Reducing pesticides in agriculture: Unveiling the impact of landscape features on natural pest control and farm income.

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Abstract

Future trajectories of agricultural productivity need to incorporate environmental targets, including the reduction of pesticides use. Landscape features supporting natural pest control (LF-NPC) offer a nature-based solution that can serve as a partial substitute for synthetic pesticides, thereby supporting future productivity levels. Here, we introduce a novel approach to quantify the contribution of LF-NPC to agricultural yields and its associated economic value to crop production in a broad-scale context. Using the European Union as case study, we combine granular farm-level data, a spatially explicit map of LF-NPC potential across agricultural land, and a regional agro-economic supply and market model. The results reveal that farms located in areas characterized by higher LF-NPC potential experience lower productivity losses in a context of reduced synthetic pesticides use. Specifically, we estimate that a one-unit increase in LF-NPC potential, on average, leads to a 6.1% increase in agricultural income. These results highlight the significance of LF-NPC for agricultural production, and provide a valuable reference point for farmers and policymakers aiming to successfully invest in landscape features to achieve pesticides reduction targets.

Main

Sustainable use and management of biodiversity, including valuing, maintaining and enhancing ecosystem functions and services, is among the four long-term goals of the Kunming-Montreal Global Biodiversity Framework (GBF) adopted by the UN Convention on Biological Diversity\(^1\). Amongst others, the framework sets the 2030 global target of reducing the overall risk from pesticides and highly hazardous chemicals by at least 50%. Similarly, the European Green Deal promotes biodiversity preservation and restoration, and targets a reduction of pesticides use by 50% by 2030\(^2\). These goals are a direct response to mounting societal concerns and scientific evidence pointing at the negative environmental impacts resulting from intensive agricultural systems\(^3\)–\(^7\). The expansion of agricultural land for example, and the intensive use of agrochemicals have resulted in simplified landscape structures and a loss of biodiversity in Europe and other regions of the world\(^8\)–\(^12\). The loss of biodiversity has also led to a reduction in functional biodiversity, including natural enemies\(^11,13\)–\(^15\). These organisms, such as predatory insects, parasitoids, or birds are a valuable tool for sustainable pest management in agriculture, as they reduce pest populations, providing the ecosystem service of natural pest control (NPC)\(^16\). Consequently, they can reduce reliance on synthetic pesticides and in theory mitigate the suggested adverse impacts on agricultural productivity and its consequences resulting from the targeted 50% reduction in synthetic pesticides use\(^17\)–\(^20\).

In agricultural systems, NPC can be promoted through landscape complexity\(^21\), which refers to small areas of natural or semi-natural vegetation within an agricultural landscape that can provide ecosystem services, promote biodiversity, and are often denoted as agricultural landscape features\(^22,23\). Agricultural landscape features can support the abundance of natural enemies, by providing shelter and alternative prey, thus allowing them to persist over time\(^24,25\). Accordingly, in scientific literature it has long been
established that landscape complexity, with its associated diversity in flora and fauna, plays a crucial role in promoting NPC in agricultural systems and reduce reliance on chemical inputs. Several recent empirical studies provide evidence of enhanced NPC resulting from higher landscape complexity.

While current research provides pivotal insights, it remains bottlenecked regarding the general quantification of the ecosystem service of NPC. Furthermore, links of NPC to crop yields, which is one of the main drivers of a farm’s operability, are difficult to establish and often missing due to multifaceted challenges. These challenges arise from insufficient data, inconclusive results, the underlying ecological complexity, or because results remain highly context-specific.

An additional challenge is the economic valuation of NPC as an ecosystem service. Losey & Vaughan (2006) estimate the monetary value of NPC in the United States at 4.5 billion USD per year, but acknowledge lack of data to further refine the evaluation. Other studies have estimated the monetary value of NPC, but focus on a specific crop, pest, or geographic location, and hence do not provide a general economic evaluation. However, especially under pesticides reduction targets, as outlined by the GBF and Green Deal, it becomes crucial to establish the economic value of NPC to crop production in more general terms. Policymakers and farmers must be aware of the financial benefits associated with landscape-driven NPC to undertake timely and appropriate investments in landscape management to meet the GBF and Green Deal targets without encountering severe losses in agricultural production.

