Land reallocation to increase production and reduce nitrogen surplus: Impacts on crop diversity in England and Wales

Murilo Almeida-Furtado[ab]; Miranda P.M. Meuwissen[a]; Frederic Ang[ac]
[a]Business Economics, Wageningen University, P.O. Box 8130, 6700, EW, Wageningen, the Netherlands; [b]murilo.dealmeidafurtado@wur.nl; [c]frederic.ang@wur.nl;

Selected Paper prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA; July 28-30, 2024

1 Introduction

Agricultural production is the main driver of nitrogen (N) pollution and diversity losses, with these two factors transgressing the planetary boundaries (Campbell et al. 2017; Steffen et al. 2015). In croplands, over half of the applied N is lost to the environment (Lassaletta et al. 2020; Gu et al. 2023). Conventional agricultural practices have significantly narrowed the diversity of cultivated species. From a range of over 50,000 edible plants, only 15 species provide 90% of the world's energy intake, with rice, maize, and wheat alone providing about two-thirds of the calories consumed globally (Gruber 2017). This reduced diversity has increased vulnerability to extreme weather events, pests, and diseases, all of which are expected to increase with climate change (FAO 2017; FAO 2018). Meanwhile, population growth and demand for food are increasing (FAO 2017; FAO 2018). As a result, increasing food production, reducing N pollution, and increasing diversity have become major agricultural policy issues (Kanter et al. 2020; Pe'er et al. 2019). Soil N balances can be positive, leading to pollution, or negative, affecting future production. Given crop-specific N demands, it is crucial to understand the relationship between crop selection, production, and N balances. In this paper, we assess the potential for cropland reallocation to increase production and decrease N balances, and its consequences for crop diversity.

N balances are predominantly positive, primarily due to two factors. First, excess N is a non-point source pollutant that affects the environment rather than the farm. Second, farmers often overapply fertilisers as a risk mitigation strategy, driven by concerns over potential shortfalls in crop production. The economic and behavioural reasons behind this practice are well-documented (Del Rossi et al. 2023; Pannell 2017; Paulson and Babcock 2010; Sheriff 2005). However, studies have shown that improving farm management can decrease N balances without compromising production (Gu et al. 2023; Lamkowsky et al. 2021). Additionally, reallocating crops offers opportunities to increase production and decrease N balances.

Inadequate land allocation has been identified as a important source of inefficiencies (Folberth et al. 2020; Adamopoulos and Restuccia 2022; Beyer et al. 2022; Ang et al. 2018). Crop allocation not only affects production and N balances but also determines crop diversity. In this direction, several studies have found synergies between increasing production and increasing crop diversity (Ang et al. 2018; Tamburini et al. 2020); and also between increasing crop diversity and decreasing N balances, for instance, through practices such as crop rotations (Renwick et al. 2019), cover and catch crops (Renwick et al. 2019; Valkama et al. 2015) and intercropping (Duchene, Vian and Celette 2017; Gaudin et al. 2015; Singh, Schöb and Iannetta 2023; Bedoussac et al. 2015; Pelzer et al. 2014).

Our research contributes in two ways. First, we examine the potential of cropland reallocation for simultaneously increasing production and decreasing N balances. Previous studies in production economics have explored land reallocation to mitigate greenhouse gases emissions (Wang, Ang and Oude Lansink 2023) and reduce pesticides (Kahindo and Blancard 2022). However, the specific impacts of cropland reallocation on production and nitrogen balances, as well as its implications for crop diversity, remain underexplored. Folberth et al. (2020) analysed the global effects of cropland allocation focusing on production and the impacts on N fertilisers, but without explicitly targeting the reduction of N balances. Their study relied predominantly on yields, which can overlook broader input-output relationships and efficiency (Coelli et al. 2005). Our study addresses this gap by explicitly modelling the production relationships between inputs, outputs and N balances, thereby providing further understanding of the role of land allocation for production and N balances.

Second, we consider the dynamic spillover effect of N balances on crop production, an aspect often overlooked in empirical production economics (Kuosmanen 2014; Kuosmanen and Kuosmanen 2013). Unlike previous research, which models N balances statically, we introduce a more realistic, dynamic model of crop production where N balances in the previous period serve as an input for the production in the current period. This approach also enables us to capture the impact of potentially beneficial N management practices that have been highlighted in the literature (Gu et al. 2023). Although N is highly mobile, there is a dynamic effect from fertiliser applications and crop choices of previous years (Grant et al. 2016). For instance, N from organic sources release more slowly and can enhance water retention and overall nutrient availability (Smith et al. 2015; Gutser et al. 2005). Thus, our modelling approach considers how the quality and quantity of nitrogen applied in the previous period affects crop production in the current period.

Our empirical application focuses on English and Welsh crop farms for the years 2015 to 2019. England and Wales provide a pertinent context for our study, since N and diversity currently high priorities in agricultural policies and regulation (DEFRA and EA 2022; Bateman and Balmford 2018). The significance of these factors has grown, given the need to develop new agricultural policies following Brexit (Smith et al. 2023). We use a robust order-m Data Envelopment Analysis (DEA) approach described by Cazals et al. (2002), and extend the by-production approach of Murty, Russell and Levkoff (2012) by dynamic modelling of N balances in crop production and allowing for optimal land reallocation. In our model, the N balances from the previous year serve as an input for the production technology of crop outputs. We assess how efficiency and cropland reallocation can increase production and decrease N balances in three steps. First, we examine a scenario that simultaneously increases production and decreases N balances without land reallocation (BAU+YN). Second, we examine a scenario that increases production allowing for land reallocation (RLC+Y). Third, we examine a scenario that simultaneously increases production and decreases N balances allowing for land reallocation (RLC+YN). The comparison between the scenarios RLC+YN and RLC+Y reveals the opportunity cost of reducing N balances. In addition, we investigate the impacts of the reallocation scenarios (RLC) on crop diversity.

The remainder of this paper is divided into five sections. The first part of section 2 presents the theoretical framework on the properties of the production technologies for crop production and N balances. In the remaining parts of section 2, we detail the data and our empirical strategy to explore the potential of land reallocation to increase crop production and decrease N balances. Section 3 reports the main findings of our study, which are subsequently discussed in section 4. Section 5 addresses limitations and directions for further research. Section 6 concludes.

2 Methods

2.1 Production technologies

Following Murty et al. (2012), we distinguish between two types of sub-technologies, one for the production of intended crop outputs and another one for the unintended production of N balances. The Environmental Zones (EnZs) (Metzger et al. 2005), shown in FIGURE 1, define the edaphoclimatic context for these production technologies.

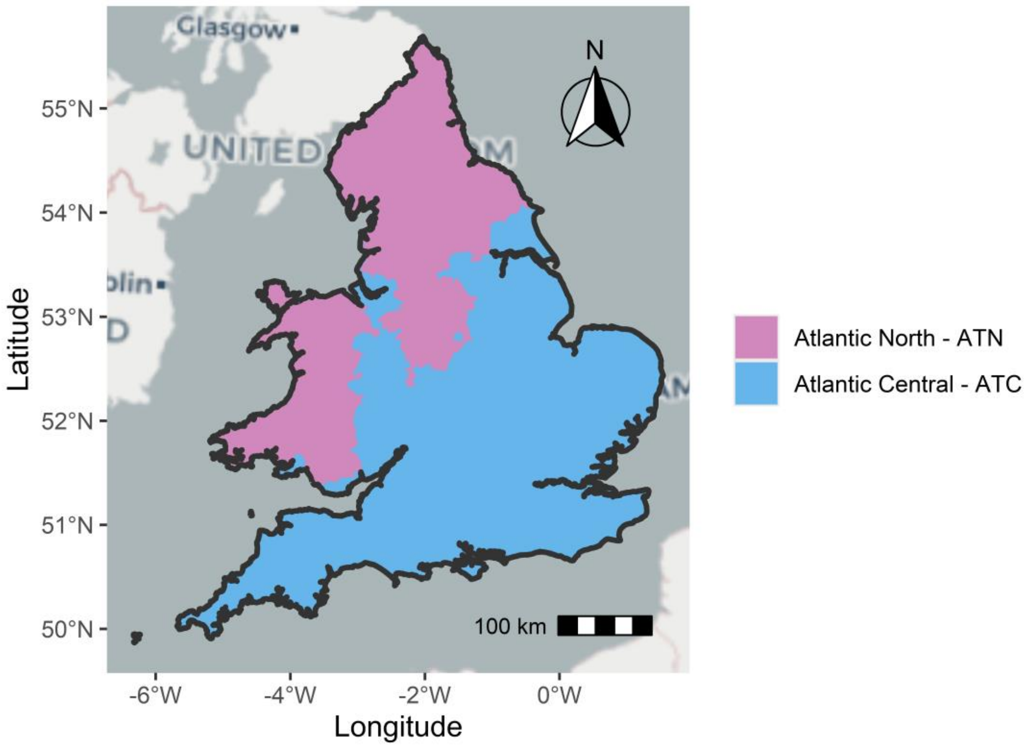

FIGURE 1 - ENVIRONMENTAL ZONES IN ENGLAND AND WALES – CLASSIFICATION BASED ON NUTS2[1] REGIONS.

The sub-technology of crop outputs ($\boldsymbol{\mathcal{T}}_{zt}$) for the environmental zone $\mathbf{z} \in \mathbb{R}^{Z}$ at time $\mathbf{t} \in \mathbb{R}^{T}$ is formally defined by

$$\boldsymbol{\mathcal{T}}_{zt} = \{(\mathbf{x}_{czt}, x_{fzt}, \mathbf{x}_{vzt}, b_{zt-1}, y_{azt}, y_{szt}) \in \mathbb{R}^{C+V+4} \colon \mathbf{x}_{c}, \mathbf{x}_{f}, \mathbf{x}_{v}, and\ b_{t-1}\ can\ produce\ \mathbf{y}_{a}\ and\ \mathbf{y}_{s}\} \tag{1}$$

where the inputs consist of $\mathbf{x}_{czt} \in \mathbb{R}_{+}^{\mathrm{C}}$ farm land use areas of selected crops, $x_{fzt} \in \mathbb{R}_{+}^{1}$ fertilizer expenses, $\mathbf{x}_{vzt} \in \mathbb{R}_{+}^{\mathrm{V}}$ other agricultural inputs, and $b_{zt-1} \in \mathbb{R}^{1}$ the N balances (details on the estimation are provided in appendix A1) from previous year. These inputs define the conditions to produce agricultural outputs, represented by $y_{azt} \in \mathbb{R}^{1}$ crop output and $y_{szt} \in \mathbb{R}^{1}$ livestock output. $\boldsymbol{\mathcal{T}}_{zt}$ takes the classical assumptions of

---

[1] The Nomenclature of Territorial Units for Statistics (NUTS) classification is a territorial division based on national administrative divisions. The NUTS 2 level consists of regions suited for the application of regional policies (Eurostat 2015).

closedness, convexity, free disposability of inputs and outputs, and variable returns to scale (Banker, Charnes and Cooper 1984). Accounting for edaphoclimatic differences that affect the possibilities for agricultural production and N losses, we distinguish production technologies based on the EnZs Atlantic North (ATN) and Atlantic Central (ATC) (Metzger et al. 2005). In addition, we control for interannual weather variability by only considering observations from the same year t in the estimation. N balances from the previous year are recognized as inputs, and can substitute other inputs, in the production of the current year. This dynamic approach addresses the limitations of previous studies that only characterise N balances as static (Kuosmanen 2014; Kuosmanen and Kuosmanen 2013).

The sub-technology of nitrogen balances ($\boldsymbol{\mathcal{N}}$) for the EnZ $\boldsymbol{z}$ at time $\boldsymbol{t}$ is formally defined by:

$$\boldsymbol{\mathcal{N}}_{\mathrm{zt}} = \left\{\left(\boldsymbol{x}_{\mathrm{czt}}, x_{fzt}, \mathrm{b}_{\mathrm{zt}}\right) \in \mathbb{R}^{C+2} \colon \mathbf{x}_c \text{ and } \mathbf{x}_f \text{ can produce } \boldsymbol{b}_{\mathrm{t}}\right\}, \tag{2}$$

where cropland uses ($\mathbf{x}_{czt}$) and fertilizer expenses (x_{fzt}) define the production of N balances ($b_{zt} \in \mathbb{R}^1$). Following Murty et al. (2012), the disposability assumptions in $\boldsymbol{\mathcal{N}}$ are different than the ones in $\boldsymbol{\mathcal{T}}$. This determines that there is a minimal and efficient level of N balances. Formally, for a given level of $\mathbf{x}_{czt}$ and x_{fzt} there is minimum level of b_{zt}, thus if $\mathrm{b}'_{\mathrm{zt}} \leq \mathrm{b}_{\mathrm{zt}} \rightarrow \left(\mathbf{x}_{\mathrm{czt}}, x_{fzt}, \mathrm{b}'_{\mathrm{zt}}\right) \in \boldsymbol{\mathcal{N}}_{\mathrm{zt}}$. Higher fertiliser use (x_{fzt}) is assumed to increase the N balance, *ceteris paribus*: $x'_{fzt} \geq x_{fzt} \rightarrow \left(\boldsymbol{x}_{\mathrm{czt}}, x'_{fzt}, \mathrm{b}_{\mathrm{zt}}\right) \in \boldsymbol{\mathcal{N}}_{\mathrm{zt}}$. However, for land use ($\boldsymbol{x}_{\boldsymbol{czt}}$), the larger the area, *ceteris* paribus, the greater the opportunity to decrease the N balances via crop production, thus $\mathbf{x}'_{czt} \leq \mathbf{x}_{czt} \rightarrow \left(\mathbf{x}'_{czt}, x_{fzt}, b_{zt}\right) \in \boldsymbol{\mathcal{N}}_{zt}$. This means that, in our model, land is a N-mitigating input. This is motivated by the fact that (i) there is a negative balance between air deposition, leaching, and volatilisation in the United Kingdom (Ludemann et al. 2023), and (ii) land uses are a source of inefficiencies associated with suboptimal N removals from crop production. This differs from Hoang and Coelli (2011), Serra et al. (2014), and Ait Sidhoum et al. (2020) which have treated land as an N-generating input.

