insights into the regulation's impact.

3.1. The PSM-DID analysis

The distinctive trait of the current application is that there exists no "natural" control group devoid of treatment, given that compliance with CD regulations is mandatory for all farms falling within the regulation criteria. However, a considerable number of farms had already adopted CD practices prior to the policy's implementation. Consequently, while the CD measures imposed a change in cropping choices for non-compliant farms, compliant farms must continue to comply with the new obligation, yet with no need to amend their previous choices. In this scenario, the first option is to view farms that were asked to change (non-compliant farms) as subject to 'treatment A', and already-compliant farms as subject to 'treatment B', thus conceptualising a binary treatment without any unaffected control group. Under this first interpretation, our PSM-DID model estimates the effect of receiving 'treatment A' compared to receiving 'treatment B'. However, an alternative point of view is to consider non-already-compliant farms as strongly-treated and those already-compliant as weakly-treated, and to assume that the direction of effects is not different across the two groups. Under this second interpretation, our PSM-DID model estimates lower bounds of the effect of 'treatment A', i.e. the request of change because of the introduction of the CD requirement. Despite keeping in mind these two interpretations, for the sake of conciseness, we will refer to non-already-compliant farms as 'treated' and already-compliant ones as 'control' farms hereafter. Note that this strategy enables the generation of results across the entire sub-population of non-already compliant farms, offering a range of insights that is not available in the current literature, including heterogeneity by farm size and type.

We combine the PSM and DID strategies to obtain causal identification, following four key steps. First, we identify the population of farms under the scope of the CD regulation[2] in the pre-treatment year, 2014. This is done by comparing each farm's declared cropping choices to the regulatory criteria, thus distinguishing between non-already-compliant and already-compliant units.

Second, we construct a propensity score model to associate treated (non-already-compliant) units with control (already-compliant) units that resemble them closely; this is done in recognition of the fact that non-already-compliant farms may in general differ from already-compliant ones. We use the Covariate Balancing Propensity Score (CBPS) approach (Imai and Ratkovic, 2013) to improve covariate overlap and balance. This method was chosen for its effectiveness in addressing potential misspecifications in propensity score models, that might result in biased estimates of treatment effects. The CBPS method models treatment assignment, while simultaneously optimising covariate balance, by estimating the propensity score under moment conditions that ensure covariate balancing. Imai and Ratkovic (2013) have shown that CBPS can enhance both the effectiveness of propensity score

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[2] Specifically, the farms under the scope of CD regulation are formed by a) Farms with 10 to 30 or over 30 ha of AL where less than 75 % of their arable land is used to produce grasses or other herbaceous forage, or is land lying fallow; and b) Farms where between 75 and 99 % of arable land is used to produce grasses or other herbaceous forage, or is land lying fallow, provided that their residual arable land exceeds 30 ha. The study focuses only on group a) because of the lack of sufficient observations in the group b).

weighting and matching methods. As control variables for the PSM specification, we incorporate country dummies in order to account for variations in climate conditions and regulatory contexts. Additionally, we include farm type; ha of land allocated to AL, vineyards, other permanent crops, permanent grassland; and standardised livestock units. These variables are included in order to compare farm units whose structure is as similar as possible. Moreover, we integrated paid labor input, quantified in Annual Working Units, in order to differentiate between family and non-family farms and to account for variability in labor intensity. All control variables are evaluated in their 2014 values. Finally, we control for over-time variations in the number of crops cultivated during the pre-treatment period 2012–2014. It is important to note that the variables directly expressing compliance with the CD obligation, such as the number of AL crops and the proportion of AL allocated to main crops, were used to define treatment and control groups and thus mechanically exhibit differences between groups; these variables are not included in the specification of PSM. A partial compensation is given by the inclusion of control variables capturing over-time variations in the number of crops cultivated during the pre-treatment period.

In the third step, for each non-already compliant treated farm we identify the most similar compliant control farm, based on the CBPS estimations and enforcing the exact matching for country and farm type. The matching process adopts a nearest-neighbor approach with a 2 percentage-point.

In the final step, we evaluate the impact of the diversification requirement on each outcome, following the DID methodology. The impact is estimated as the differential change in outcomes from before to after the treatment, between the non-already-compliant and the already-compliant farm groups. We implement a two-way fixed effects model (Roth et al., 2023) with survey design weights, estimated on the balanced panel of matched treated and control farms from 2014 to 2017,[3] as follows:

$$Y_{it} = \gamma_i + \lambda_t + \delta_t D_{it} + \epsilon_{it} \tag{1}$$

where Y_{it} indicates the outcome Y for farm i at time t, D_{it} is the treatment indicator variable, $\mathrm{D}_{\mathrm{it}} = 1$ in treatment group and post-treatment period, and 0 otherwise, γ_i and λ_t are the farm- and year-specific fixed effects and ϵ_{it} the error term.

For each outcome, δ_t provides an estimate of the differential change from pre-treatment year t (2014) to year $t+1$ (2015), $t+2$ (2016) or $t+3$ (2017), materialising for treated farms when compared to their counterfactuals. This is the Average Treatment Effect on the Treated (ATET), representing the impact that may be attributed to the policy intervention.