Taking the European Union (EU) as a case study, in this paper we provide a comprehensive assessment of the contribution of NPC potential driven by landscape features (hereafter referred to as LF-NPC potential), quantifying its impact on crop yields and the associated economic value in agricultural production under a reduced synthetic pesticides framework. For the assessment, we combine a European-wide dataset on yield observations derived from the EU Farm Accountancy Data Network (FADN) and a map of the continent's LF-NPC potential at 100-meter resolution. The LF-NPC map has been derived by merging high-resolution geospatial layers depicting landscape elements with extensive field surveys of insects flying predators and parasitoids. The landscape elements considered were small woody features, grasslands, and forests, and their contribution to LF-NPC potential was determined based on observed flying insect abundance. The resulting indicator is the only one available which establishes LF-NPC potential across the European continent. At the same time, FADN provides farm-level yield observations and characteristics across the EU. Since synthetic pesticides are largely avoided in organic agriculture, we use the reported farm typology (organic or conventional) under FADN as a starting point to establish yield gaps capturing the difference in productivity between intensive (conventional) and less-intensive (organic) farming systems. To further narrow down the differences in yield gaps that can be attributed specifically to the avoidance of synthetic pesticides in organic farming, we control for other influential factors that can affect yield differences between organic and conventional farms, such as mineral fertilizers. After estimating the regional yield gaps attributed to pesticides use for major crops, we investigate whether regions with higher LF-NPC potential exhibit a lower yield gap. Finally, to evaluate the economic implications of LF-NPC potential, we parametrize a
partial equilibrium model and simulate the EU agricultural sector in 2030 taking into account a reduction in pesticides use and the previously estimated yield gaps, which are a function of a region's landscape complexity. By employing this approach we aim to provide, cutting-edge insights into the role of landscape design in shaping agricultural profitability in the context of reduced pesticides use.

**Results**

The analysis included the following eight arable crops: wheat, barley, oats, corn, potatoes, legumes, rye and fodder corn (see supplementary information section 1 for more details on crop selection). For these crops, we estimated yield gaps attributable to differences in pesticides use between organic and conventional farming practices. These yield gaps have then been compared to the regional LF-NPC potential.

**Yield gaps between organic and conventional farming**

Yield gaps are estimated for each FADN region of the EU provided that a minimum number of organic farms operate in a region. To ensure statistical robustness, FADN regions with fewer than 16 organic farms cultivating a specific crop were excluded from the analysis. Following this filtering process, a total of 503 regions and crop combinations remained, for which each time a uniform econometric model per crop and region was employed. The models utilized the same farm-level variables as explanatory factors (see Methods for the selection of explanatory variables). This methodology resulted in 503 estimations of crop-specific regional yield gaps attributed to differences in synthetic pesticides usage. The regional, crop-specific econometric models have been provided with data points ranging from as little as 32 to as many as 37,000 for regions and crops categories with extensive observations. The average regional yield gap in the EU between organic and conventional farming attributable to pesticides use from our estimations is -16.5%, with important differences associated to crops, ranging between −8% in legumes, -25% in wheat and −27% in rye (see Fig. 1 and Supplementary Table 1). Regional differences are also substantial, for example varying between −5.4% (Lorraine- France) to -17.7% (Thraki- Greece) in fodder maize. The p-value of the included farm-level explanatory variables is predominantly statistically significant (see Supplementary Fig. 1). The mean absolute error (MAE) is further used as a metric to assess the performance of the predictive models. The MAE between predicted and reported yields is 12.3%. The error distribution is centred around 0, with a slight positive skewness due to outliers (see Supplementary Fig. 2).