2.2 Scenarios

To assess the impact of efficiency and cropland reallocation, we analyse crop production and N balances in four different scenarios: (i) business as usual without land reallocation (BAU), (ii) business as usual without land reallocation, maximising production and minimising N balances (BAU+YN), (iii) with land reallocation and maximising production (RLC+Y), and (iv) with land reallocation, maximising production and minimising N balances (RLC+YN). The maximum potential for simultaneously increasing production and decreasing N balances without land reallocation is assessed by comparing scenarios BAU and BAU+YN. The maximum potential of land reallocation for increasing production is assessed by comparing BAU+YN and RLC+Y. The comparison between the scenarios RLC+Y and RLC+YN allows assessing the potential trade-off between N and crop production. In the context of these scenarios, we compute production and N values for each farm, based on production frontier estimates. We use data envelopment analysis (DEA) (Banker et al. 1984; Charnes, Cooper and Rhodes 1978) to empirically estimate the frontier encompassing the intersection between $\boldsymbol{\mathcal{T}}_{zt}$ and $\boldsymbol{\mathcal{N}}_{zt}$. In what follows, we further investigate the production frontier projections for each farm in scenarios BAU+YN (section 2.3), RLC+Y and RLC+YN (both in section 2.4).

2.3 Efficiency improvements without reallocation

We first investigate the extent to which farms can increase crop output and decrease N balances without reallocation (BAU+YN) by the following DEA model:

$$\max_{\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\beta}} \left(\beta_{ak_ot} + \beta_{bk_ot}\right) \tag{3}$$

$s.t.$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}\mathbf{x}_{ckt} \leq \mathbf{x}_{ck_ot} \tag{3.1}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}x_{fkt} \leq x_{fk_ot} \tag{3.2}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}\mathbf{x}_{vkt} \leq \mathbf{x}_{vk_ot} \tag{3.3}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}b_{kt-1} \leq b_{k_ot-1} \tag{3.4}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}y_{akt} \geq y_{ak_o} + \beta_{ak_ot} \tag{3.5}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}y_{skt} \geq y_{sk_ot} \tag{3.6}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} = 1 \tag{3.7}$$

$$\boldsymbol{\lambda}_{kt} \geq 0 \tag{3.8}$$

$$\sum_{k_z=1}^{K_z} \mu_{kt}\mathbf{x}_{ckt} \leq \mathbf{x}_{ck_ot} \tag{3.9}$$

$$\sum_{k_z=1}^{K_z} \mu_{kt}x_{fkt} \geq x_{fk_ot} \tag{3.10}$$

$$\sum_{k_z=1}^{K_z} \mu_{kt}b_{kt} \leq b_{k_ot} - \beta_{bk_ot} \tag{3.11}$$

$$\sum_{k_z=1}^{K_z} \mu_{kt} = 1 \tag{3.12}$$

$$\boldsymbol{\mu}_{kt} \geq 0 \tag{3.13}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}\mathbf{x}_{ckt} = \sum_{k=k_z}^{K_z} \mu_{kt}\mathbf{x}_{ckt} \tag{3.14}$$

$$\beta_{ak_ot} \geq 0 \tag{3.15}$$

$$\beta_{bk_ot} \geq 0 \tag{3.16}$$

$$\forall\, k, k_o \in \{k_z, \dots, K_z\} \tag{3.17}$$

where $k_z \in \mathbb{R}^{K_z}$ denote the farm observations in each EnZ, β_{ak_o}represents the potential to increase crop production, and β_{bk_o} the potential to decrease N balances for the farm k_o under evaluation. The *lambdas* ($\boldsymbol{\lambda}$) are the intensity weights linked with $\boldsymbol{\mathcal{T}}_{zt}$ and the *mus* ($\boldsymbol{\mu}$) are linked with $\boldsymbol{\mathcal{N}}_{zt}$. This DEA problem is solved for every farm k observed at year t.

Constraint (3.14) equalises the cropland allocation in both sub-technologies. It is somewhat similar to the dependence constraint of Dakpo (2015) and Lozano (2015), which imposes that the optimal values of polluting inputs of both sub-technologies are equal. However, we permit optimal levels of other inputs to differ in both technologies. In line with Murty and Russell (2020), such a specification still leads to projected output and N levels that fall within the intersection of the crop and the N sub-technologies. Additionally, the consideration of independent betas ($\boldsymbol{\beta}_a$ for crop production and $\boldsymbol{\beta}_b$ for N balances) guarantees the frontier projections are efficient on both sub-technologies. As a result, our specification seeks for optimal land allocations, while imposing minimal assumptions consistent with our theoretical framework.

We apply the robust order-m DEA approach developed by Cazals et al. (2002) to mitigate the impact of atypical observations and the set of unrealistic frontier projections. For the subset of inefficient farms, , those for which $\beta_{akt} > 0 \vee \beta_{bkt} > 0$, we draw $m \in \mathbb{R}^M$ random samples with replacement taking 70 percent of the observations, conditioned that all observations in the subsample may have equal or better performance than the farm under assessment. After solving the DEA problem $M = 1000$ times, we have the optimal values

$$y_{akt}^{*} = y_{akt} + \frac{1}{M} \cdot \sum_{m=1}^{M} \beta_{aktm} \tag{4}$$

and

$$b_{kt}^{*} = b_{kt} - \frac{1}{M} \cdot \sum_{m=1}^{M} \beta_{bktm} \tag{5}$$

which we also use in the next steps of land reallocation.

2.4 Efficiency improvements through reallocation

We estimate the inefficiencies associated with crop allocation by assessing whether optimal crop allocation can increase the crop production value derived from Equation (4) and decrease the N balances identified in equation (5). To achieve this, we modify the DEA models to include cropland uses as decision variables. In these modified DEA models, the output values for each farm are the crop production values found with equation (5) and the N balances found with equation (6). The DEA model for the two reallocation scenarios is given by

$$\begin{cases} \max\limits_{\substack{\boldsymbol{\lambda}.\boldsymbol{\beta} \\ \mathbf{x}_{ck_ot}^{RLC+Y},b_{k_ot}^{RLC+Y}}} \beta_{ak_ot}^{RLC+Y}, & if\ scenario\ is\ RLC+Y \\ \max\limits_{\substack{\boldsymbol{\lambda}.\boldsymbol{\beta} \\ \mathbf{x}_{ck_ot}^{RLC+YN}}} \beta_{ak_ot}^{RLC+YN} + \beta_{bk_ot}^{RLC+YN}, & if\ scenario\ is\ RLC+YN \end{cases} \tag{6}$$

$s.t.$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}\mathbf{x}_{ckt} \leq \begin{cases} \mathbf{x}_{ck_ot}^{RLC+Y}, & if\ scenario\ is\ RLC+Y \\ \mathbf{x}_{ck_ot}^{RLC+YN}, & if\ scenario\ is\ RLC+YN \end{cases},\ \ c \in [1, C'] \tag{6.1}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}\mathbf{x}_{ckt} \leq \mathbf{x}_{ck_ot},\ \ c \in \,]C', C] \tag{6.2}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} x_{fkt} \leq x_{fk_o t} \tag{6.3}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} \mathbf{x}_{vkt} \leq \mathbf{x}_{vk_o t} \tag{6.4}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} b_{kt-1} \leq b_{k_o t-1} \tag{6.5}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} y^*_{akt} \geq \begin{cases} y^*_{ak_o t} + \beta^{RLC+Y}_{ak_o t}, & if\ scenario\ is\ RLC+Y \\ y^*_{ak_o t} + \beta^{RLC+YN}_{ak_o t}, & if\ scenario\ is\ RLC+YN \end{cases} \tag{6.6}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} y_{skt} \geq y_{sk_o t} \tag{6.7}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt} = 1 \tag{6.8}$$

$$\boldsymbol{\lambda}_{kt} \geq 0 \tag{6.9}$$

$$\sum_{k=k_z}^{K_z} \mu_{kt} \mathbf{x}_{ckt} \leq \begin{cases} \mathbf{x}^{RLC+Y}_{ck_o t}, & if\ scenario\ is\ RLC+Y \\ \mathbf{x}^{RLC+YN}_{ck_o t}, & if\ scenario\ is\ RLC+YN \end{cases}, \quad c \in [1, C'] \tag{6.10}$$

$$\sum_{k=k_z}^{K_z} \mu_{kt} \mathbf{x}_{ckt} \leq \mathbf{x}_{ck_o t}\,, \quad c \in \,]C', C] \tag{6.11}$$

$$\sum_{k=k_z}^{K_z} \mu_{kt} x_{fkt} \geq x_{fk_o t} \tag{6.12}$$

$$\sum_{k=k_z}^{K_z} \mu_{kt} b^*_{kt} \leq \begin{cases} b^{RLC+Y}_{k_o t}, & if\ scenario\ is\ RLC+Y \\ b^*_{kt} - \beta^{RLC+YN}_{bk_o t}, & if\ scenario\ is\ RLC+YN \end{cases} \tag{6.13}$$

$$\sum_{k=k_z}^{K_z} \mu_{kt} = 1 \tag{6.14}$$

$$\boldsymbol{\mu}_{kt} \geq 0 \tag{6.15}$$

$$\sum_{k=k_z}^{K_z} \lambda_{kt}\mathbf{x}_{ckt} = \sum_{k=k_z}^{K_z} \mu_{kt}\mathbf{x}_{ckt} \tag{6.16}$$

$$\sum_{c=1}^{C'} \mathbf{x}_{ck_ot} = \begin{cases} \sum_{c=1}^{C'} \mathbf{x}_{ck_ot}^{RLC+Y}, & if\ scenario\ is\ RLC+Y \\ \sum_{c=1}^{C'} \mathbf{x}_{ck_ot}^{RLC+YN}, & if\ scenario\ is\ RLC+YN \end{cases} \tag{6.17}$$

$$0 \leq \begin{cases} \beta_{ak_ot}^{RLC+Y}, & if\ scenario\ is\ RLC+Y \\ \beta_{ak_ot}^{RLC+YN}, & if\ scenario\ is\ RLC+YN \end{cases} \tag{6.18}$$

$$\beta_{bk_ot}^{RLC+YN} \geq 0,\ \ if\ scenario\ is\ RLC+YN \tag{6.19}$$

$$\forall\ k, k_o \in \{k_z, \dots, K_z\} \tag{6.20}$$

where $\mathbf{x}_{ck_ot}^{RLC+Y}$ and $\mathbf{x}_{ck_ot}^{RLC+YN}$ are the cropland uses that are reallocated in each scenario. Note, from constraints (6.1) and (6.10), that we only allow reallocation for the crops $c \in [1, C']$ which were the most representative crops in our sample (see details in the Data section 2.6). Constraint (6.17) guarantees that the farm size is kept constant after reallocation. The DEA problem is solved for every farm k observed at year t.

2.5 Crop diversity analysis

The results of our reallocation model have consequences to crop diversity. To measure these impacts, we first need to measure crop diversity. We measure diversity at the farm-level, as the consequence of different cropland uses. We use the Hill-Shannon index (Hill 1973) as our measure crop diversity, herein referred as "crop diversity" and the "effective number of cropland uses", which is the exponential of the Shannon index

$$HSI_{kt} = exp\left(-\sum_{c=1}^{C_H} L_{ckt} \times ln\, L_{ckt}\right), \tag{7}$$

where L_c is the proportion occupied by land use c out of C_H land uses. We calculate crop diversity at the farm level and regional level. This formulation rewards evenness of land allocation and the number of crops. This formulation allows us to express the crop diversity in units of species (Roswell, Dushoff and Winfree 2021). We are mainly interested in the changes of HSI comparing the scenarios before and after reallocation. To rigorously assess the statistical interpretation of changes in HSI, we compute bootstrapped confidence intervals and permutation tests. In appendix A2, we present the details of these statistical approaches.

2.6 Data

The Farm Business Survey (Duchy College 2022b; Duchy College 2022a; Duchy College 2020; Duchy College 2019b; Duchy College 2019a) is the dataset from which we extract farm level inputs and outputs for the period of 2015 until 2019. Table 1 details the input and output variables introduced in equations (1) and (2) and presents the units associated with them.

Table 1 Variable description and units

Variable	Description and units
$\mathbf{x}_{ckt} \in \mathbb{R}^{10}$	Crop areas [ha]: of which nine $(\mathrm{C}' = 9)$ can be reallocated - linseed, barley, beans, beetroot, oats, peas, potatoes, rapeseed, and wheat. The 10th area (C) is classified as "Other crops with N removal".
$x_{fkt} \in \mathbb{R}^1$	Fertilizer use expenses [GBP 2019]
$\mathbf{x}_{vkt} \in \mathbb{R}^6$	Other agricultural inputs: • other land uses [ha] • unpaid labour [hours] • depreciation [GBP 2019] • livestock costs [GBP 2019] • livestock feed [GBP 2019] and • Other variable costs [GBP 2019]
$\mathrm{b}_{kt} \in \mathbb{R}^1$ and $\mathrm{b}_{kt-1} \in \mathbb{R}^1$	Nitrogen balances [kg of N] at year t and $t-1$, respectively.
$y_{akt} \in \mathbb{R}^1$	Crop output [GBP 2019]
$y_{skt} \in \mathbb{R}^1$.	Livestock output [GBP 2019]

We select the reallocation crops based on their representativeness and availability of N coefficients. We extract the N removal and fixing coefficients per crop from IPNI (2013) and Ludemann et al. (2023). To identify the most representative crops we divide England and Wales into four major regions aggregating the official regions into North-East (NE - "North East", and "Yorkshire & the Humber"), North-West (NW - "North West", "West Midlands"), South-East (SE - "South East", "East Midlands", "London", and "East of England"), and South-West (SW - "South West", and "Wales").