Our choice of outcome variables is guided by the aim to explore the impact of regulations across multiple dimensions: adherence to regulatory standards, shifts in land usage patterns and overall crop diversity. Additionally, we investigate how regulations affect the farm crop diversity and intensity of pollutant input usage, and the consequential trade-offs with economic outcomes. The diversity of crops is quantified by a normalised Shannon index, where 0 indicates that the entire farm is monocultural and 1 indicates that each farm is equally divided into the number of crops considered (further details on outcomes are available in SM, Tables A1 to A3).

The solidity of our empirical methodology is further supported by a battery of validation and robustness checks. First, matching results are validated in terms of the balance in covariates. Second, the parallel trend assumption is tested for all outcome variables. Third, to account for the issues of false positive related to performing multiple tests, we adopt the approach by Benjamini and Hochberg (1995) based on False Discovery Rates (FDR). Fourth, as a placebo test, we repeat the PSM-DID exercise by imposing organic farms as the treated group; organic farms are exempted from the regulation and we should not find any significant effect. Finally, we estimate a non-linear DID for the number of crops, taking the count nature of this variable into account.

3.2. *The RD analysis*

As mentioned in Section 2, the CD implementation's efficacy relies on specific criteria that enforce limitations across various farming methods. These criteria are defined by thresholds based on farm size metrics that dictate adherence to administrative regulations. Similarly to Sauquet (2022), we implement a sharp RD on farms potentially under the CD regulation. The LATE can be identified in a neighbourhood around the cut-off,[4] assuming perfect compliance with treatment assignment based on AL. Starting from the following equation.

$$\mathrm{Y_i} = \alpha + \beta \mathrm{I}[\mathrm{AL_i} > \zeta] + \epsilon_{\mathrm{i}} \tag{2}$$

where Y is one of the outcomes and I[.] is the identity function that takes the value of 1 where a farm's AL is greater than a cut-off ζ introduced by the regulation (i.e., 10 and 30 ha) and AL (ALi) is the running variable.

We estimate β such as.

$$\beta(\zeta) = \mathrm{E}[\mathrm{Y_i}(1) - \mathrm{Y_i}(0)\,|\mathrm{AL_i} = \zeta]$$

where $\mathrm{Y_i}(1)$ and $\mathrm{Y_i}(0)$ represent potential outcomes for holdings that receive and do not receive treatment, respectively; $\mathrm{E}[\mathrm{Y}(1)|\mathrm{AL_i} = \zeta]$ and $\mathrm{E}[\mathrm{Y_i}(0)|\mathrm{AL_i} = \zeta]$ denote average potential outcomes.

as smooth functions of the score (i.e., regression curves). The treatment status is determined as.

$\mathrm{T_i} = \mathrm{I}[\mathrm{AL_i} > \zeta]$ for the known cut-off ζ.

The RD exercise requires a large number of observations around the threshold; for this reason, we performed the analysis using the entire EU sample and enhanced model (2) with controls for holding types, countries and for the economic size of the holdings. The optimal bandwidth is determined by using the automated selection procedures, specifically, the common mean squared error (MSE)-optimal bandwidth selector (see Calonico et al., 2014).

Similarly to the PSM-DID analysis, the outcome variables are related to the following aspects: regulation requirements, land allocation, economic performance and environmental outcomes.

Internal validity is verified by both running a placebo test - performing the RD analysis on thresholds different from those specified in the policy - and by testing for the absence of discontinuity in the running variables around the threshold by means of the McCrary (2008) manipulation test. The Benjamini and Hochberg (1995) procedure is also applied to RD results for dealing with the problem of multiple comparison.

4. Empirical results

4.1. *The PSM-DID analysis*

Treated and control farms for the PSM-DID analysis are identified by extracting the farms that always remained under the scope of CD from 2012 to 2017 from the FADN dataset. Within this panel, formed by 3443 treated and 16,249 potential controls per year, 17.5 % of the farms were non-already-compliant with CD requirements in 2014, and are

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[3] Note that 2014 marks the introduction of the updated crop classification by FADN. To maximize the number of crops available for defining the number of crops, we estimate the model using the 2014–2017 panel. This approach allows us to utilize the most comprehensive set of crops possible.

[4] We make this assumption in a manner that is consistent with previous literature, although no farms classified under regulatory requirements have 100 % adherence to the CD obligations among FADN, as discussed in the data analysis.

categorised as treated.

Table 1 illustrates that analysed non-compliant farms typically have smaller AL and total output compared to compliant farms. They cultivate fewer crops and allocate a larger proportion of their land to main crops than farms that are already compliant. Farms ranging in size from 30 to 50 ha are over-represented, whereas those over 100 ha are significantly under-represented when compared to already-compliants. Additionally, non-compliant farms are more likely to focus on field crops when compared to their compliant counterparts; they tended to reduce their crops on average more than already-compliant farms as a notable difference over the period before the treatment, from 2012 to 2014. Unfortunately, the extraction of balanced panel produce an uneven loss of observations across countries.[5]

The CBPS is estimated, and it allows for excellent reductions in Standardised Mean Differences (SDMs). The matching procedure identifies 3218 matches between treated and control units, after discarding 225 matches that differed by over 2 percentage points in terms of propensity scores, in order to improve the matching and to guarantee the overlap assumption. After the matching procedure, all SDMs were far below 0.10, which is the threshold level used as a rule of thumb. This indicates that a good control group has been identified (Results are available in SM, Table A4).