**Contribution of LF-NPC potential to agricultural production**

Correlating the LF-NPC potential of a region to the estimated crop-specific yield gap between organic and conventional farming due to pesticides use, shows a positive correlation for seven out of the eight analysed crops (Fig. 2). The strength of correlation (Pearson) varied among crops, with values ranging from 0.16 for fodder corn to 0.43 for corn. For crops with a large number of observations (barley, oat, wheat, and corn), the relationship was most of the times statistically significant (see Supplementary Table 2). Rye did not show any trend in the relationship between LF-NPC potential and yield gap.
Logarithmic and polynomial fitting methods did not provide a more accurate fit than the initial linear regression (see Supplementary Table 2).

A mixed effect model was used to quantify the effect of LF-NPC on yield gaps. Results of the implemented mixed effect model were first obtained with a total of 245 observations including all eight crops and allowing both slopes and intercepts to vary across crop groups. The results indicate a statistically significant positive main effect of LF-NPC potential to yield gaps. Increasing a region's LF-NPC potential by one unit results in a 6.2% reduction in yield gap on average for all crops (Supplementary Fig. 3). The variation in the effect between crops is not very large, ranging between 5.4 to 6.7%, suggesting to drop the random component in the slope. On the contrary, the random intercept variance in the model is significantly large, indicating a need to maintain a random effect in the intercept. Therefore, a mixed effect model, with only the intercept allowed to vary between crop groups, keeping the slope constant, is used. Using this model, the average effect of a one unit increase of LF-NPC potential on yield gaps is 6.1% (see Supplementary Fig. 3), aligning closely with the previous estimation of 6.2%. The marginal R-square of 0.19, indicates that LF-NPC potential is able to explain 19% of the variability observed in regional crop yield gaps (see Supplementary Fig. 3). Therefore, using the established mixed model, regional yield gaps as a function of a region's LF-NPC potential are estimated.

**Quantification of the financial benefit of LF-NPC to agricultural production**

By incorporating these newly estimated, LF-NPC dependant yield gaps into the agro-economic, partial-equilibrium model CAPRI (Common Agricultural Policy Regionalised Impact Modelling System), insights are gained regarding the financial benefit of LF-NPC to agricultural production. Specifically, we simulate a scenario in which all EU regions reduce their pesticides use and cost to level's observed in organic farming by 2030 and adopt yield gaps according to their LF-NPC profile (hereafter referred to as LF-NPC scenario). The results of the LF-NPC scenario are then compared to a business-as-usual scenario (baseline scenario), where no yield changes, nor synthetic pesticides use reductions have been implemented. By comparing the income change between the baseline scenario and LF-NPC scenario between regions with varying LF-NPC potential, one can evaluate the financial benefits of LF-NPC in a reduced pesticide usage scenario, as the LF-NPC scenario considers factors such as the reduction in synthetic pesticide usage and cost, the LF-NPC potential of each region, and the corresponding crop-specific yield gap. This assessment is conducted holding all other factors constant, allowing for a focused analysis of the financial agricultural benefits associated with LF-NPC. Results show that, on average, a one-unit increase in the LF-NPC potential improves farm revenue by 5.1% and farm income by 6.2% per hectare (Fig. 3).

While on average a higher LF-NPC potential is linked to positive revenue and income changes, results also point at an important variability across regions with similar LF-NPC potential. This variability relates to differences in the agricultural structure of each region, such as the crop mixture grown, the associated yield gaps and the existing cost structure. To illustrate, one can consider two French regions, Bourgogne
and Provence-Alpes-Cote d’Azur, which have similar LF-NPC scores. It is observed that the revenue in Bourgogne experiences a more substantial reduction compared to Provence-Alpes-Cote d’Azur. This is mainly attributed to the fact that Provence-Alpes-Cote d’Azur focuses primarily on growing fodder crops, which use and depend less on synthetic pesticides and thus the reduction in pesticides use has a smaller productivity and hence revenue impact. Conversely, Bourgogne grows crops, where the yield gap due to lower pesticides use is higher and hence, the reduction in pesticides use has a stronger negative impact on production and revenue levels. This being said, the reduction in pesticides cost due to the reduction in use is stronger in Bourgogne, nevertheless not sufficient to compensate for the loss in revenue. In some cases, when pesticides cost represent a very large share of the total cost, and the regions LF-NPC profile is very high hence the yield gap small, the revenue loss can be compensated by the cost reduction. Latter finding emphasises that the economic value of LF-NPC is especially high in regions where synthetic pesticides represent a large share of the total cost structure.