This regional grouping links the farm structural surveys, that are given at the highest tier of sub-national division in England (DEFRA 2023) and Wales (StatsWales 2023), and the EnZs. Based on crops produced on both EnZs, the availability of N coefficients and the threshold of having at least one year with $15\ \mathrm{farms.region}^{-1}.\mathrm{year}^{-1}$ producing a specific crop in these regions, we select 9 crops for potential reallocation. Crops with N removal coefficients, utilized by fewer farms, were aggregated and categorized under 'other crops with N removal'. Although these 'other crops with N removal' contribute to the N balance equations, they are not considered for reallocation. The category “Other land uses” under “Other agricultural inputs” all other agricultural areas lacking N removal coefficients, predominantly representing pasture land. For the crop diversity analysis, we use these 11 different land uses classes (C_H), which includes all the aforementioned land use classes.

We deflate monetary values to reflect 2019 values using price indices from EUROSTAT (2022). The variable “Other variable costs” combine expenses related to seeds and young plants, electricity, total heating fuel, crop protection, energy, paid labour, and other crop costs. The variable “Livestock costs” aggregated veterinary expenses and other veterinary costs. To combine and calculate implicit quantities for these categories we use Törnqvist price indices (Balk 2008, p.72).

Given the focus on crop farms, we restrict our sample to farms focusing primarily on crop production, where the crop output exceeds 67% and non-crop output (consisting of livestock, and non-agricultural outputs) is less than 33% of the total output. We exclude farms that incurred fertilizer costs without associated nitrogen (N) quantities and farms that reported crop production without a designated area. Furthermore, we only include farms listed in the FBS that were present for at least two consecutive years, as our model requires N balances from two consecutive years.

We use sample weights to adjust our sample to correctly represent the farm structure of each of the four main regions (NW, NE, SW, and SE) mentioned earlier. Each farm in our sample is given a weight defined by

$$w_{kt} = \sum_{p=1}^{P} \left(\frac{FarmArea_{pt}}{\sum_{p=1}^{P} \left(FarmArea_{pt} \right)} \cdot \frac{PopulationArea_{pt}}{SampleArea_{pt}} \right) \tag{8}$$

where $FarmArea_p$ is the area occupied by each crop $p \in \mathbb{R}^{\mathrm{P}}$. The $PopulationArea_p$ is retrieved from farm structure reports provided by DEFRA (2023) for England and StatsWales (2023) for Wales. We introduce p as a new notation for crop area because the farm structure reports only provide information for the following $p \in [1, P']$ groups of crops: barley, field beans and peas, maize, oats, rapeseed, potatoes, and wheat. Thus, field beans and peas are grouped in one category. For all other land uses, such as $p \in]P', P]$, we assume a sampling intensity $\left(\frac{PopulationArea_{pt}}{SampleArea_{pt}} \right)$ equal to what is on average observed for the P' crops.

Our sample consists of English and Welsh farms for the period of 2015 until 2019, with an average of 542 observations per year. Table 2 presents the descriptive statistics of the farm-level inputs and outputs encompassing all years. Appendix A3 details the sample size per year, region and EnZ.

Table 2 Descriptive statistics of farm level inputs and outputs – yearly averages and standard deviation between parentheses, without weights

Variables	**England and Wales**	**Atlantic Central (ATC)**	**Atlantic North (ATC)**
Linseed area (ha)	0.7 (4.6)	0.9 (5.3)	0.2 (1.6)
Barley area (ha)	28.2 (49.7)	30.3 (56.8)	23.1 (23.8)
Beans area (ha)	5.3 (14.3)	6.0 (15.5)	3.6 (10.6)

Variables	England and Wales	Atlantic Central (ATC)	Atlantic North (ATC)
Beetroot area (ha)	5.9	8.1	0.4
	(23.1)	(26.9)	(4.3)
Oats area (ha)	5.0	5.1	4.7
	(15.0)	(16.1)	(11.7)
Peas area (ha)	3.0	4.0	0.6
	(13.6)	(15.8)	(3.8)
Potatoes area (ha)	3.9	4.2	3.2
	(18.9)	(21.0)	(11.9)
Rapeseed area (ha)	17.1	20.1	9.7
	(31.1)	(34.5)	(18.3)
Wheat area (ha)	60.8	72.5	31.9
	(84.7)	(94.1)	(43.1)
Other crops with N removal (ha)	8.9	10.9	3.7
	(42.5)	(49.6)	(11.8)
Other land uses (ha)	79.1	73.4	93.1
	(89.6)	(87.6)	(92.7)
Unpaid Labour (hours)	946.7	941.1	960.7
	(1,385.7)	(1,425.0)	(1,283.8)
Depreciation (GBP 2019)	48,477.9	52,178.7	39,299.8
	(66,092.3)	(74,510.8)	(36,298.6)
Livestock feed (GBP 2019)	58,661.6	56,311.1	64,491.3
	(184,740.1)	(188,459.9)	(175,155.3)
Livestock costs (GBP 2019)	20,161.1	17,969.8	25,595.8
	(36,222.0)	(37,072.0)	(33,430.3)
Variable costs (GBP 2019)	119,077.7	141,531.7	63,389.7
	(324,978.8)	(378,801.2)	(85,870.1)
Fertilizer costs (GBP 2019)	26,763.7	29,394.9	20,238.1
	(31,825.2)	(35,408.0)	(18,879.9)
Crop output (GBP 2019)	204,960.9	243,431.7	109,549.4
	(417,333.8)	(476,205.3)	(176,175.6)
Livestock output (GBP 2019)	137,426.1	127,433.1	162,209.8
	(326,102.2)	(335,069.7)	(301,496.9)
Nitrogen surpluses - previous year (kg)	9,025.7	8,277.4	10,881.5
	(25,269.0)	(28,687.5)	(13,292.7)
Nitrogen surpluses (kg)	8,653.8	7,725.9	10,955.2
	(27,255.9)	(31,103.7)	(13,380.5)

Variables	England and Wales	Atlantic Central (ATC)	Atlantic North (ATC)
Observations	542	386	156

3 Results

3.1 Comparison between efficiency and reallocation models

Our results show that it is possible to simultaneously increase crop production and decrease N balances by increasing efficiency and optimising land use allocation. Henceforth, we express all monetary values in GBP 2019 terms. On average for England and Wales, between 2015 to 2019, removing inefficiency without land reallocation (BAU+YN) can increase crop production from 905.17 GBP per ha to 915.48 GBP per ha, and decrease the N balance from 41.93 kg per ha to 40.88 kg per ha. The first reallocation scenario (RLC+Y), initially focused on increasing production, also achieved a reduction in N balances, it yields a maximum crop output of 988.91 GBP per ha and a minimum N balance of 38.87 kg per ha. The second reallocation scenario (RLC+YN), designed for the simultaneous increase of crop production and decrease of N balances, is estimated to result in a maximum crop production of 977.05 GBP per ha and a minimum N balance of 33.88 kg per ha. Thus, including the objective of reducing N balances reveals an opportunity cost, which is of 2.37 GBP per kg of N. In what follows, we present these results highlighting the differences between the EnZs ATC and ATN.

FIGURE 2 shows the potential crop output in each scenario. Crop output per hectare is higher in ATC than in ATN. The absolute potential for increasing production is greater for ATC than for ATN in all scenarios, although this distinction becomes less pronounced when assessed in relative terms with respect to the BAU scenario.

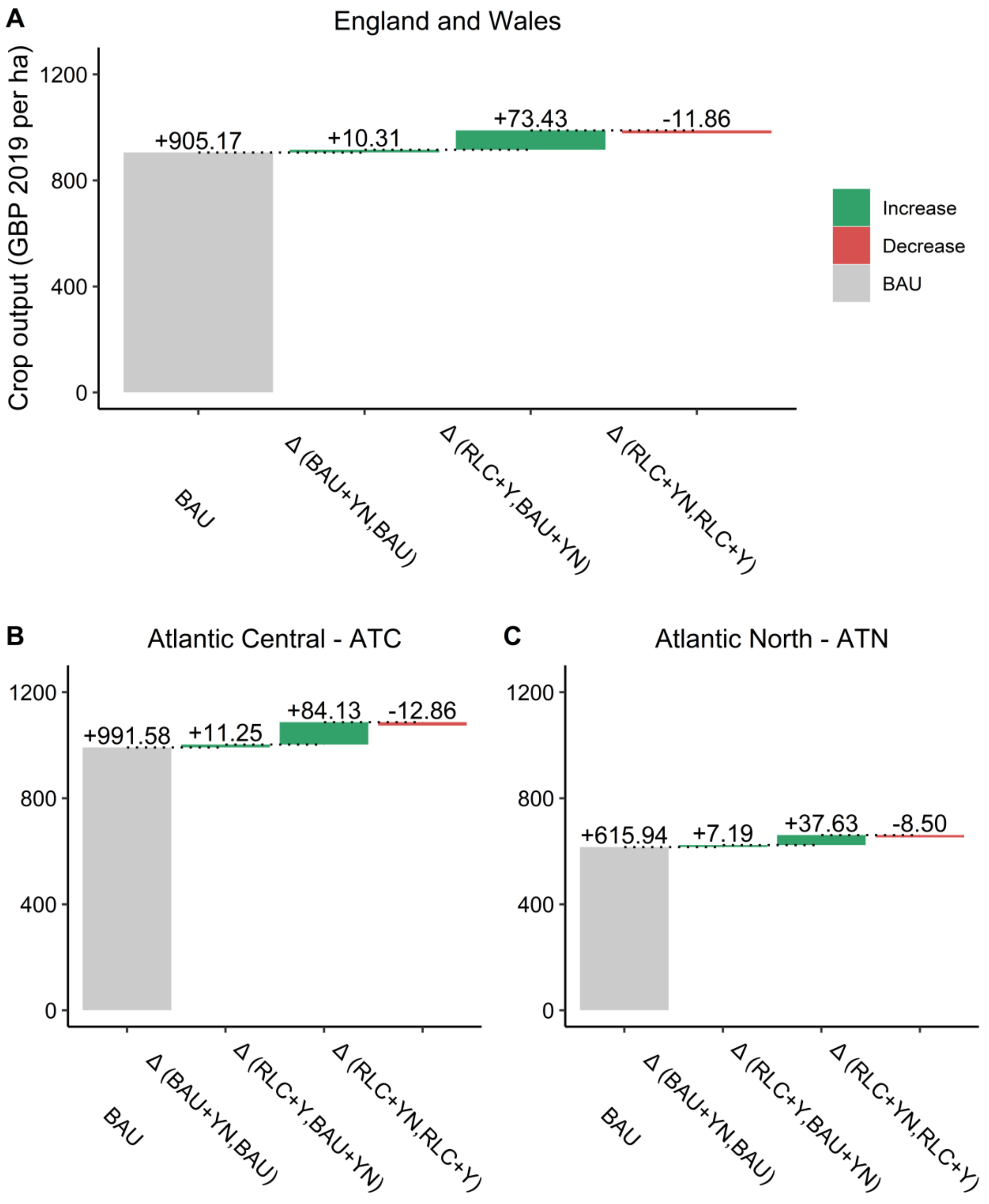

FIGURE 2 Potential crop output for each scenario in (A) England and Wales, (B) Atlantic Central - ATC, and (C) Atlantic North – ATN. Scenarios: business as usual without land reallocation (BAU), business as usual without land reallocation, maximising production and minimising N balances (BAU+YN), with land reallocation and maximising

production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

FIGURE 3 shows that N balances per ha are higher in ATN than in ATC. However, when expressed in relative terms, the proportional reductions in ATN are smaller than those observed in ATC, unlike in the crop production results. Consequently, farms in the ATC produce on average more crop output per kg of N than those in ATC. The potential increases in production for the scenario RLC+Y also reduce N balances in both EnZs. This pattern is consistent except for 2017 in ATN. Detailed annual results for the crop production and N balances are available in the appendix A4.