When comparing pre-policy dynamics between these two groups, the parallel trend assumption is rejected at 5 % of significance only for two variables (see Supplementary Material, Table A5 and Fig. A1), expenditure in fuels and electricity per ha; this has no implications for general results, as these variables are not significantly impacted by the regulation. The parallel trend assumption is backed by the fact that there are no further violation of parallel trends prior to the start of the regulation, across all outcomes and consistently at the 95 % confidence level.

The results produced by our validation and robustness exercises further support the validity of our identification strategy. We do not find any significant unexpected impact from the policy for organic farms. The non-linear DID for the number of crops provided results consistent with the linear specification. To ensure the robustness of the results for selected variables (e.g., number of crops, share of main crop, normalised CDI), estimations are repeated by excluding one of the major three countries at a time. Additionally, estimations are conducted without using design weights. No statistically significant deviations are detected in either approach (see SM, Table A6).

Table 2 displays (cumulative) ATETs realised over the three years following the policy's introduction, from 2015 to 2017, which we label $t+1$, $t+2$ and $t+3$ respectively, on a range of outcomes. The first set of results are related to policy requirements directly. They measure the changes intervened thanks to the regulation in: number of crops, shares of AL dedicated to both the first and the first two crops and shares of farms compliant with the two regulatory requirements. Each estimated ATET indicates, on average, the change in the outcome of treated farms attributable to, i.e. caused by, the regulation's introduction.

The estimated impact on regulation-related outcomes are all significant and increased, in absolute terms, over the analysed period, thereby indicating a progressively adaptive response from non-adherent farms to regulation. Treated farms are gradually adapting to the policy by increasing their number of crops. On average, the number of crops from non-already-compliant farms grew by 0.463 after one year and by 0.622 after three years, when compared to what would have happened if they were not requested to change by the regulation. These values indicate the CD regulation's significant impact and, as discussed previously, may count only the lower bounds of true changes in number of crops. The proportions of the area dedicated to main crops decrease: the share of AL dedicated to both the first and first two main crops also significantly decreased of 16.3 and 14.0 percent points in 2017. As a result, 68.2 % of farms that were previously non-compliant became compliant three years after the policy's introduction. The full compliance is not reached for at least two significant reasons: member states were permitted to introduce equivalent practices to Greening requirements, so that farms that were compliant with these agricultural equivalent practices were not required to comply with CD. Moreover, some farms may have diversified by shifting to crops of different botanical species, but within the same FADN class as previously. In this case, the change may not be detected by using FADN.

The second set of findings illustrates the impact of regulations on the allocation of AL. The size of AL, after a temporary increase, remains fairly stable over time. Regarding land reallocation, the regulations show a significant negative effect on the size of land dedicated to cereals, on average. At the same time, we observe a significantly positive impact, in terms of land dedicated to industrial crops, which was just below a change of 20 % on average in 2017. This represents an average expansion of 1.157 ha compared to the initial average of 5.715 ha. Additionally, there are noteworthy (albeit not always significant) increases observed in crops included in the category of protein crops, root and tubers.

In examining economic outcomes, there is some evidence to suggest positive significant changes in economic output after three years, but not on farms' value added. These findings suggest that the regulation put in place did not have a noticeable effect on farm profitability.

The evaluation of the regulatory impact extends into the examination of farms categorised by their distinct farming systems, namely crops, livestock, or mixed farms (Table 3), and in terms of size of AL (Table 4) in the third year after the starting of the regulation.

The dynamics of land reallocation appear more pronounced within the category of crops farms, concerning the classification by type, as evidenced by their notable reduction in AL allocated to cereals, in favour of crops such as industrial crops, fodder and fallows, and, temporary, protein crops during the first two years. The level of compliance observed among crops farms by the year 2017 reached its highest value, 71.6 %. Moreover, the regulation seems to have yielded significant impacts on economic performance for the year 2017 for crops and livestock farms. Crops farms experienced an increase in output from crops. This suggests that the redistribution of land resources may have contributed to the improved output observed in crop farms subsequent to the regulation's implementation. In contrast, livestock farms experienced an increase in output from livestock.

As far as the size of AL is considered, the impact of regulation on land reallocation reveals a decrease in land dedicated to cereals across all classes of AL size, with significant effects observed for farms with over 100 ha of AL, as illustrated in Table 4. Noteworthy fluctuations in land allocation to the remaining crops are evident, thereby indicating temporal instability. Only fodder and fallows show consistent increases over three-year periods for smaller farms.

Importantly, when assessing economic performance, the regulation appears to have yielded a notably positive impact, particularly benefiting those farms in the smallest size category, those with AL below 30 ha.