**Discussion**

Recent global and EU targets for reducing pesticide use require an acceleration in the exploration of alternative pest control strategies that can reduce reliance on chemical inputs. In our study, we investigate the economic advantages of incorporating landscape complexity to enhance LF-NPC potential and support agricultural productivity under a reduced pesticides scenario. Specifically, we compare the agricultural economic performance of regions with higher LF-NPC potential to those with lower potential. We estimated that a one-unit increase in LF-NPC potential, on average, results in a 6.1% increase in productivity and a similar increase in overall farm income.

In this study, LF-NPC serves as a proxy for potential species richness providing NPC to sustain agricultural productivity when less synthetic pesticides are used. Therefore, the measured positive impact of LF-NPC can be interpreted as the beneficial feedback of species richness on farming productivity in the context of reduced synthetic pesticides use. Opposed to experimental field designs, the approach chosen is similar to the category of causal inference using a potential-outcome framework: Observational data and domain assumptions are applied to build a statistical model connecting LF-NPC (proxy of species richness) to agricultural productivity. Notably, our focus lied on the direct benefits of LF-NPC potential for agricultural production and does not measure other positive externalities of LF-NPC, such as soil erosion or carbon sequestration. The inclusion of these public goods would increase the total economic value of LF-NPC. Additionally, our study does not undertake a comprehensive appraisal of the positive ramifications arising from a reduced use of synthetic pesticides, such as cost savings in water purification, health benefits for workers or nearby residents. Furthermore, although we explore the potential positive feedback loop of an enhanced landscape design supporting LF-NPC, we did only account for the costs related to reduced pesticides use and did not explore the costs associated with redesigning the agricultural landscape to increase LF-NPC potential. Further investigation is needed to estimate these costs, involving different data sources. Nevertheless, the explored and quantified benefit of LF-NPC to support agricultural production fills the existing gap of a missing general
quantification, which paves the way to further investment in redesigning the agricultural landscape, aligning also with the biodiversity strategy for 2030 that promotes incorporating landscape features in agricultural land.

Previous studies have provided economic valuations of NPC in specific contexts, focusing on a specific location, crop or pest. For instance, one study valued NPC for soybean aphid management between 4.2 to 32.6 Euro per ha, while another found a 18% decrease in net farm income due to the loss of natural enemies in pear production. Our study provides a general quantification of the regional benefits of LF-NPC potential across Europe, considering multiple crops. The general quantification of LF-NPC potential allowed us to parametrize an agro-economic partial equilibrium model in such way that we can examine the general economic value of LF-NPC potential for agricultural production. Taking into account regional agricultural sector characteristics, we obtain an estimate on the positive economic contribution of landscape features to farm income under reduced pesticides use. It is worth to note that when running a partial equilibrium scenario without considering trade feedbacks and related price effects from agri-food markets, lower yields generally result in decreased overall farm income. The main reason for this outcome is the decline in production levels while prices remain unchanged. When allowing for market and price feedback, higher prices due to lower production levels can potentially increase overall agricultural income compared to the business-as-usual (baseline) scenario. However, these price-related effects are not the focus of our analysis. The key insight here is the relative benefit of regions with higher LF-NPC potential compared to regions with lower LF-NPC potential in a reduced pesticides context. The financial benefit has been derived from the positive coefficient associated with LF-NPC potential in the regression analysis, when comparing a region’s LF-NPC potential to future income changes. Our analysis also highlights the potential economic variability of outcomes given the same LF-NPC profile. Reducing synthetic pesticide use will have different financial impacts on regions, depending on their crop mix and cost structure. Regions growing crops with lower LF-NPC benefits and higher yield impacts due to reduced synthetic pesticides use, will experience more severe consequences. This variability should be taken into account in future research and policies aimed at optimizing pesticide reduction strategies.