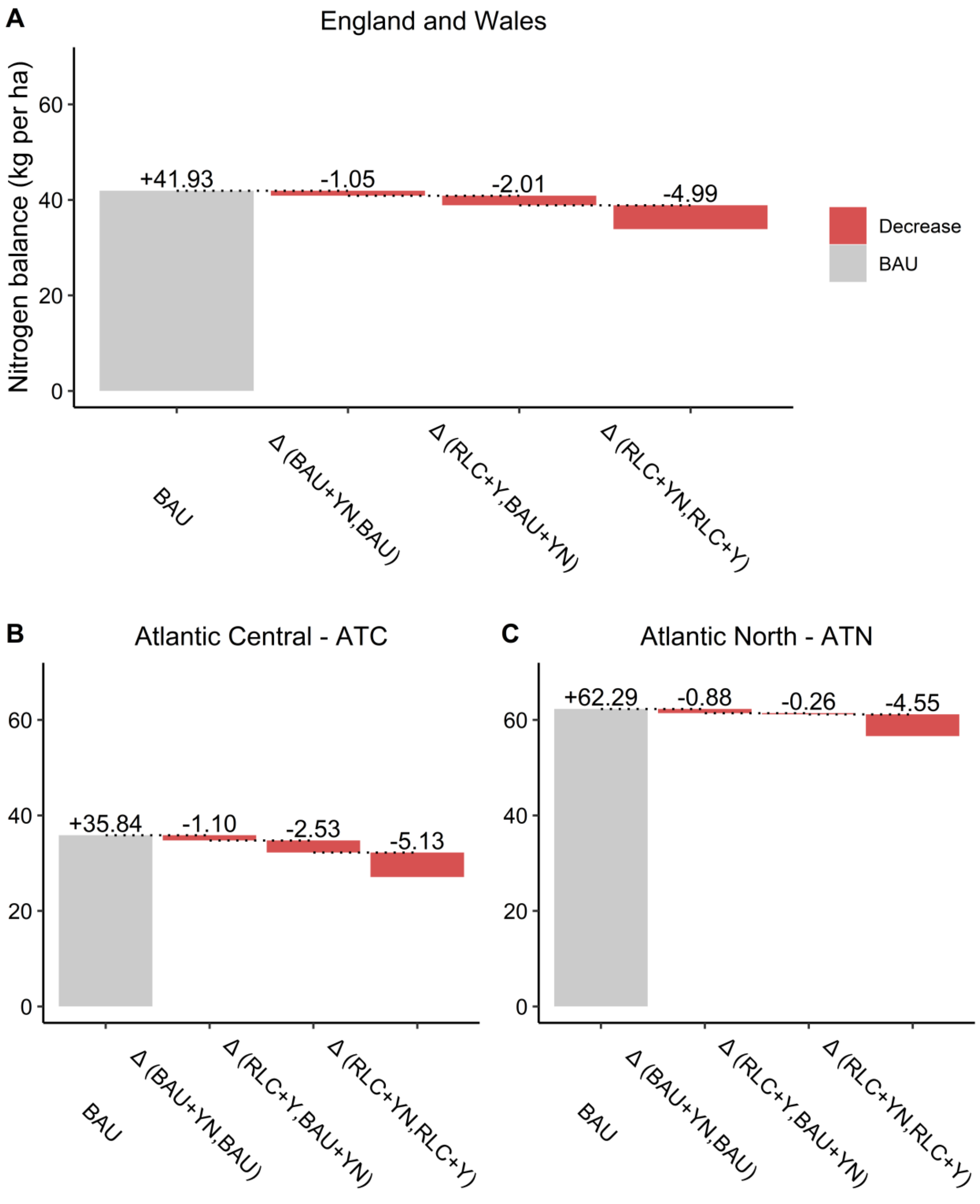

FIGURE 3 Potential N balances for each scenario in (A) England and Wales, (B) Atlantic Central - ATC, and (C) Atlantic North – ATN. Scenarios: business as usual without land reallocation (BAU), business as usual without land reallocation, maximising production and minimising N balances (BAU+YN), with land reallocation and maximising

production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

The output difference between the reallocation scenarios can be interpreted as the opportunity cost between including the reduction of N balances as a farm objective. The yearly estimates for these opportunity costs are shown in FIGURE 4. Our results suggest that the opportunity costs for the farms in ATC are greater than for those farms in the ATN, this pattern occurs in most years except 2019, when the opportunity costs at ATN was 2.31 GBP per kg of N and at ATC was 1.77 GBP per kg of N.

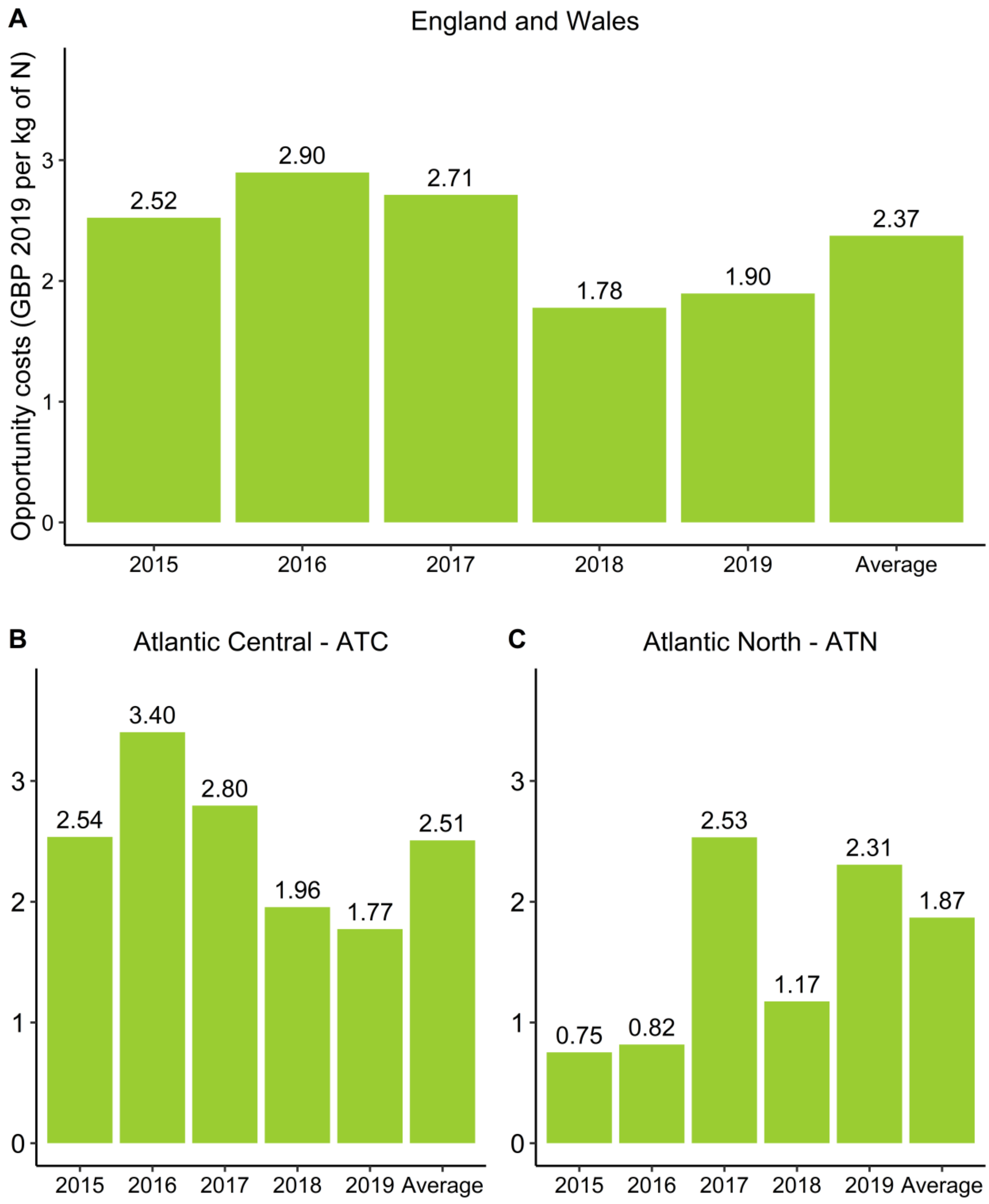

FIGURE 4 Opportunity costs of decreasing N in crop production reallocation scenarios in (A) England and Wales, (B) Atlantic Central - ATC, and (C) Atlantic North – ATN.

3.2 The potential impact of optimal reallocation on cropland diversity

We now analyse how optimal land reallocation changes the Hilll-Shannon index for crop diversity. We first discuss the results at the farm level. FIGURE 5 shows how optimal land reallocation would change the distribution of land uses in our sample. Before reallocation, the median farm in England and Wales has an effective number of species of 3.13. After optimal land reallocation, the median diversity would increase from 3.37 species to 3.61 species in RLC+Y, and from 3.36 species to 3.59 species in RLC+YN (median equal to 3.36 species). The increases in diversity are greater in ATC (0.24 species for RLC+Y and 0.23 species for RLC+YN) than in ATN (0.15 species for RLC+Y and 0.14 species for RLC+YN).

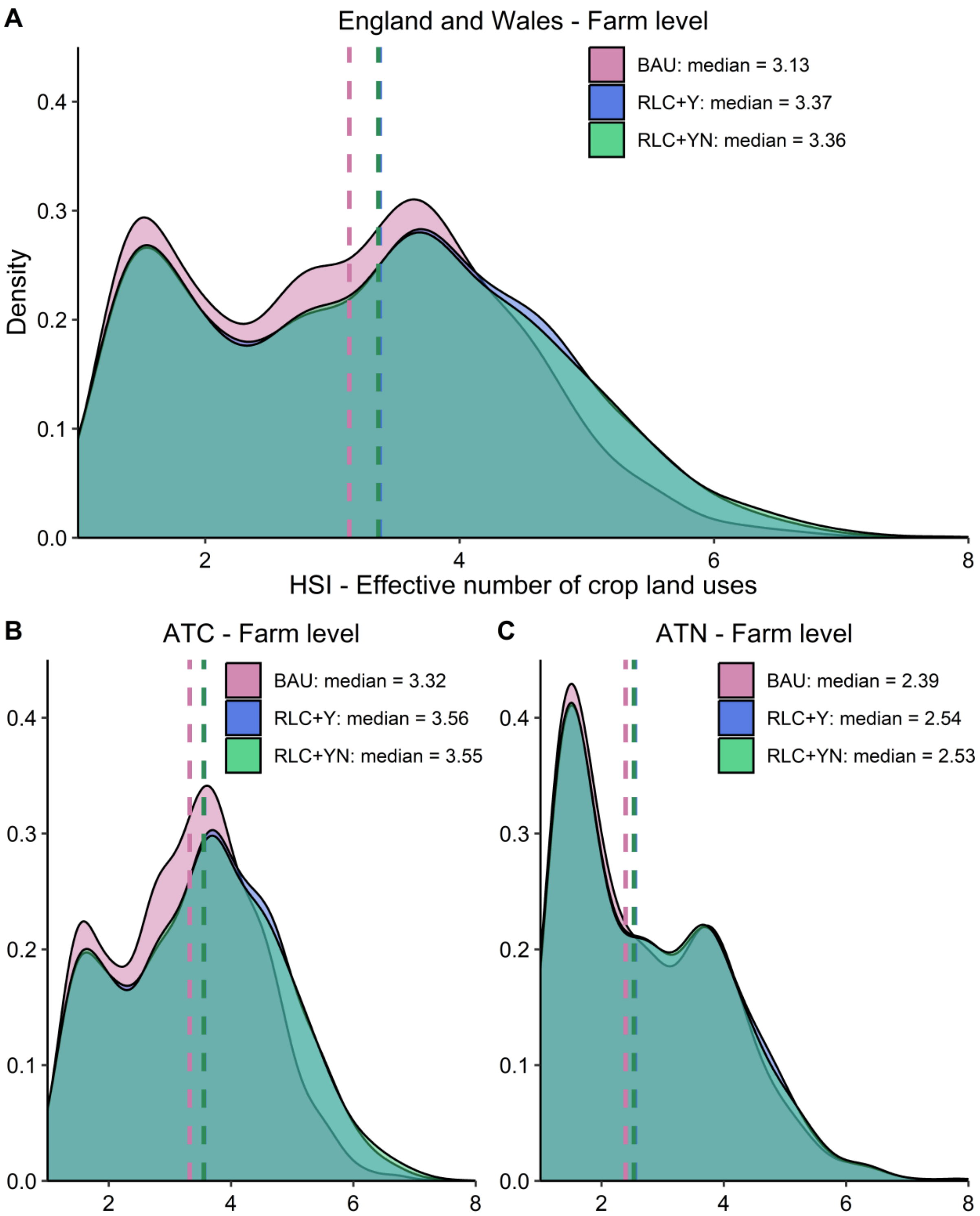

FIGURE 5 Hill-Shannon diversity (HSI), or effective number of species, at the farm level. Weighted density distribution before and after reallocation - vertical lines represent the group medians. (A) England and Wales, (B) Atlantic Central - ATC, and (C) Atlantic North – ATN. Scenarios: business as usual without land reallocation (BAU), with land reallocation and maximising production (RLC+Y), and with land

reallocation, maximising production and minimising N balances (RLC+YN).

The distributions of farm diversity are very similar for the scenarios of RLC+Y and RLC+YN. In appendix A2, we present the yearly median farm level diversity for England and Wales and for each EnZ, and the details of the statistical tests that we use to compare the distributions. The results from bootstrapped and permutation tests for the medians show that in general the RLC+YN led to a lower diversity than the ones observed at RLC+Y. Although they are statistically different medians, there is a consistent overlap over the years between the confidence intervals of the medians. The median difference is 0.01 species for England and Wales. This difference is statistically significant yet very small in magnitude.

Table 3 exhibits the farm level diversity implications for England and Wales and the EnZs. The diversity in ATC exceeds the diversity in ATN. At the aggregated level the diversity implication become less pronounced, especially in ATN, when compared to the differences observed at the farm-level. However, for ATC the difference between RLC+Y and RLC+YN becomes larger.

Table 3 Farm level diversity implications for England and Wales and for the EnZs. Scenarios business as usual without land reallocation (BAU), with land reallocation and maximising production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

Region	Year	BAU	RLC+Y	RLC+YN
England and Wales	2015	5.35	5.35	5.40
	2016	5.24	5.32	5.40
	2017	5.72	5.74	5.77
	2018	5.85	5.99	6.01
	2019	5.67	5.71	5.80
	All	5.57	5.63	5.69

Region	Year	BAU	RLC+Y	RLC+YN
ATC	2015	5.57	5.56	5.64
	2016	5.52	5.65	5.74
	2017	6.11	6.12	6.17
	2018	6.22	6.40	6.41
	2019	6.02	6.07	6.19
	All	5.90	5.97	6.04
ATN	2015	4.10	4.09	4.09
	2016	3.94	3.94	3.93
	2017	4.07	4.09	4.07
	2018	4.35	4.36	4.37
	2019	4.17	4.19	4.18
	All	4.14	4.15	4.14

3.3 Cropland use changes

We now further analyse cropland uses for the scenarios of RLC+Y and RLC+YN. For the scenario RLC+Y, optimal land reallocation would have led to an increase in beetroot (+0.79%), potatoes (+0.45%), rapeseed (+0.33%), peas (+0.15%), and linseed (+0.03%), compensated by a decrease in barley (-1.18%), oats (-0.34%), beans (-0.15%), and wheat (-0.07%) in percentage points relative to the available area for reallocation. For the scenario RLC+YN, optimal land reallocation would have led to an increase in linseed (+0.88%), beetroot (+0.62%), potatoes (+0.27%), rapeseed (+0.27%), and peas (+0.02%), and a decrease in barley (-0.89%), oats (-0.45%), wheat (-0.45%), and beans (-0.27%) in percentage points. Nevertheless, there is some heterogeneity between ATC and ATN.