Bottom panels in Tables 2 to 4 display cumulative ATETs realised on the outcomes related to the environment, as available in FADN according to Brutti et al. (2023). The CD regulation lead to improvements in the normalised Shannon index at the farm level. The index increases of 7.7 percentage points in 2014 and 9.4 percentage points in 2017. This enhancement moved crop diversification from 15.5 % to 25 % of the potential maximum of 100 %. The analysis, by type of farms, highlights that crop diversification increased more for crops farms than it did for livestock farms. Regarding the class size of AL, the regulation significantly increased crop diversification for farms with 30 to 50 ha of AL, followed by those with 10 to 30 ha, and then 50 to 100 ha. Although the regulation had a less pronounced impact on farms within the largest class, the effect was still significant. No additional significant results were detected, except where compliance with the regulation was

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[5] Croatia is not included in the panel because joined EU since 2013. A severe loss of observations regards also Romania.

Table 1
FADN farms (All) and FADN farms with AL larger than 10 ha (AL >10 ha), Treated and Untreated groups formed using the Balanced Panel. Percent distributions by country, type, and size of AL, and further descriptive statistics. Year 2014.

	All	AL > 10 ha	Untreated	Treated		All	AL > 10 ha	Untreated	Treated
BEL	0.6	0.3	1.4	0.9	*Regulation related variables*				
BGR	2.4	3.0	1.2	0.8	N. of crops	2.1	3.5	4.4	1.9
CYP	0.2	0.3	0.1	0.3	Share main crop	0.7	0.6	0.5	0.8
CZE	0.4	0.2	0.9	0.2	Shares of .two main crops	0.9	0.8	0.7	1.0
DAN	0.6	0.1	0.1	0.1	Share satisfying CD req.	0.8	0.8	1.0	0.0
DEU	3.9	1.4	9.1	3.6					
ELL	7.2	8.9	3.6	5.1	*Farm descriptives*				
ESP	11.5	11.0	13.7	40.8	Arable land (ha)	22.5	62.1	79.0	47.2
EST	0.2	0.1	0.2	0.2	Perm. grassland (ha)	9.6	13.4	9.9	7.6
FRA	6.2	2.5	20.0	5.8	Permanent crops (ha)	2.2	1.5	1.1	2.4
HRV	1.7	1.9	–	–	Total outputs (1000 Euro)	71.1	141.8	155.4	120.6
HUN	2.1	1.6	5.2	4.8					
IRE	1.8	2.3	0.4	2.5	*Distribution by type of farm specialization (%)*				
ITA	11.1	11.3	4.8	12.2	Fieldcrops	27.4	49.7	54.7	65.4
LTU	1.3	0.7	0.2	0.4	Horticulture	3.4	1.1	0.9	1.8
LUX	0.0	0.0	0.1	0.0	Wine,other permanent	17.0	2.8	1.6	3.9
LVA	0.5	0.3	0.5	0.6	Milk	12.8	13.4	12.0	7.0
MLT	0.1	0.1	0.0	0.0	Other grazing livestock	17.2	12.5	5.1	8.3
NED	1.0	0.8	1.3	1.9	Granivores	2.7	4.0	5.0	4.3
OST	1.9	1.6	4.0	0.3	Mixed	19.6	16.6	20.6	9.3
POL	15.3	13.3	25.9	10.5					
POR	2.1	2.5	0.4	2.0	*Distribution by size of AL (%)*				
ROU	23.6	33.2	0.1	0.0	0–10 ha	66.4			
SUO	0.8	0.0	2.3	3.1	10–30 ha	17.2	51.3	42.4	42.2
SVE	0.6	0.0	1.7	0.6	30–50 ha	6.1	18.1	16.5	30.1
SVK	0.1	0.0	0.3	0.1	50–100 ha	5.7	17.0	20.6	19.5
SVN	0.9	1.2	0.3	0.1	Over 100 ha	4.6	13.6	20.5	8.1
UKI	2.0	1.2	2.1	3.1					
Total	100.0	100.0	100.0	100.0	*Number of farms*	82,739	42,037	16,249	3,443

Table 2
Estimated average treated effects on treated (ATET) in one-to-three years (2015 to 2017) after the policy implementation. Selected outcomes.