Despite the observed variability in income, regions with a higher LF-NPC profile generally experience positive changes in income due to the established positive link between LF-NPC potential and yield gaps. Based on the FADN data, the average yield gap between organic and conventional farms used to determine the contribution of LF-NPC-potential is -16.5%, with important differences across crops and regions. Meta-analyses comparing organic and conventional yields often conclude that yields are highly contextual, depending on the system, site-specific characteristics and management practices. These meta-analyses report average yield gaps between 19–25%, with considerable standard deviations. Notably, organic fruits and oilseed crops show smaller gaps compared to conventional, whereas cereals and vegetables demonstrate larger gaps. Such differences might be related to the better organic performance of perennial over annual crops, and legumes over non-legumes. Our findings also confirm this, showing for example an average yield gap of -8% for legumes and -25% for wheat.
supplementary Table 1). Additionally, field experiments that specifically assessed the effects of pesticides on yields also support our estimations. For example, Delin et al. (2008) found yield gaps ranging from -8% to -37% in wheat when comparing systems with and without pesticides use in Sweden, with all other production characteristics being equal. Trials of Hossard et al. (2014) generated -5% to -13% wheat yield losses from a 50% pesticide reduction in France, corresponding to -24% to -33% in a zero-pesticide system.

In the subsequent stage of our analysis, the estimated yield gaps were used to quantify the impact of LF-NPC potential on yield gaps using a mixed effect model. We found that higher LF-NPC profiles are positively linked to lower yield gaps, suggesting that landscapes providing more favourable habitats for beneficial insects not only enhance NPC but also reduce the existing productivity gap when less synthetic pesticides are applied. On average, a one-unit increase in LF-NPC leads to a 6.1% reduction in the yield gap. The general quantification of LF-NPC’s effect on agricultural productivity is crucial given the varying outcomes of NPC at local level. Nevertheless, it should be noted that while we have observed a higher LF-NPC potential linked to lower yield gaps, it does not guarantee effective pest control at local level. The effectiveness of NPC at a local level can be influenced by various factors, including the severity of pest infestations, the balance between pest populations and natural enemies in the area, the effects of climate and climate change, and neighbouring agricultural practices. Therefore, while our findings provide valuable insight into the general benefits of LF-NPC for reducing yield gaps, caution is warranted in interpreting these results as a guarantee of success at the local level.

By analysing the relationship between yield gaps and landscape design at a broader scale and at regional resolution, we overcome the limitations posed by local variability and identify a general trend of the benefits and value of LF-NPC for agricultural production. While the local level is ultimately crucial to realise the performance of LF-NPC, our results provide a so far missing reference point for farmers and policymakers on the potential of landscape features in contributing to agricultural productivity under pesticides reduction targets.

Methods

The methodological approach is divided into three major parts. First, we estimate regional crop yield gaps between conventional and organic farming that can be attributed to differences in pesticides use. Second, we measure the contribution of LF-NPC potential to crop yield gaps, and third, we parametrize a partial equilibrium model to derive the economic value of LF-NPC potential.

Input data

During the analysis two high-resolution data sources were used:

1) A spatially explicit indicator of the LF-NPC potential at 100-meter resolution. This indicator was derived by combining high resolution geospatial datasets on the presence of landscape features.
interspersed in the agricultural matrix with field level observations on the abundance of flying natural enemies associated to different landscape features.

2) Farm level data collected under the EU Farm Accountancy Data Network (FADN). FADN surveys annually a large sample of agricultural holdings (around 80,000) across all EU Member States covering a wide range of farm types and sizes. The data collected under FADN includes information on the physical characteristics of the farm, such as land use, yields or livestock numbers, farming management (organic or conventional) as well as economic and structural data, such as income and expenditure, assets and liabilities, and subsidies received. As FADN data does not provide the geo-specific locations of farms, observations of one farm cannot be directly linked to the geo-specific LF-NPC potential of that farm. However, FADN data does report the region (FADN region) within which a farm is located, and thus regional estimates of yield gaps can be estimated and paired to regional estimates of LF-NPC potential. Working at regional level due to the lack of information regarding the geolocation of farms, can limit our understanding of the influence of context-specific factors explaining the relationship between LF-NPC potential and yield gaps. However, it also enables us to mitigate the variability caused by unique circumstances and identify more widespread patterns that are applicable across Europe.