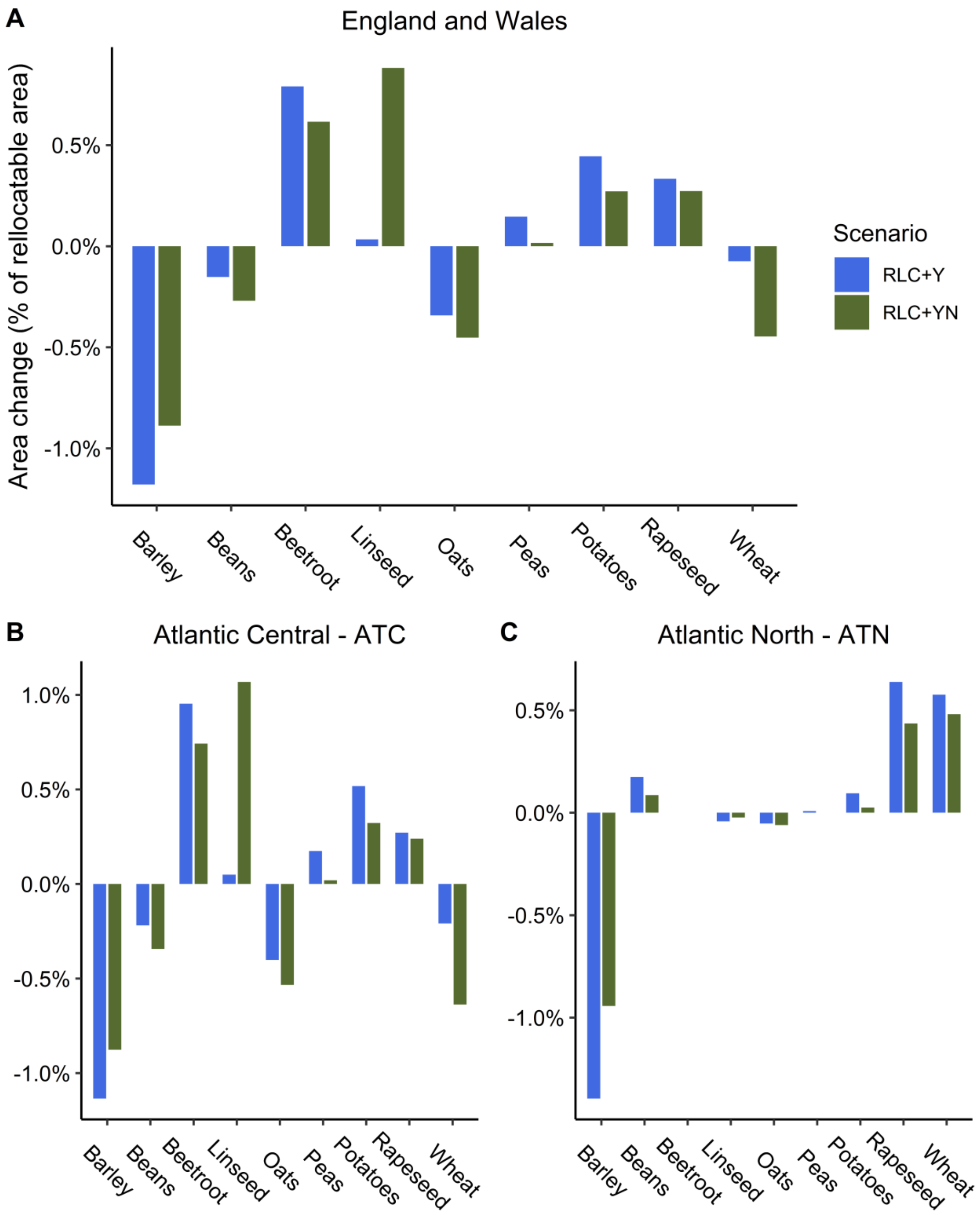

FIGURE 6 Cropland use changes in percentage points relative to the available area for reallocation in (A) England and Wales, (B) Atlantic Central - ATC, and (C) Atlantic North – ATN.

The importance of each crop depends on the EnZ and scenario considered. Barley consistently exhibits a reduction across all scenarios and zones, yet it shows a greater decline under RLC+Y compared to RLC+YN. Linseed is particularly important for ATC increasing its presence under the RLC+YN scenario. For all other crops there is some variations depending on the year and scenario. Notable changes under RLC+Y include a decrease in barley of -1.13% in ATC and -1.39% in ATN, contrasted by more positive trends in rapeseed with increases of +0.27% in ATC and +0.64% in ATN; while wheat shows opposite results, it decrease by -0.21% in ATC and increases by +0.58% in ATN. For the RLC+YN scenario, there is a decrease in barley by -0.88% in ATC and -0.94% in ATN, while rapeseed demonstrates an increase of +0.24% in ATC and of +0.44% in ATN. In appendix A5 we present the observed yearly variation.

4 Discussion

The aim of this study is to assess the extent to which land reallocation can simultaneously increase crop production and decrease N balances, and its implications for crop diversity. In line with other studies, our study finds that there is scope to reduce inefficiency through land reallocation (Folberth et al. 2020; Adamopoulos and Restuccia 2022; Ang and Kerstens 2016; Beyer et al. 2022; Ang et al. 2018). Overall, we find potential synergies between increasing crop production, reducing N balances and increasing crop diversity. These results can be compared to other studies that find a similar association between increasing crop production and reducing N balances (Gray Betts et al. 2023; Gu et al. 2023), increasing crop production and diversity (Ang et al. 2018; Tamburini et al. 2020; Beillouin et al. 2021; Donfouet et al. 2017; Isbell et al. 2015; Ponisio et al. 2015), and reducing N balances and increasing diversity (Duchene et al. 2017; Gaudin et al. 2015; Singh et al. 2023; Bedoussac et al. 2015;

Pelzer et al. 2014; Renwick et al. 2019; Valkama et al. 2015; Zhang et al. 2015). However, Folberth et al. (2020) find that optimal cropland allocation to maximise land sparing incentivised monocropping globally. If there are synergies between increasing crop production, decreasing N balances, and increasing crop diversity, why have farmers not being exploring it?

Overcoming the information gaps and policies that disincentivise crop diversity could be crucial. As farmers are typically risk averse (Bowman and Zilberman 2013), it would be expected from them to use crop diversity to reduce their risk exposure. However, the empirical evidence on this is mixed. Some studies find that risk-averse behaviour leads to diversification (Slijper et al. 2020) while others do not (Van Winsen et al. 2016; Hellerstein, Higgins and Horowitz 2013). This discrepancy may stem from limited knowledge about the economic benefits of diversification, which impedes informed decision making, combined with other factors such as labour and management complexity (Sánchez et al. 2022; Bowman and Zilberman 2013; Ang et al. 2018; Van Winsen et al. 2016). Furthermore, agricultural policies that decouple risk from crop choices, such as price support, may further incentivise specialisation (Di Falco and Perrings 2005). However, it is important to acknowledge that factors such as economies of scale, streamlined processes, and competitive advantages of specialisation (Abson 2019; Bowman and Zilberman 2013) often overshadow the long-term and indirect benefits of diversification. In summary, the challenge to explore the synergies between increasing crop production and reducing N balances may lie in tackling these information gaps, management difficulties and policies that disincentivise crop diversity.

Behavioural aspects may also explain inefficiency in production and N. In our results, the potential decrease in N balances exceeds the potential increase in crop production in relative terms. This happens especially in the scenarios BAU+YN and RLC+YN that consider the simultaneous increase in crop production and decrease in N balances. This may be connected to N pollution being characterised as a non-point source pollutant. That is, the negative effects of N pollution are predominantly far from the polluting farms. Additionally, in response to loss aversion, farmers often apply fertilizers beyond the economic optimum as a risk mitigation strategy (Del Rossi et al. 2023; Pannell 2017; Paulson and Babcock 2010; Sheriff 2005).

Improving farm management can simultaneously reduce production inefficiency and N inefficiency. This potential is shown in scenario BAU+YN. Examples of cost-effective management practices that could increase crop production and decrease N balances are detailed in Gu et al. (2023). Examples include precision agriculture and ‘4R nutrient stewardship’ (right fertiliser type, right amount, right placement and right time) combined with soil testing, crop allocation, genetic improvement (Han et al. 2015), optimal irrigation, and soil conservation measures (e.g. optimal tillage).

There are positive opportunity costs in decreasing N in crop production, which are evident in the comparison between the scenarios RLC+Y and RLC+YN. These results go in line with other studies that perceived positive cost of abating N (Dakpo, Desjeux and Latruffe 2023; Shaik, Helmers and Langemeier 2002; Mandrini et al. 2022) in agriculture. Our results also show that the magnitude of these trade-offs depend on the edaphoclimatic context, which calls for targeted management and policy recommendations.

Our findings indicate that certain crops may simultaneously increase production and decrease N balances to varying degrees. In terms of the economic benefits of specific crops, we can compare our results with Ang et al. (2018). Their study focus on a dynamic profit maximisation from 2007 until 2013 for crop farms in the East of

England. They consistently observed positive outcomes over the years for beans and beetroots. When comparing their overall findings with ours in the ATC EnZ (the predominant EnZ of East of England), our results align in the projected increase for beetroot and peas, and the projected decrease for beans and wheat. In contrast, our results suggest an increase for potatoes and a decrease for barley and oats. Similar to Ang et al. (2018), we note annual variability, which is likely driven by factors such as market and weather. This highlights the importance of these factors in crop allocation decision. While imperfect information on weather and market factors may contribute to observed inefficiencies in crop allocation, our results foster crop diversity, which, in turn, serves a risk mitigation strategy against these factors.

5 Limitations and directions for further research

It is important to recognise the limitations posed by high dimensionality and potential unobserved heterogeneity. Our results indicate a relatively small potential for increasing crop production and reducing N balances in the BAU+YN scenario. These conservative results may partly be attributed to the high dimensionality of our model. In DEA, increasing the number of variables and constraints tends to reduce the identification of inefficient farms (Fried, Lovell and Schmidt 2008, p.319). the reallocation scenario reduces the dimensionality problem due to less modelling restriction, the results related to crop changes require careful interpretation. This is due to potential unobserved heterogeneity in local edaphoclimatic conditions or other constraints that that could hinder the suggested crop allocations. To mitigate the impact of dimensionality, we have adopted a robust DEA approach that reduce efficiency gaps between farms. We also control for heterogeneity in edaphoclimatic conditions by considering different technologies per year and EnZ. Nonetheless, stakeholders should consider these limitations when interpreting our findings.

There can be unobserved heterogeneity in accounting for N balances that can affect our estimates. The N balances do not include N contributions from seeds, irrigation and rainfall. Due to a lack of data, we do not account for deposits from irrigation and seeds. Deposits from rainfall are partially controlled for using annual technologies. Our model assumes that N deposition, leaching, and volatilisation are controlled by different land uses (treated as inputs in $\boldsymbol{\mathcal{N}}$), which is a more careful approach compared to other studies that treat these factors as fixed constants across entire countries or regions (Ludemann et al. 2023). Nevertheless, such factors can in practice vary by local edaphoclimatic conditions. We applied fixed coefficients for crop N fixation and removal, yet these can vary due to genetic variety, harvesting time, and other factors (Oenema, Kros and De Vries 2003). Consequently, such variability could compromise the accuracy of our N balance estimates and thus affect our frontier estimates.

The relationship between crop allocation, crop production and N balances, could be further explored to include other species, levels, scales, and modelling approaches. Our results are mainly valid for farms cultivating the specific crops we allowed for reallocation. While we selected crops that are representative of the crop sector in England and Wales, including a broader range of crops might suggest different outcomes. Our results suggest benefits from diversifying farms and regions. The results suggest that regions may benefit from diversity at the farm level and the regional level. However, in our models diversity is an implication, rather than an objective. Additionally, exploring different levels of diversity, such as functional and temporal, along with varying scales (e.g., from field to landscape), could uncover novel relationships. This could prove valuable to farmers and policymakers who are interested in understanding how different scales and levels of diversity interact with crop production and N balances.

Further studies could use our models to include livestock, investigate circularity aspects, and assess differences in the quality of N fertilisers. We focused on crop production to mitigate additional uncertainties involved in including livestock, particularly those from estimating N content in feed and animal products. However, when data limitations are resolved, similar methods can also be applied to explore N issues in livestock production, as demonstrated by Lamkowsky et al. (2021). Additionally, including livestock enables the implementation of network models that connect livestock and crop production, as illustrated by Wang et al. (2023). These models are crucial for the further understanding of the relationship between crop production and N balance. In this light, interesting avenues for future research include the study of input self-sufficiency and the differences between organic and synthetic N sources. Our model can be readily adapted to include livestock enterprises in particular, and farm circularity in general.

6 Conclusion

This study investigates the issue of increasing crop production and decreasing N balances from a crop allocation perspective. Our main contributions relate to approaching this issue from a crop allocation perspective and by modelling the dynamic effect that the N balance from the previous year has on crop production for the current year. We analysed data from 909 farms in England and Wales between 2015 and 2019, resulting in 2,711 observations across two environmental zones. Our application combines several state-of-the-art methods in non-parametric estimation of production frontiers. We estimate an efficient frontier in a robust DEA approach that is less sensitive to extreme values. Using a by-production framework, we model separate technologies for crop production and N balances. By exploring suitable modelling techniques based in the production economics framework, we were able to assess the potential of efficiency and reallocation to increase crop production and decrease N balances.