	$\overline{Y}_t$	$\Delta Y_{t+1,t}$	$\Delta Y_{t+2,t}$	$\Delta Y_{t+3,t}$
Regulation related outcomes				
Number of crops	1.982	0.463*	0.594*	0.622*
Share of main crop	0.817	−0.130*	−0.157*	−0.163*
Share of the two main crops	0.825	−0.105*	−0.134*	−0.140*
Share of farms satisfying CD requirements	0.000	0.551*	0.665*	0.682*
Land allocation (ha)				
Arable land	48.836	0.802*	0.753	0.717
Cereals	30.143	−1.232*	−1.109*	−1.457*
Protein crops	1.366	0.367*	0.130	0.534
Root and tubers	0.654	0.222*	0.270	0.178
Industrial crops	5.715	0.738*	1.081*	1.157*
Vegetables and flowers	0.917	−0.010	0.020	0.002
Fodder and fallows	9.690	0.735	0.413	0.575
Harvested green and other AL	0.343	−0.018	−0.052	−0.273
Permanent grassland	7.269	−0.658	−1.056	−0.767
Permanent crops	2.150	0.003	−0.034	−0.031
Economic performance (1000 Euro)				
Total of outputs	113.487	0.558	2.884	6.327*
Total output from crops	58.436	1.749	1.857	2.275
Total output from livestock	50.146	−1.426	0.563	2.753
Farm Net Value Added	42.834	−1.003	0.112	1.707
Drivers of environmental outcomes				
Normalised CD Index	15.5	7.7*	9.4*	9.5*
Purchases - per ha				
Fertilizers (value)	160.238	5.477	3.932	7.78
of which Nitrogen (quintals)	27.248	−2.975	0.562	−2.746
of which Phosphorus (quintals)	1.612	4.263	6.331	4.356
of which Potassium (quintals)	0.941	2.056	2.518	2.094
Plant protection products (value)	85.979	3.523	4.724	1.225
Manure (value)	0.84	0.039	−1.145	−0.764
Fuel (value)	141.164	0.722	1.477	5.628
Electricity (value)	40.832	−1.026	−0.039	0.846
Seeds (value)	135.576	4.094	0.876	−3.52
Feed (value per livestock unit)	333.82	−19.428*	−16.125	−10.473

associated with a reduction in expenditures for livestock feed. These findings suggest that the regulations put in place did not have a significant effect on most aspects of agricultural practices that might impact upon environment well-being, with the exception of crop diversification and minor improvements in feed expenditure reduction.

In the end, to address the concerns associated with multiple testing, we applied the Benjamini and Hochberg (1995) to compute adjusted *p*-values. In this more demanding inference method, we consider significant only those results whose associated adjusted p-value is below the threshold of 0.10. For the PSM-DID analysis, the overall findings remain largely unchanged. For a limited number of coefficients, mostly those associated to land allocation choices, the adjusted statistical significance drops below the threshold value (see Supplementary Material, Tables A9-A11), while continuing to constitute valuable qualitative indications.

In summary, in line with Bertoni et al. (2021), our findings indicate strong effects on farms with lower compliance levels. We also confirm a significant reduction in land allocated to cereals and an increase in protein crops, though these last changes are significant one year post-intervention but not after three years. However, unlike Bertoni et al. (2021), we do not observe significant reductions in chemical input use, and, when economic results are significant, they display increases rather than decreases displayed in the study by Bertoni et al. (2021). As Sauquet (2022), we find that compliance increased across all farm sizes, and that the highest compliance change occur in farms sized around 30 to 50 ha.

A common finding shared with Louhichi et al. (2018) is the evidence of stronger changes for fieldcrops specialist and small size farms. However, the rest of our results are not directly comparable with the ex-ante simulations of the impact of Greening. Notably, the simulations of Louhichi et al. (2018) assume full compliance with all three Greening measures, and not only with CD. Moreover, their results average the effects across both compliant and non-compliant farms, whereas our estimations focus solely on the impact on non-compliant farms.

Table 3

Estimated impact in 2017 compared to 2014 ($\Delta Y_{t+3,t}$) by type of farm.

	Crops farms	Livestock farms	Mixed farms
Regulation related outcomes			
Number of crops	0.644*	0.558*	0.537*
Share of main crop	−0.174*	−0.128*	−0.143*
Share of the two main crops	−0.156*	−0.100*	−0.086*
Share of farms satisfying CD requirements	0.716*	0.589*	0.599*
Land allocation (ha)			
Arable land	0.902	1.299	−1.599
Cereals	−1.754*	−0.713	−0.446
Protein crops	0.674	0.230	0.005
Root and tubers	0.280	0.028	−0.269
Industrial crops	1.440*	0.617	0.452
Vegetables and flowers	0.022	−0.012	−0.139
Fodder and fallows	0.613*	1.162	−1.106
Harvested green and other arable land	−0.374	−0.015	−0.096
Permanent grassland	−0.445	−1.743	−1.057
Permanent crops	−0.046	0.008	−0.013
Economic performance (1000 Euro)			
Total of outputs	4.780*	13.444*	3.435
Total output from crops	3.067*	−0.253	1.442
Total output from livestock	0.032	12.860*	2.115
Farm Net Value Added	2.555	0.702	−1.027
Drivers of environmental outcomes			
Normalised CD Index	10.2*	6.9*	9.1*
Purchases - per ha			
Fertilizers (value)	9.262	0.593	12.768
of which Nitrogen (quintals per ha)	−3.608	0.238	4.656
of which Phosphurus (quintals per ha)	6.201	0.205	0.535
of which Potassium (quintals per ha)	2.900	−3.154	0.686
Plant protection products (value)	2.469	−0.336	1.876
Manure (value)	−1.096	−5.967	0.188
Fuel (value)	9.773	6.263	−1.973
Electricity (value)	−0.888	0.593	1.739
Seeds (value)	−4.495	2.518	−8.336
Feed (value per livestock unit)	−3.148	−64.042	−43.219

Table 4

Estimated impact in 2017 ($\Delta Y_{t+3,t}$) by size of arable land.