**Yield gaps between organic and conventional farming**

Using FADN data, we confine the estimation of yield gaps to each FADN region to have both representative data and to limit the heterogeneity of the operating environment of farms. As neither quantity nor type of applied pesticide are available in FADN, and since synthetic pesticides are largely avoided in organic agriculture, we make use of the organic status reported for each farm to analyze the potential impact of variations in pesticide use on crop yields. We first define the (log) crop-yields ($y$) using a linear multiple regression to control through $X_1$ for structural and geographical characteristics of the farm, farming practices, as well as year-specific shocks, such that the coefficient ($\beta_2$) of the organic status variable ($\text{Organic\_status}$) is narrowed down to capture yield differences that are attributable to the use of pesticides.

$$\log (y) = \beta_0 + \beta_1 X_1 + \beta_2 \text{Organic\_status} + \epsilon$$

Then we estimate the yield gap between organic and conventional farming attributable to differences in pesticides use in percentage as:

$$\%\Delta YIELD_{\text{crop,region}} = \left( e^{\hat{\beta}_2} - 1 \right) \times 100$$

To ensure that we capture the effect of year-specific shocks that may influence yields in a local area, we include time dummies in $X_1$. To better control for factors such as soil quality, water availability, natural constraints and other local factors, we also include sub-regional (NUTS 3) and altitude dummies. Furthermore, to control for structural characteristics and farming practices we include specialization dummies, irrigation system, the share of unpaid labour, ratio of subsidies to gross income, the share of...
rented land, the ratio of assets to liabilities, assets per hectare, the capital-labour ratio, the physical size of the farm in terms of UAA, and the share of revenues coming from crop activities. All these variables are aimed to control for the technological and professional nature of the farm as well as the possible presence of economies of scale which may have an influence on its performance. Moreover, to exclude the effect of mineral fertilizers (not allowed under organic farming) on yield gaps, we also control for purchased fertilizers and soil improvers. Finally, by focusing on yield gaps rather than solely organic yields, we also account for variations in yield standards, such as climate, that is not reported in the FADN database. The assumption is that after controlling for all these factors the obtained yield gap is attributable to the farming practices related to pesticide use. In other words, the organic status coefficient \( \beta_2 \) is expected to capture the change in yield related to pesticides use between organic and conventional farming.

**Contribution of LF-NPC potential to agricultural production**

By confronting the obtained regional yield gaps to a region’s LF-NPC potential, we investigate across Europe, whether regions with higher LF-NPC potential face a lower yield gap due to the reinforced presence of beneficial insects (Fig. 4). To obtain the median LF-NPC potential of a region, we compute zonal statistics \(^67\) of each region in Europe based on the 100-meter resolution map of LF-NPC elaborated by Rega et al 2018. Additionally, to further account for natural conditions, which are required to describe the effective capacity of the ecosystem to deliver the service \(^68\), we standardized the index based on each region’s biogeographical classification \(^69\). The normalized regional LF-NPC indexes are then paired with the obtained regional yield gaps.

To quantify the contribution of a region’s median LF-NPC potential to the estimated yield gap, we employ a mixed effect model. Linear mixed models are often used when there is a nested structure to the data, meaning that the relationship between response and explanatory variable can be grouped into different classes \(^70\). In our model, we group the relation between LF-NPC potential and yield gap into different crop categories, allowing each crop group to have its individual relation (slope and intercept) to LF-NPC potential, while accounting for observations across crop groups. Crop category therefore becomes the random effect. Estimates of the model’s coefficients capture the change in yield gap attributable to a one-unit increase of LF-NPC potential. The model is specified as:

\[
y_i = \text{NPC}_i \cdot \beta + \text{NPC}_i \cdot b_i + \epsilon_i
\]

\[
b_i \sim N(0, \Psi)
\]

\[
\epsilon_i \sim N(0, \sigma^2 I)
\]

where \( y_i \) is a vector representing yield gaps between conventional and organic farms, \( \text{NPC}_i \) a vector of known regional LF-NPC potential values, \( \beta \) a vector of fixed effect coefficients, \( b_i \) a vector of random effects coefficients and \( \epsilon_i \) the error term representing the unaccounted variability in the observations. The random effect vector \( b_i \) and the error term \( \epsilon_i \) follow multivariate normal distributions with \( \Psi \) as the
covariance matrix for the random effects and $\sigma^2 I$ the covariance matrix for the error component \(^71\). Furthermore, we calculate marginal and conditional R2 values to analyse the variation explained by fixed versus random effects \(^72\).