Our findings indicate that both efficiency improvements and land reallocation can simultaneously increase crop production and reduce N balances, with reallocation offering greater benefits. Specifically, efficiency improvements resulted in a 10.31 GBP per ha increase in crop production and a 1.05 kg per hectare reduction in N balances compared to a business-as-usual scenario. Meanwhile, the first reallocation scenario, initially focused on increasing production, also achieved a reduction in N balances, with increases of 83.74 GBP 2019 per ha in crop production and decreases of 2.01 kg per ha in N balances. However, including the objective of reducing N balances in the reallocation model revealed a trade-off, with crop production increasing by 71.88 GBP 2019 per ha and N balances decrease by 4.99 kg per ha. Thus, resulting in an opportunity costs of 2.37 GBP 2019 per kg of N between the reallocation objectives. Our analysis also noted variations across different years and environmental zones. Moreover, the high dimensionality and potential unobserved heterogeneity within our data may affect our estimates. Thus, it is important for farmers and policymakers to consider these limitations when interpreting our results.

Policymakers need to simultaneously address the issues of N pollution and specialisation in agriculture. Further research is needed to explore how these issues interact with diversity across multiple levels and scales. Our results indicate synergies between increasing production, decreasing N balance, and increasing crop diversity at the farm level. It is crucial to address existing information gaps, particularly regarding behavioural and management challenges, that prevent farmers from exploiting these synergies. For example, by engaging educational and extension services to support and inform about the benefits of the '4R nutrient stewardship' (right fertiliser type, right amount, right placement, right time) and better crop allocation. Moreover, our research encourages further exploration of the allocation problem, considering other dimensions such as intra-species diversity, temporal variations, different scales, and their interactions.

7 References

Abson, D.J. 2019. “The Economic Drivers and Consequences of Agricultural Specialization.” In *Agroecosystem Diversity*. Elsevier, pp. 301–315. Available at: https://linkinghub.elsevier.com/retrieve/pii/B9780128110508000194 [Accessed August 19, 2022].

Adamopoulos, T., and D. Restuccia. 2022. “Geography and Agricultural Productivity: Cross-Country Evidence from Micro Plot-Level Data.” *The Review of Economic Studies* 89(4):1629–1653.

Ait Sidhoum, A., T. Serra, and L. Latruffe. 2020. “Measuring sustainability efficiency at farm level: a data envelopment analysis approach.” *European Review of Agricultural Economics* 47(1):200–225.

Ang, F., and P.J. Kerstens. 2016. “To Mix or Specialise? A Coordination Productivity Indicator for English and Welsh farms.” *Journal of Agricultural Economics* 67(3):779–798.

Ang, F., S.M. Mortimer, F.J. Areal, and R. Tiffin. 2018. “On the Opportunity Cost of Crop Diversification.” *Journal of Agricultural Economics* 69(3):794–814.

Balk, B.M. 2008. *Price and Quantity Index Numbers: Models for Measuring Aggregate Change and Difference* 1st ed. Cambridge University Press. Available at: https://www.cambridge.org/core/product/identifier/9780511720758/type/book.

Banker, R.D., A. Charnes, and W.W. Cooper. 1984. “Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis.” *Management Science* 30(9):1078–1092.

Bateman, I.J., and B. Balmford. 2018. “Public funding for public goods: A post-Brexit perspective on principles for agricultural policy.” *Land Use Policy* 79:293–300.

Bedoussac, L., E.-P. Journet, H. Hauggaard-Nielsen, C. Naudin, G. Corre-Hellou, E.S. Jensen, L. Prieur, and E. Justes. 2015. “Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review.” *Agronomy for Sustainable Development* 35(3):911–935.

Beillouin, D., T. Ben-Ari, E. Malézieux, V. Seufert, and D. Makowski. 2021. “Positive but variable effects of crop diversification on biodiversity and ecosystem services.” *Global Change Biology* 27(19):4697–4710.

Beyer, R.M., F. Hua, P.A. Martin, A. Manica, and T. Rademacher. 2022. “Relocating croplands could drastically reduce the environmental impacts of global food production.” *Communications Earth & Environment* 3(1):49.

Bowman, M.S., and D. Zilberman. 2013. “Economic Factors Affecting Diversified Farming Systems.” *Ecology and Society* 18(1):art33.

Campbell, B.M., D.J. Beare, E.M. Bennett, J.M. Hall-Spencer, J.S.I. Ingram, F. Jaramillo, R. Ortiz, N. Ramankutty, J.A. Sayer, and D. Shindell. 2017. “Agriculture production as a major driver of the Earth system exceeding planetary boundaries.” *Ecology and Society* 22(4):8.

Cazals, C., J.-P. Florens, and L. Simar. 2002. “Nonparametric frontier estimation: a robust approach.” *Journal of Econometrics* 106(1):1–25.

Charnes, A., W.W. Cooper, and E. Rhodes. 1978. “Measuring the efficiency of decision making units.” *European Journal of Operational Research* 2(6):429–444.

Coelli, T.J., D.S. Prasada Rao, C.J. O’Donnell, and G.E. Battese. 2005. *An Introduction to Efficiency and Productivity Analysis* 2nd ed. New York: Springer-Verlag. Available at: http://link.springer.com/10.1007/b136381 [Accessed February 1, 2023].

Dakpo, H. 2015. “On modeling pollution-generating technologies: a new formulation of the by-production approach.” *European Association of Agricultural Economists (EAAE) PhD workshop*:30.

Dakpo, K.H., Y. Desjeux, and L. Latruffe. 2023. “Cost of abating excess nitrogen on wheat plots in France: An assessment with multi-technology modelling.” *Journal of Agricultural Economics* 74(3):800–815.

DEFRA. 2023. “Structure of the agricultural industry in England and the UK at June.” Available at: https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june [Accessed January 10, 2024].

DEFRA and EA. 2022. “Using nitrogen fertilisers in nitrate vulnerable zones.” *GOV.UK*. Available at: https://www.gov.uk/guidance/using-nitrogen-fertilisers-in-nitrate-vulnerable-zones [Accessed November 28, 2023].

Del Rossi, G., M.M. Hoque, Y. Ji, and C.L. Kling. 2023. “The Economics of Nutrient Pollution from Agriculture.” *Annual Review of Resource Economics* 15(1):105–130.

Di Falco, S., and C. Perrings. 2005. “Crop biodiversity, risk management and the implications of agricultural assistance.” *Ecological Economics* 55(4):459–466.

Donfouet, H.P.P., A. Barczak, C. Détang-Dessendre, and E. Maigné. 2017. “Crop Production and Crop Diversity in France: A Spatial Analysis.” *Ecological Economics* 134:29–39.

Duchene, O., J.-F. Vian, and F. Celette. 2017. “Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review.” *Agriculture, Ecosystems & Environment* 240:148–161.

Duchy College. 2022a. “FBSFarm Business Survey, 1982- : Special Licence AccessFarm Business Survey, 2018-2019: Special Licence Access.” Available at: https://beta.ukdataservice.ac.uk/datacatalogue/doi/?id=8607#2 [Accessed May 16, 2024].

Duchy College. 2022b. “FBSFarm Business Survey, 1982- : Special Licence AccessFarm Business Survey, 2019-2020: Special Licence Access.” Available at: https://beta.ukdataservice.ac.uk/datacatalogue/doi/?id=8816#2 [Accessed May 16, 2024].

Duchy College, R.B.S. 2019a. “FBSFarm Business Survey, 1982- : Special Licence AccessFarm Business Survey, 2015-2016: Special Licence Access.” Available at: https://beta.ukdataservice.ac.uk/datacatalogue/doi/?id=8158#3 [Accessed May 16, 2024].

Duchy College, R.B.S. 2019b. “FBSFarm Business Survey, 1982- : Special Licence AccessFarm Business Survey, 2016-2017: Special Licence Access.” Available at: https://beta.ukdataservice.ac.uk/datacatalogue/doi/?id=8451#2 [Accessed May 16, 2024].

Duchy College, R.B.S. 2020. “FBSFarm Business Survey, 1982- : Special Licence AccessFarm Business Survey, 2017-2018: Special Licence Access.” Available at: https://beta.ukdataservice.ac.uk/datacatalogue/doi/?id=8452#3 [Accessed May 16, 2024].

Efron, B., and R. Tibshirani. 1986. “Bootstrap Methods for Standard Errors, Confidence Intervals, and Other Measures of Statistical Accuracy.” *Statistical Science* 1(1). Available at: https://projecteuclid.org/journals/statistical-science/volume-1/issue-1/Bootstrap-Methods-for-Standard-Errors-Confidence-Intervals-and-Other-Measures/10.1214/ss/1177013815.full [Accessed May 15, 2024].

Eurostat. 2022. “Price indices of agricultural products (apri_pi).” Available at: https://ec.europa.eu/eurostat/cache/metadata/en/apri_pi_esms.htm [Accessed August 9, 2022].

Eurostat ed. 2015. *Regions in the European Union: nomenclature of territorial units for statistics ; NUTS 2013/EU-28*. Luxembourg: European Union. Available at: https://ec.europa.eu/eurostat/documents/3859598/6948381/KS-GQ-14-006-EN-N.pdf/b9ba3339-b121-4775-9991-d88e807628e3?t=1444229719000.

FAO. 2018. “Guidelines for the measurement of productivity and efficiency in agriculture.” Available at: https://www.fao.org/3/ca6395en/ca6395en.pdf.

FAO. 2017. *The future of food and agriculture: trends and challenges*. Rome: Food and Agriculture Organization of the United Nations.

Folberth, C., N. Khabarov, J. Balkovič, R. Skalský, P. Visconti, P. Ciais, I.A. Janssens, J. Peñuelas, and M. Obersteiner. 2020. “The global cropland-sparing potential of high-yield farming.” *Nature Sustainability* 3(4):281–289.

Fried, H.O., C.A.K. Lovell, and S.S. Schmidt eds. 2008. *The measurement of productive efficiency and productivity growth*. New York: Oxford University Press.

Gaudin, A.C.M., K. Janovicek, B. Deen, and D.C. Hooker. 2015. “Wheat improves nitrogen use efficiency of maize and soybean-based cropping systems.” *Agriculture, Ecosystems & Environment* 210:1–10.

Grant, C.A., J.T. O’Donovan, R.E. Blackshaw, K.N. Harker, E.N. Johnson, Y. Gan, G.P. Lafond, W.E. May, T.K. Turkington, N.Z. Lupwayi, D.L. McLaren, B. Zebarth, M. Khakbazan, M. St. Luce, and R. Ramnarine. 2016. “Residual effects of preceding crops and nitrogen fertilizer on yield and crop and soil N dynamics of spring wheat and canola in varying environments on the Canadian prairies.” *Field Crops Research* 192:86–102.

Gray Betts, C., D. Hicks, M. Reader, and P. Wilson. 2023. “Nitrogen balance is a predictor of farm business performance in the English Farm Business Survey.” *Frontiers in Sustainable Food Systems* 7:1106196.

Gruber, K. 2017. “Agrobiodiversity: The living library.” *Nature* 544(7651):S8–S10.

Gu, B., X. Zhang, S.K. Lam, Y. Yu, H.J.M. Van Grinsven, S. Zhang, X. Wang, B.L. Bodirsky, S. Wang, J. Duan, C. Ren, L. Bouwman, W. De Vries, J. Xu, M.A. Sutton, and D. Chen. 2023. “Cost-effective mitigation of nitrogen pollution from global croplands.” *Nature* 613(7942):77–84.

Gutser, R., Th. Ebertseder, A. Weber, M. Schraml, and U. Schmidhalter. 2005. “Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land.” *Journal of Plant Nutrition and Soil Science* 168(4):439–446.

Han, M., M. Okamoto, P.H. Beatty, S.J. Rothstein, and A.G. Good. 2015. “The Genetics of Nitrogen Use Efficiency in Crop Plants.” *Annual Review of Genetics* 49(1):269–289.

Hellerstein, D., N. Higgins, and J. Horowitz. 2013. “The predictive power of risk preference measures for farming decisions.” *European Review of Agricultural Economics* 40(5):807–833.

Hill, M.O. 1973. “Diversity and Evenness: A Unifying Notation and Its Consequences.” *Ecology* 54(2):427–432.

Hoang, V.-N., and T. Coelli. 2011. “Measurement of agricultural total factor productivity growth incorporating environmental factors: A nutrients balance approach.” *Journal of Environmental Economics and Management* 62(3):462–474.

IPNI. 2013. “Crop Nutrient Removal Calculator.” *International Plant Nutrition Institute*. Available at: http://www.ipni.net/article/IPNI-3346 [Accessed May 2, 2024].

Isbell, F., D. Craven, J. Connolly, M. Loreau, B. Schmid, C. Beierkuhnlein, T.M. Bezemer, C. Bonin, H. Bruelheide, E. De Luca, A. Ebeling, J.N. Griffin, Q. Guo, Y. Hautier, A. Hector, A. Jentsch, J. Kreyling, V. Lanta, P. Manning, S.T. Meyer, A.S. Mori, S. Naeem, P.A. Niklaus, H.W. Polley, P.B. Reich, C. Roscher, E.W. Seabloom, M.D. Smith, M.P. Thakur, D. Tilman, B.F. Tracy, W.H. Van Der Putten, J. Van Ruijven, A. Weigelt, W.W. Weisser, B. Wilsey, and N. Eisenhauer. 2015. “Biodiversity increases the resistance of ecosystem productivity to climate extremes.” *Nature* 526(7574):574–577.