	10–30 ha	30–50 ha	50–100 ha	over 100 ha
Regulation related outcomes				
Number of crops	0.497*	0.912*	0.774*	0.391*
Share of main crop	−0.201*	−0.150*	−0.129*	−0.118*
Share of the two main crops	−0.162*	−0.136*	−0.130*	−0.112*
Share of farms satisfying CD requirements	0.646*	0.730*	0.686*	0.728*
Land allocation (ha)				
Arable land	1.486*	0.280	−0.865	0.246
Cereals	−0.218	−0.876	−1.504	−8.970*
Protein crops	0.281	0.715	0.414	1.970
Root and tubers	0.165	0.424*	0.264	−0.369
Industrial crops	0.096	1.023	1.408	4.963
Vegetables and flowers	−0.047	0.075	−0.353	0.731
Fodder and fallows	1.215*	0.059	−0.789	1.791
Harvested green and other AL	−0.003	−1.140	−0.307	0.125
Permanent grassland	−0.320	−0.083	−1.774	−3.303
Permanent crops	−0.065	−0.090	−0.120	0.337
Economic performance (1000 Euro)				
Total of outputs	6.033*	3.538	7.756	14.045
Total output from crops	0.799	1.586	5.500*	2.460
Total output from livestock	4.904*	0.411	−0.160	7.655
Farm Net Value Added	2.445*	0.675	1.638	2.243
Drivers of environmental outcomes				
Normalised CD Index	9.9*	10.8*	9.2*	7.5*
Purchases - per ha				
Fertilizers (value)	8.089	6.865	8.376	4.326
of which Nitrogen (quintals per ha)	0.636	1.361	−78.398	88.248
of which Phosphurus (quintals per ha)	0.461	−0.046	6.752	22.880
of which Potassium (quintals per ha)	0.549	0.070	1.151	12.742
Plant protection products (value)	−4.946	9.196*	2.439	6.226
Manure (value)	−1.362	−0.185	−0.197	0.426
Fuel (value)	−0.939	18.539*	5.153	−0.128
Electricity (value)	−2.984	3.023	4.745*	4.134*
Seeds (value)	−20.713	10.967	18.220	−3.901
Feed (value per livestock unit)	−20.849	−22.810	18.821*	7.413

4.2. *The RD analysis*

The sample of farms under treatment for the RD analysis was identified by extracting holdings that were potentially under CD obligations in 2017 from the FADN dataset. In the subsequent analysis, it is assumed that farms falling under regulatory requirements were subject to a treatment based on whether their AL exceeded or fell below the specified 10 and 30 ha thresholds.

We consider two subsets, one consisting of 12,767 medium farms which needed to comply with the requirements close to the 10 ha threshold and the other of 39,701 medium-large farms close to the 30 ha threshold. The outcome variables are those analysed previously.

Nevertheless, it is important to recall that -unlike the estimation proposed by the PSM-DID analysis- the coefficient β is estimated by local linear estimators and by using observations around the bandwidth; the RD effects are local as the difference is calculated at a single point and do not necessarily generalise; they provide a LATE. For this reason, the sign and magnitude of estimated coefficients might differ with respect to those obtained by the PSM-DID analysis for which the (cumulative) ATET is estimated.

Tables 5 and 6 show the LATEs of CD by using RD at both the 10 and 30 ha thresholds. The findings indicate that the implementation of Greening regulations has discernible local impacts, especially in terms of adaptation to the regulation-related requirements. Tables 5 and 6 demonstrate the significance of CD regulation on policy response variables. Notably, the local increase in the number of crops is approximately 0.13 at the 10 ha and about 0.28 at the 30 ha threshold. Concurrently, the proportion of main crops decreases. This evidence aligns with expectations and with what shown in Sauquet (2022) on a sample of French farms.

With respect to land allocation, there is a local increase in the proportion of land dedicated to cereals, with an additional 0.28 ha at the 10 ha threshold and 2.13 ha at the 30 ha threshold. In contrast, the areas allocated to fodder and fallows and to permanent grassland decreased locally at the 30 ha threshold by 2.32 and 5.85 ha, respectively, among medium and large farms. As for the economic performance, the net value added significantly decreased only around in terms of the 10 ha threshold.

Concerning the driver of environmental outcomes, the crop diversity index shows a positive and significant local impact at both the 10 and 30 ha thresholds (i.e., 3.1 and 3.5 percentage points, respectively). Medium-sized farms actively respond at the 10-ha threshold by increasing their use of fertilizers and electricity expenditures. This could be because smaller farms had to adjust their production methods more significantly than medium and large farms to comply with the CD regulation. Finally, the purchase of manure decreased locally at both the 10 and 30 ha thresholds.

Note that RD results around the 10 ha threshold are often statistically significant only at the 10 % level, and adjusting for multiple testing using the Benjamini-Hochberg formula causes their statistical significance to drop below this conventional threshold (See Supplementary

Table 5
Estimated impact (LATEs) of CD measure at 10-ha.