Two advantages of employing a mixed-effect model in our analysis can be highlighted. Firstly, while the relationship between LF-NPC potential and yield gap may vary between crops, a higher LF-NPC potential is expected to generally reduce the yield gap. Therefore, observations in one crop group should not be modelled completely independently, as would be the case in a simple linear regression conducted by crop. The mixed-effect model allows us to model all crop groups together, while accounting for each crop group's individual relation to LF-NPC potential, thus providing a more accurate representation of the data. Secondly, as we are working at regional level, fewer observations are available for each crop (not all considered crops are present in all regions). By pooling observations across crop groups in a mixed-effect model, we can compensate for the reduced sample size at the regional level. Thus, this approach ensures that the study has sufficient statistical power to accurately estimate the effect of LF-NPC potential on crop yields across Europe. Therefore, by using a mixed-effect model, we can address the potential confounding effects of crop type and regional variation in LF-NPC potential on yield gaps, providing a more comprehensive understanding of the contribution of LF-NPC potential to agricultural production.

**Parametrization of the agro-economic partial equilibrium model**

To evaluate the economic benefit of LF-NPC under reduced pesticides conditions, we parametrize the Common Agricultural Policy Regionalised Impact (CAPRI) modelling system. CAPRI is a global, comparative static, partial equilibrium model for the agriculture and the primary processing sectors. CAPRI has a highly detailed and disaggregated representation of regional agricultural production and supply within the EU. Specifically, the CAPRI EU supply module comprises about 280 independent optimization models that represent regional agricultural production activities at the EU NUTS 2 level (Nomenclature of Territorial Units for Statistics). These optimization models consider intermediate inputs for production activities, incorporate non-linear cost functions, and include constraints related to land availability, nutrient balances, and policy restrictions at the regional level. The EU supply models are interlinked with an international market model via an iterative process: commodity prices from the global market module enter the profit maximisation system of the EU regions, while EU agricultural supply from the regions is fed into the market module, which in turn re-calculates the market balance and commodity prices. CAPRI is frequently used for impact assessments of agricultural, environmental, climate change and trade related issues, both at EU \(^73–75\) and global level \(^76,77\). In this study, we project all EU regions to reduce their pesticides use to levels observed under organic farming by 2030, and adopt the estimated yield gaps, taking into account each region's LF-NPC potential and the pesticides reduction. The latter is implemented by changing yields and pesticides cost under the regional agricultural supply modules of CAPRI (Fig. 5). The market module is activated in an additional scenario to allow that changes in trade
and international commodity prices enter the profit maximisation of the supply module (see supplementary information section 3).

Declarations

Data availability


2. Natural pest control provided by landscape features (LF-NPC) as per Rega et al 2018: https://www.sciencedirect.com/science/article/pii/S1470160X18302309

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55. European Union. EU 2030 Biodiversity strategy: Bringing nature back into our lives. *EU Green Deal.* Published online 2020:81-86.


**Figures**

![Distribution of yield gap (%) estimation by crop.](image_url)
Figure 2

Pearson correlation ($\rho$) between LF-NPC potential and yield gap (%) by crop.
Figure 3

LF-NPC potential (x-Axis) versus income changes in percentage (y-axis).
Figure 4

*Schematic workflow to estimate the contribution of LF-NPC potential to agricultural production.*
Figure 5

*Partial equilibrium model with description of changes ingested into the supply module.*

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- LFNPC09082023SupplementaryInformation.docx
- CodeData.zip
- nrreportingsummary.pdf