Kahindo, S., and S. Blancard. 2022. “Reducing pesticide use through optimal reallocation at different spatial scales: The case of French arable farming.” *Agricultural Economics* 53(4):648–666.

Kanter, D.R., O. Chodos, O. Nordland, M. Rutigliano, and W. Winiwarter. 2020. “Gaps and opportunities in nitrogen pollution policies around the world.” *Nature Sustainability* 3(11):956–963.

Kuosmanen, N. 2014. “Estimating stocks and flows of nitrogen: Application of dynamic nutrient balance to European agriculture.” *Ecological Economics* 108:68–78.

Kuosmanen, N., and T. Kuosmanen. 2013. “Modeling Cumulative Effects of Nutrient Surpluses in Agriculture: A Dynamic Approach to Material Balance Accounting.” *Ecological Economics* 90:159–167.

Lamkowsky, M., O. Oenema, M.P.M. Meuwissen, and F. Ang. 2021. “Closing productivity gaps among Dutch dairy farms can boost profit and reduce nitrogen pollution.” *Environmental Research Letters* 16(12):124003.

Lassaletta, L., G. Billen, B. Grizzetti, J. Anglade, and J. Garnier. 2020. “Long Term Trends in Agronomical and Environmental Performances of World Cropping Systems: The Relationship Between Yield and Nitrogen Input to Cropland at the Country and Regional Scales.” In M. A. Sutton, K. E. Mason, A. Bleeker, W. K. Hicks, C. Masso, N. Raghuram, S. Reis, and M. Bekunda, eds. *Just Enough Nitrogen*. Cham: Springer International Publishing, pp. 29–45. Available at: http://link.springer.com/10.1007/978-3-030-58065-0_2 [Accessed April 22, 2024].

Lozano, S. 2015. “A joint-inputs Network DEA approach to production and pollution-generating technologies.” *Expert Systems with Applications* 42(21):7960–7968.

Ludemann, C.I., N. Wanner, P. Chivenge, A. Dobermann, R. Einarsson, P. Grassini, A. Gruere, K. Jackson, L. Lassaletta, F. Maggi, G. Obli-Laryea, M.K. Van Ittersum, S. Vishwakarma, X. Zhang, and F. Tubiello. 2023. “A global reference database in FAOSTAT of cropland nutrient budgets and nutrient use efficiency: nitrogen, phosphorus and potassium, 1961–2020.” ESSD – Land/Land Cover and Land Use. Available at: https://essd.copernicus.org/preprints/essd-2023-206/ [Accessed August 22, 2023].

Mandrini, G., C.M. Pittelkow, S. Archontoulis, D. Kanter, and N.F. Martin. 2022. “Exploring Trade-Offs Between Profit, Yield, and the Environmental Footprint of Potential Nitrogen Fertilizer Regulations in the US Midwest.” *Frontiers in Plant Science* 13:852116.

Metzger, M.J., R.G.H. Bunce, R.H.G. Jongman, C.A. Mücher, and J.W. Watkins. 2005. “A climatic stratification of the environment of Europe: A climatic stratification of the European environment.” *Global Ecology and Biogeography* 14(6):549–563.

Murty, S., and R.R. Russell. 2020. “Bad Outputs.” In S. C. Ray, R. Chambers, and S. Kumbhakar, eds. *Handbook of Production Economics*. Singapore: Springer Singapore, pp. 1–53. Available at: http://link.springer.com/10.1007/978-981-10-3450-3_3-1 [Accessed May 15, 2024].

Murty, S., R.R. Russell, and S.B. Levkoff. 2012. “On modeling pollution-generating technologies.” *Journal of Environmental Economics and Management* 64(1):117–135.

Oenema, O., H. Kros, and W. De Vries. 2003. “Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies.” *European Journal of Agronomy* 20(1–2):3–16.

Pannell, D.J. 2017. “Economic perspectives on nitrogen in farming systems: managing trade-offs between production, risk and the environment.” *Soil Research* 55(6):473.

Paulson, N.D., and B.A. Babcock. 2010. “Readdressing the Fertilizer Problem.” *Journal of Agricultural and Resource Economics* 35(3):368–384.

Pe’er, G., Y. Zinngrebe, F. Moreira, C. Sirami, S. Schindler, R. Müller, V. Bontzorlos, D. Clough, P. Bezák, A. Bonn, B. Hansjürgens, A. Lomba, S. Möckel, G. Passoni, C. Schleyer, J. Schmidt, and S. Lakner. 2019. “A greener path for the EU Common Agricultural Policy.” *Science* 365(6452):449–451.

Pelzer, E., N. Hombert, M.-H. Jeuffroy, and D. Makowski. 2014. “Meta-Analysis of the Effect of Nitrogen Fertilization on Annual Cereal–Legume Intercrop Production.” *Agronomy Journal* 106(5):1775–1786.

Ponisio, L.C., L.K. M’Gonigle, K.C. Mace, J. Palomino, P. De Valpine, and C. Kremen. 2015. “Diversification practices reduce organic to conventional yield gap.” *Proceedings of the Royal Society B: Biological Sciences* 282(1799):20141396.

Renwick, L.L.R., T.M. Bowles, W. Deen, and A.C.M. Gaudin. 2019. “Potential of Increased Temporal Crop Diversity to Improve Resource Use Efficiencies.” In *Agroecosystem Diversity*. Elsevier, pp. 55–73. Available at: https://linkinghub.elsevier.com/retrieve/pii/B9780128110508000042 [Accessed November 28, 2023].

Richter, S.J., and M.H. McCann. 2007. “Multiple Comparison of Medians Using Permutation Tests.” *Journal of Modern Applied Statistical Methods* 6(2):399–412.

Roswell, M., J. Dushoff, and R. Winfree. 2021. “A conceptual guide to measuring species diversity.” *Oikos* 130(3):321–338.

Sánchez, A.C., H.N. Kamau, F. Grazioli, and S.K. Jones. 2022. “Financial profitability of diversified farming systems: A global meta-analysis.” *Ecological Economics* 201:107595.

Serra, T., R.G. Chambers, and A. Oude Lansink. 2014. “Measuring technical and environmental efficiency in a state-contingent technology.” *European Journal of Operational Research* 236(2):706–717.

Shaik, S., G.A. Helmers, and M.R. Langemeier. 2002. “Direct and Indirect Shadow Price and Cost Estimates of Nitrogen Pollution Abatement.” *Journal of Agricultural and Resource Economics* 27(2):420–432.

Sheriff, G. 2005. “Efficient Waste? Why Farmers Over-Apply Nutrients and the Implications for Policy Design.” *Review of Agricultural Economics* 27(4):542–557.

Singh, A., C. Schöb, and P.P.M. Iannetta. 2023. “Nitrogen fixation by common beans in crop mixtures is influenced by growth rate of associated species.” *BMC Plant Biology* 23(1):253.

Slijper, T., Y. De Mey, P.M. Poortvliet, and M.P.M. Meuwissen. 2020. “From risk behavior to perceived farm resilience: a Dutch case study.” *Ecology and Society* 25(4):art10.

Smith, A.C., P.A. Harrison, N.J. Leach, H.C.J. Godfray, J.W. Hall, S.M. Jones, S.S. Gall, and M. Obersteiner. 2023. “Sustainable pathways towards climate and biodiversity goals in the UK: the importance of managing land-use synergies and trade-offs.” *Sustainability Science* 18(1):521–538.

Smith, P., M.F. Cotrufo, C. Rumpel, K. Paustian, P.J. Kuikman, J.A. Elliott, R. McDowell, R.I. Griffiths, S. Asakawa, M. Bustamante, J.I. House, J. Sobocká, R. Harper, G. Pan, P.C. West, J.S. Gerber, J.M. Clark, T. Adhya, R.J. Scholes, and M.C. Scholes. 2015. “Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils.” *SOIL* 1(2):665–685.

StatsWales. 2023. “Crops by year and area.” Available at: https://statswales.gov.wales/Catalogue/Agriculture/Agricultural-Survey/Annual-Survey-Results/crops-in-hectares-by-year [Accessed January 10, 2024].

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. De Vries, C.A. De Wit, C. Folke, D. Gerten, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. “Planetary boundaries: Guiding human development on a changing planet.” *Science* 347(6223):1259855.

Tamburini, G., R. Bommarco, T.C. Wanger, C. Kremen, M.G.A. Van Der Heijden, M. Liebman, and S. Hallin. 2020. “Agricultural diversification promotes multiple ecosystem services without compromising yield.” *Science Advances* 6(45):eaba1715.

Valkama, E., R. Lemola, H. Känkänen, and E. Turtola. 2015. “Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries.” *Agriculture, Ecosystems & Environment* 203:93–101.

Van Winsen, F., Y. De Mey, L. Lauwers, S. Van Passel, M. Vancauteren, and E. Wauters. 2016. “Determinants of risk behaviour: effects of perceived risks and risk attitude on farmer’s adoption of risk management strategies.” *Journal of Risk Research* 19(1):56–78.

Wang, S., F. Ang, and A. Oude Lansink. 2023. “Mitigating greenhouse gas emissions on Dutch dairy farms. An efficiency analysis incorporating the circularity principle.” *Agricultural Economics* 54(6):819–837.

Zhang, X., E.A. Davidson, D.L. Mauzerall, T.D. Searchinger, P. Dumas, and Y. Shen. 2015. “Managing nitrogen for sustainable development.” *Nature* 528(7580):51–59.

8 Funding and acknowledgments

This work was supported by the European Commission (Horizon 2020, grant 862357). The funding source had no influence on contents or submission of this document. Please note that this document reflects only the authors’ views and that the European Commission is not responsible for any use that may be made of the information it contains.

A Appendix

A1 Farm-level estimation of N balances

The N balances (b_{kt}) are calculated, for each farm $k \in \mathbb{R}^{\mathrm{K}}$, at time $\boldsymbol{t}$, as follows

$$b_{kt} = q_{ekt} - \sum_{d=1}^{D} \left(\boldsymbol{\alpha}_{\boldsymbol{dkt}}^{\boldsymbol{RMV}} - \boldsymbol{\alpha}_{\boldsymbol{dkt}}^{\boldsymbol{FIX}} \right) \cdot \boldsymbol{q}_{\boldsymbol{dkt}} \tag{9}$$

where $q_{ekt} \in \mathbb{R}^1$ represents the quantity of N in fertilisers applications (including organic), $\boldsymbol{\alpha}_{\boldsymbol{dkt}}^{\boldsymbol{RMV}} \in \mathbb{R}^{\mathrm{D}}$ is the coefficient describing the quantity of N removal per quantity of crop produced, $\boldsymbol{\alpha}_{\boldsymbol{dkt}}^{\boldsymbol{FIX}} \in \mathbb{R}^{\mathrm{D}}$ is the coefficient describing the quantity of N fixed per quantity of crop produced, and $\boldsymbol{q}_{\boldsymbol{dkt}} \in \mathbb{R}^{\mathrm{D}}$ is the quantity of crop $\boldsymbol{d} \in \mathbb{R}^{\mathrm{D}}$ produced by the farm. Due to our specification of $\mathcal{N}_{zt}$, factors such as N deposition, leaching and volatilisation are implicitly considered (i.e. considered constant depending on the EnZ and year, but also scaled due to the consideration of land uses), which is in line with multiple studies that used fixed coefficients ($N \cdot area^{-1} \cdot year^{-1}$) for these factors at country or regional levels (Ludemann et al. 2023; Oenema et al. 2003; Zhang et al. 2015).

A2 Hill-Shannon index confidence intervals and permutation tests

To rigorously assess the impact of crop reallocation on changes in the Hill-Shannon index, we implement bootstrapped confidence intervals (Efron and Tibshirani 1986)and permutation tests (Richter and McCann 2007). In the bootstrap approach, we resample the original dataset 1000 times with replacement, adjusting the probability of selection based on sample weights attributed to each farm. For each resample we calculate the median HSI. With the resampled medians we calculate the 5th, 50th, and 95th percentiles, forming the 95% confidence intervals. In the permutation tests we assess the statistical significance of observed median difference in HSI two scenarios. This involves randomly shuffling the scenarios under comparison. The p-value is computed based on the proportion of permuted results where the permuted differences are as extreme as or more extreme than the observed difference. If the original difference exceeds the 95th percentile of the permuted differences, it suggests that the effect of reallocation on crop diversity is statistically significant at the 5% level. We do 10,000 permutations to ensure the reliability of results. This permutation test validates the impact of reallocation on crop diversity without relying on assumptions about the underlying data distribution.