	$\bar{Y}$	coeff		bin	N_r	N_l
Regulation related outcomes						
N. of crops	2.33	0.132	*	3.3	4603	3018
Share of main crop	0.73	−0.021	°	2.9	4014	2680
Share of the two main crops	0.92	−0.013	*	3.5	4951	3229
Land allocation (ha)						
Cereals	3.41	0.280	*	3.8	5301	3432
Protein crops	0.18	−0.063		4	5597	3602
Root and tubers	0.22	−0.009		3.8	5363	3468
Industrial crops	0.65	−0.122		2.3	3125	2072
Vegetables and flowers	0.49	0.066		3.2	4491	2947
Fodder and fallows	2.23	−0.140		2.5	3396	2260
Harvested green and other	0.03	−0.019		3.6	5077	3304
Permanent grassland	9.46	−1.119		1.8	2433	1636
Permanent crops	1.65	−0.325		2.1	2871	1913
Economic performances (thousands of euros)						
Total of outputs	46,545.89	−2735.7		2.7	3744	2502
Total output from crops	23,400.75	−2044.1		2.6	3632	2430
Total output from livestock	19,817.26	−1639		4.2	6001	3805
Farm Net Value Added	22,751.61	−2719.7	°	2.6	3600	2392
Environmental Indirect Outcomes						
Normalised CD Index	24.0	3.1	*	3.3	4665	3047
Purchases - value in euro per ha						
Fertilizers (value)	147.64	3.73		2.8	3898	2597
of which Nitrogen (quintals per ha)	0.68	0.09	*	4.5	6398	4049
of which Phosphurus (quintals per ha)	0.33	0.05	*	4	5609	3607
of which Potassium (quintals per ha)	0.39	0.105	*	4.1	5961	3767
Plant protection products (value)	93.00	2.05		2.1	2925	1941
Manure (value)	5.15	−3.066	*	2.9	2666	3988
Fuel (value)	156.66	5.128		3.3	3076	4695
Electricity (value)	51.62	10.99	*	2.5	2354	3545
Seeds (value)	169.68	−9.432		2.2	2017	3044
Feed (value) per LSU	443.09	44.08		2.6	2383	3580

Notes: $\bar{Y}$ denotes the mean outcome at the threshold for the lower bandwidth; N_r and N_l show the number of observations used to the right and to the left of the cutoff, respectively; ° and * denote 10 % and 5 % significance, respectively.

Table 6
Estimated impacts (LATEs) of CD measure at 30-ha.

	$\bar{Y}$	coeff		bin	N_r	N_l
Regulation related outcomes						
N. of crops	3.03	0.284	*	12.9	9915	5573
Share of main crop	0.62	−0.037	*	12.1	9179	5293
Share of the two main crops	0.86	−0.025	*	11.8	8804	5149
Land allocation (ha)						
Cereals	10.77	2.131	*	11.7	8789	5141
Protein crops	0.64	0.052		10.7	7845	4752
Root and tubers	0.67	0.147		12.5	9473	5404
Industrial crops	1.77	−0.204		12.9	9899	5564
Vegetables and flowers	0.65	−0.072		10.6	7830	4744
Fodder and fallows	5.81	−2.131	*	13.8	10,809	5902
Harvested green and other	0.09	0.128		14.2	11,223	6029
Permanent grassland	11.99	−5.858	*	14	10,941	5959
Permanent crops	1.43	−0.392		9.9	7070	4414
Economic performances (thousands of euros)						
Total of outputs	72,752.12	−4091.6		14.7	11,635	6182
Total output from crops	30,439.83	2684.7		11.7	8780	5137
Total output from livestock	37,255.08	−7350		16.6	13,768	6835
Farm Net Value Added	34,357.90	−3799.9		10.7	7872	4763
Environmental Indirect Outcomes						
Normalised CD Index	32.0	3.5	*	12	8998	5238
Purchases - value in euro per ha						
Fertilizers (value)	122.93	3.968		7.7	5318	3529
of which Nitrogen (quintals per ha)	0.82	0.051		13.1	10,140	5632
of which Phosphurus (quintals per ha)	0.30	0.039	*	12	9114	5276
of which Potassium (quintals per ha)	0.37	0.022		10.3	7572	4642
Plant protection products (value)	72.54	5.466		8.9	6226	3972
Manure (value)	2.27	−2.036	*	9.6	6864	4318
Fuel (value)	124.98	−0.668		8.9	6256	3995
Electricity (value)	43.56	−0.341		10.8	7945	4785
Seeds (value)	114.64	10.45		10.5	7691	4691
Feed (value) per LSU	416.20	−53.83		12.1	9185	5295

Notes: see Notes to Table 5.

Material, Table A12). These challenges are due to the relatively limited number of FADN farms located around this threshold, and the data-intensive nature of the RD method. Nevertheless, we believe these results still provide useful qualitative insights that can inform our understanding of the underlying relationships in the data.

These results are broadly consistent with the expectation of limited environmental and economic impacts of greening measures, as demonstrated by Diop and Védrine (2025) using a sample of French farms, and by Louhichi et al. (2018) through an EU-level simulation study employing the Individual Farm Model for CAP Analysis (IFM-CAP).