Table A 1 Hill-Shannon index confidence intervals and permutation tests for the medians. Scenarios: business as usual without land reallocation (BAU), with land reallocation and maximising production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

		Median Confidence Interval									**Permutation test**		
Region	**Year**	**BAU**			**RLC+Y**			**RLC+YN**			**(BAU,RLC+Y)**	**(BAU,RLC+YN)**	**(RLC+Y,RLC+YN)**
		5%	**50%**	**95%**	**5%**	**50%**	**95%**	**5%**	**50%**	**95%**			
England and Wales	2015	2.96	3.07	3.21	3.10	3.24	3.40	3.09	3.21	3.39	0.162 (<.001)	0.140 (<.001)	-0.023 (<.001)
	2016	2.80	2.94	3.12	2.96	3.20	3.41	2.94	3.20	3.38	0.262 (<.001)	0.262 (<.001)	0.000 (1.000)
	2017	2.92	3.09	3.25	3.13	3.29	3.43	3.09	3.27	3.43	0.199 (<.001)	0.179 (<.001)	-0.021 (<.001)
	2018	3.18	3.35	3.46	3.47	3.60	3.68	3.46	3.58	3.67	0.246 (<.001)	0.227 (<.001)	-0.019 (<.001)
	2019	3.11	3.25	3.41	3.42	3.54	3.65	3.40	3.54	3.64	0.288 (<.001)	0.282 (<.001)	-0.006 (<.001)
	All	3.05	3.13	3.19	3.29	3.37	3.43	3.29	3.37	3.42	0.239 (<.001)	0.234 (<.001)	-0.006 (0.010)
ATC	2015	2.99	3.16	3.27	3.18	3.31	3.49	3.18	3.31	3.44	0.148 (<.001)	0.147 (<.001)	-0.000 (0.893)
	2016	3.01	3.21	3.33	3.28	3.48	3.58	3.30	3.47	3.58	0.269 (<.001)	0.256 (<.001)	-0.013 (<.001)

		Median Confidence Interval									Permutation test		
Region	Year	BAU			RLC+Y			RLC+YN			(BAU,RLC+Y)	(BAU,RLC+YN)	(RLC+Y,RLC+YN)
		5%	50%	95%	5%	50%	95%	5%	50%	95%			
	2017	3.14	3.31	3.44	3.40	3.49	3.63	3.40	3.51	3.66	0.187 (<.001)	0.205 (<.001)	0.018 (0.001)
	2018	3.46	3.57	3.66	3.75	3.85	4.04	3.72	3.83	3.98	0.281 (<.001)	0.261 (<.001)	-0.020 (0.022)
	2019	3.47	3.58	3.65	3.70	3.79	3.89	3.69	3.78	3.89	0.203 (<.001)	0.196 (<.001)	-0.007 (0.002)
	All	3.26	3.33	3.38	3.51	3.56	3.62	3.50	3.55	3.61	0.229 (<.001)	0.227 (<.001)	-0.001 (<.001)
ATN	2015	2.39	2.74	3.25	2.45	2.74	3.25	2.45	2.74	3.25	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)
	2016	1.81	1.95	2.26	1.81	2.14	2.76	1.81	2.00	2.72	0.190 (<.001)	0.043 (<.001)	-0.146 (<.001)
	2017	2.03	2.28	2.77	2.18	2.50	2.80	2.18	2.49	2.80	0.216 (<.001)	0.213 (<.001)	-0.004 (0.104)
	2018	2.23	2.43	2.69	2.34	2.54	2.83	2.32	2.51	2.83	0.109 (<.001)	0.081 (<.001)	-0.028 (0.144)
	2019	2.16	2.44	2.61	2.25	2.54	2.69	2.23	2.54	2.64	0.105 (<.001)	0.105 (<.001)	0.000 (1.000)
	All	2.24	2.39	2.55	2.39	2.54	2.64	2.39	2.53	2.63	0.151 (<.001)	0.138 (<.001)	-0.013 (0.105)

A3 Detailed sample size and the percentage of inefficient observations

Table A2 Detailed sample size and the percentage of inefficient observations. Scenarios: business as usual without land reallocation, maximising production and minimising N balances (BAU+YN), with land reallocation and maximising production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

Region	Year	Number of observations	% of inefficient observations		
			BAU+YN	RLC+Y	RLC+YN
England and Wales	2015	366	4.1%	19.9%	21.9%
	2016	475	5.1%	31.2%	32.4%
	2017	548	3.8%	27.0%	28.6%
	2018	666	9.2%	33.0%	37.1%
	2019	656	8.5%	29.3%	33.1%
	All	2,711	6.5%	28.8%	31.5%
ATC	2015	292	4.8%	24.7%	27.1%
	2016	341	4.7%	34.9%	34.9%
	2017	387	3.4%	28.2%	31.0%
	2018	459	7.8%	37.7%	40.5%
	2019	453	6.4%	33.3%	34.4%
	All	1,932	5.6%	32.3%	34.2%
ATN	2015	74	1.4%	1.4%	1.4%
	2016	134	6.0%	21.6%	26.1%
	2017	161	5.0%	24.2%	23.0%
	2018	207	12.1%	22.7%	29.5%
	2019	203	13.3%	20.2%	30.0%
	All	779	8.9%	20.2%	25.0%

A4 Yearly results for the improvements of crop output and nitrogen balances in the regions

Table A3 Yearly results of crop output nitrogen balances Scenarios: business as usual without land reallocation (BAU), business as usual without land reallocation, maximising production and minimising N balances (BAU+YN), with land reallocation and maximising production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

Region	Year	Crop Output (GBP 2019 per ha)				Nitrogen balance (kg per ha)			
		BAU	Δ (BAU+YN, BAU)	Δ (RLC+Y, BAU+YN)	Δ (RLC+YN, RLC+Y)	BAU	Δ (BAU+YN, BAU)	Δ (RLC+Y, BAU+YN)	Δ (RLC+YN, RLC+Y)
England and Wales	2015	885.86	5.33	38.34	-9.92	35.36	-0.62	-0.41	-3.93
	2016	906.17	7.05	80.98	-13.58	59.76	-0.83	-2.62	-4.69
	2017	827.49	6.91	65.41	-16.85	38.89	-0.66	0.79	-6.21
	2018	913.29	19.41	108.09	-9.01	46.69	-1.69	-5.29	-5.07
	2019	997.28	13.44	75.22	-9.64	27.75	-1.51	-2.62	-5.08
ATC	2015	935.67	6.62	46.78	-12.30	32.09	-0.75	-0.48	-4.85
	2016	993.19	7.34	95.38	-16.61	56.42	-0.96	-2.35	-4.88
	2017	917.03	6.72	71.54	-15.51	30.48	-0.57	-0.65	-5.55
	2018	1,015.09	22.48	126.50	-10.14	39.98	-1.69	-6.76	-5.19
	2019	1,107.39	14.21	83.67	-9.23	18.58	-1.62	-2.71	-5.21
ATN	2015	680.50	0.00	3.54	-0.11	48.85	-0.06	-0.10	-0.15
	2016	611.40	6.05	32.21	-3.29	71.08	-0.38	-3.55	-4.02
	2017	537.65	7.54	45.58	-21.21	66.08	-0.94	5.45	-8.37

Region	Year	Crop Output (GBP 2019 per ha)				Nitrogen balance (kg per ha)			
		BAU	Δ (BAU+YN, BAU)	Δ (RLC+Y, BAU+YN)	Δ (RLC+YN, RLC+Y)	BAU	Δ (BAU+YN, BAU)	Δ (RLC+Y, BAU+YN)	Δ (RLC+YN, RLC+Y)
	2018	598.89	9.94	51.24	-5.53	67.41	-1.71	-0.73	-4.71
	2019	662.65	11.11	49.51	-10.86	55.61	-1.16	-2.34	-4.71

A5 Yearly results of cropland use changes

When assessing the crop changes in the scenarios RLC+Y and RLC+YN, we observe a consistent positive effect on both production and nitrogen (N) levels across all years for beetroot (ATC), potatoes (ATC), and wheat (ATN). Conversely, there is a negative relationship for both production and N in barley (ATC and ATN). An exception is noted in linseed (ATC), which generally shows a negative relationship with production and a positive relationship with N.

By comparing the differences between the RLC+Y and RLC+YN scenarios, we can identify crops that exhibit synergy between production and N balances. Barley (ATC, ATN) and linseed (ATC) demonstrate this synergy, whereas wheat (ATC) shows a negative relationship. These observations highlight some important patterns. For example, although the area allocated to barley is reduced for both EnZs, it appears to be effective in achieving both production and N efficiencies. In contrast, wheat does not perform well in this regard.

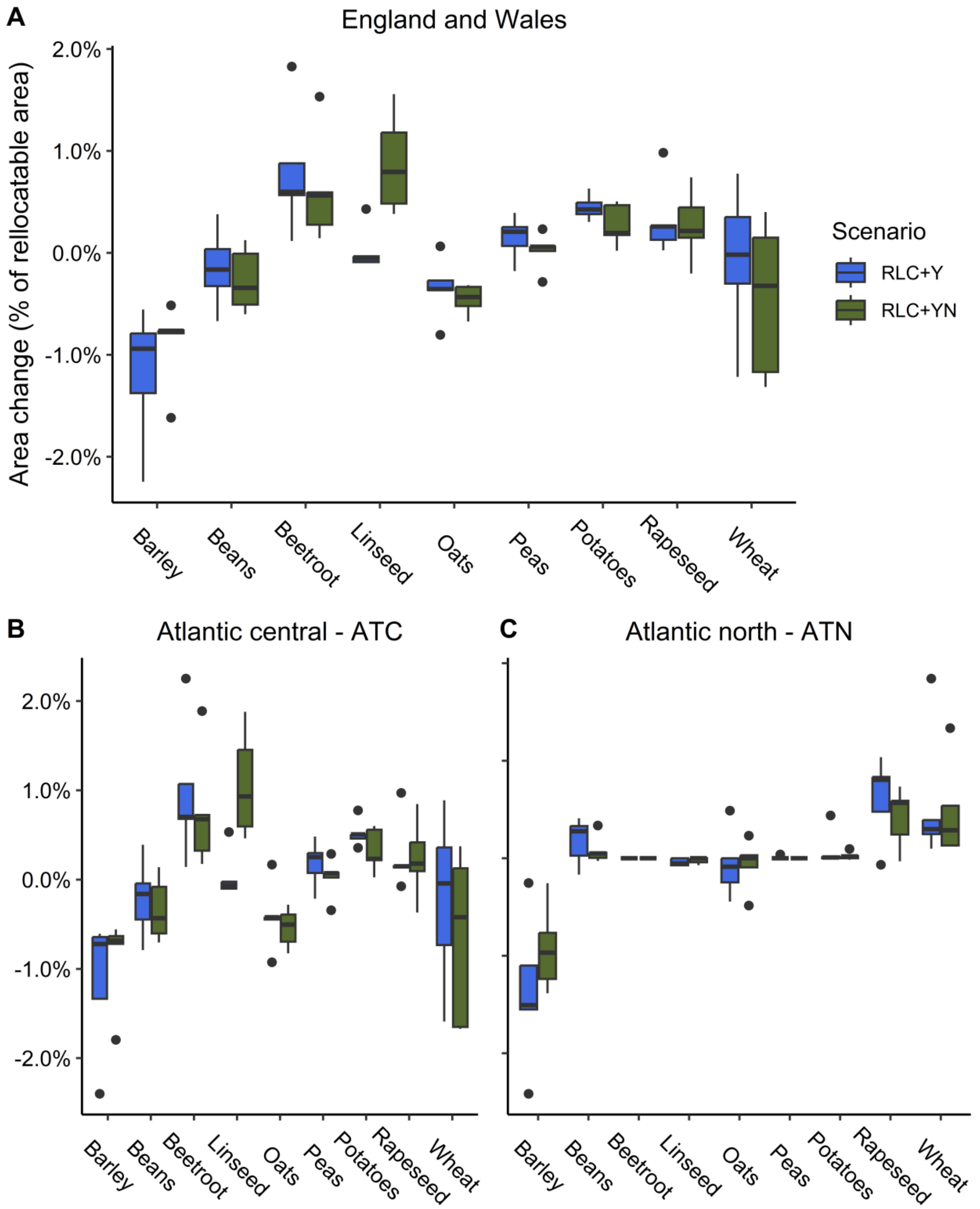

FIGURE A1 Boxplots of yearly cropland use changes in (A) England and Wales, (B) Atlantic Central - ATC, and (C) Atlantic North – ATN. Scenarios: with land reallocation and maximising production (RLC+Y), and with land reallocation, maximising production and minimising N balances (RLC+YN).

A6 Notation guide

Table A 4 Notation guide

Notation	Variable context	Description
a	$y_a \in \mathbb{R}^1$	Crop output
b	$b_t \in \mathbb{R}^1$	Nitrogen balances
c, C	$\boldsymbol{x_c} \in \mathbb{R}^C$	Land use areas of selected crops
d, D	$d \in \mathbb{R}^D$	Crop (FBS specific)
e	$\boldsymbol{q_e} \in \mathbb{R}^1$	quantity of N in fertilisers applications
f	$\mathrm{x_f} \in \mathbb{R}^1$	Fertilizer expenses
v	$\mathrm{x_v} \in \mathbb{R}^\mathrm{V}$	Other agricultural inputs
k	$\boldsymbol{k} \in \mathbb{R}^\mathrm{K}$	Individual farm observations
L	L_{ckt}	Proportion occupied by land use c
m, M	$m \in \mathbb{R}^\mathrm{M}$	Subsample for robust DEA estimation
p	$p \in \mathbb{R}^\mathrm{P}$	Crop classes in the farm structure surveys
q	$q \in \mathbb{R}^\mathrm{Q}$	Quantities
s	$y_s \in \mathbb{R}^1$	Livestock output
t, T	$\boldsymbol{t} \in \mathbb{R}^\mathrm{T}$	Year
x	$\boldsymbol{x} \in \mathbb{R}^{C+V+4}$	Inputs
y	$\boldsymbol{y} \in \mathbb{R}^2$	Outputs
z	$\boldsymbol{z} \in \mathbb{R}^Z$	Environmental zones
α	$\boldsymbol{\alpha_{dkt}^{RMV}}, \boldsymbol{\alpha_{dkt}^{FIX}}$	Coefficients of crop nitrogen removals (RMV) and fixing (FIX)

Notation	Variable context	Description
β	β_{akt}, β_{bkt}	Inefficiencies
λ	DEA	Intensity weights for the crop sub-technology
μ	DEA	Intensity weights for the nitrogen balances sub-technology
$\mathcal{N}$	$\boldsymbol{\mathcal{N}_t}$	Expected output per unit of input
$\mathcal{T}$	$\boldsymbol{\mathcal{T}_t}$	Crop production technology
ω	ω_{kt}	Weights

9 ORCID IDs

Murilo de Almeida Furtado https://orcid.org/0000-0002-7854-234X

Frederic Ang https://orcid.org/0000-0002-2323-7081

Miranda P M Meuwissen https://orcid.org/0000-0001-6929-3743