The estimated LATE based on RD are primarily comparable to the findings of Sauquet (2022) and Diop and Védrine (2025). Our study identifies stronger impacts than Sauquet (2022), particularly in terms of the number of crops and reductions in the share dedicated to the first two crops (+0.28 vs +0.12 crop, −0.16 vs −0.02 share of AL to the two main crops at 30 ha). We better align with Diop and Védrine (2025) findings at the 30 ha threshold (+0.28 crop vs +0.35), but find divergent signs at the 10 ha threshold (+0.13 crop vs not significant). However, unlike Diop and Védrine (2025), who found that the regulation mainly affected already compliant farms, our LATE results encompass both compliant and non-compliant farms, and we do not provide separate estimates for already compliant farms alone.

Overall, compared to previous studies on local effects, we provide new insights into additional outcomes, where evidence on the impact of CD regulation on these aspects was limited. Notably, there are increases in the quantities of fertilizers used per hectare and a reduction in farm profitability at the 10 ha threshold.

Significant findings shown in Tables 5 and 6 are further supported by placebo tests conducted at the 25-ha and 45-ha thresholds (see Supplementary material, Tables A7 and A8) for the 10-ha and 30-ha comparisons, respectively,[6] and by the manipulations test that rejected the continuity null hypothesis at the 10 % level for both thresholds. The McCrary statistic (McCrary, 2008) is 0.91 with a *p*-value of 0.363 at the 30 ha threshold, and is −1.35 with a p-value of 0.178 at the 10 ha threshold.

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[6] In the related empirical literature (see Sauquet, 2022; Varacca et al., 2022), placebo tests are typically conducted either using the same AL threshold in previous years or at alternative thresholds. Due to the lack of information on a number of outputs prior to 2014, we choose to perform the placebo tests at alternative thresholds. Furthermore, the selection of the 25 ha threshold is justified by the fact that the 15 ha threshold is used for the EFAs, where we might expect effects similar to those observed following the CD intervention on the outcomes under consideration. Results in the Supplementary material.

In summary, our results provide evidence that Greening CD regulations have prompted local changes in agricultural practices in order to align with policy requirements and to promote crop diversification in all farms (potentially) under the regulations. The policy has also affected land allocation locally, thereby leading to a local increase in the area that is dedicated to cereals as well as to reductions in areas assigned to permanent grassland and fodder among medium large farms.

5. Conclusions

The Greening payments represent a significant component of direct payments to farmers, rewarding them for adopting land management practices that are beneficial to the environment and aligning agricultural activities with the production of environmental public goods. The analysis developed in this study adds to the existing ex-post literature by offering an extensive investigation on the impact of the CD regulation, featuring wider geographical coverage and a greater range of farm specialisations with respect to previous related work (as summarised in Table A13 of the Supplementary material). We conducted a thorough evaluation of crop diversification's effectiveness at the farm level across 28 EU member states by utilising FADN data. In light of this policy's renewed importance for the 2023–2027 CAP cycle, our findings hold significant implications for future EU agricultural policies and provide valuable insights that would aid in the development of farm-level environmental initiatives. First, our findings contradict earlier reservations about the CD policy's ability to bring about meaningful changes in the EU agricultural landscape. In turn, the accurate quantification of policy effects opens up the avenue for more informed cost-benefit analyses on Greening and similar environmental initiatives. Second, the findings from our ex-post evaluation may constitute valuable input material to refine the calibration of EU-wide individual farm models such as IFM-CAP, which are routinely employed to generate simulations of alternative policy scenarios, which in turn feed into policy planning processes.

Although we were not able to analyse direct environmental effects in this study, due to a lack of data, we can still assert that the Greening framework has notably impacted crop diversification practices, thereby establishing a new benchmark for sustainable agriculture within the EU. The estimated impact on regulatory outcomes has increased over the period analysed, showing a progressively adaptive response from non-adherent farms to regulation. The cumulative effects of the PSM-DID analysis demonstrate that treated farms are increasingly aligning with the policy by both diversifying and increasing the number of crops, as confirmed locally by the RD analysis. These results highlight the policy's success in terms of its intensive margin: in enhancing the number of cultivated crops, reducing the proportion of land allocated to main crops and, crucially, by promoting crop diversification for the non-already compliant farms. This contribution was higher for crops farms, and for farms with smaller AL. We also detected some evidence of positive significant impacts on economic outputs. On average, no additional significant results are found regarding the drivers of environmental outcomes for non-compliant farms. However, there are small local increases in the intensity of fertilizer use for farms near the 10 ha threshold.

In sum, this study confirms that the policy has had significant effects in terms of crop diversity in the subset of farms that were targeted by the policy itself: small- and medium-size crop farms; on the other hand, the debate about the limited ambition of the policy's target and its cost-effectiveness is out of the scope of this study.

The findings obtained may form the basis for future research that may extend the evaluation both to a longer time horizon and to investigate the effect on direct environmental outcomes, should the data become available at the farm level.

CRediT authorship contribution statement

Zelda Brutti: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marzia Freo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Serlenga:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2025.108715.

Data availability

The authors do not have permission to share data.

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