

Wesemeyer, Maximilian; Müller, Daniel; Lakes, Tobia

**Article — Published Version**

## Reallocating crops raises crop diversity without changes to field boundaries and farm-level crop composition

Environmental Research Letters

**Provided in Cooperation with:**

Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale)

*Suggested Citation:* Wesemeyer, Maximilian; Müller, Daniel; Lakes, Tobia (2024) : Reallocating crops raises crop diversity without changes to field boundaries and farm-level crop composition, Environmental Research Letters, ISSN 1748-9326, IOP Publishing, Bristol, Vol. 19, Iss. 7, <https://doi.org/10.1088/1748-9326/ad59b6>, <https://iopscience.iop.org/article/10.1088/1748-9326/ad59b6>

This Version is available at:

<https://hdl.handle.net/10419/300084>

**Standard-Nutzungsbedingungen:**

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

**Terms of use:**

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*



<http://creativecommons.org/licenses/by/4.0>

ENVIRONMENTAL RESEARCH  
LETTERS

## LETTER

## OPEN ACCESS

RECEIVED  
30 August 2023REVISED  
6 June 2024ACCEPTED FOR PUBLICATION  
19 June 2024PUBLISHED  
9 July 2024

Original content from  
this work may be used  
under the terms of the  
[Creative Commons  
Attribution 4.0 licence](#).

Any further distribution  
of this work must  
maintain attribution to  
the author(s) and the title  
of the work, journal  
citation and DOI.

Reallocating crops raises crop diversity without changes to field  
boundaries and farm-level crop compositionMaximilian Wesemeyer<sup>1,\*</sup> , Daniel Müller<sup>1,2,3</sup> and Tobia Lakes<sup>1,3</sup> <sup>1</sup> Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany<sup>2</sup> Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Theodor-Lieser-Straße 2, 06120 Halle (Saale), Germany<sup>3</sup> Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

\* Author to whom any correspondence should be addressed.

E-mail: [wesemeym@hu-berlin.de](mailto:wesemeym@hu-berlin.de)**Keywords:** crop heterogeneity, crop rotation, crop diversity gap, landscape level, sustainable intensification, IACSSupplementary material for this article is available [online](#)

## Abstract

Higher crop diversity can enhance biodiversity and ecosystem services; however, it remains unclear to what extent and where crop diversity can be increased. We use spatially explicit multiscale optimization to determine potential and attainable crop diversity with field-level land use data for case studies in Brandenburg, Germany. Our model maximizes crop diversity at the landscape scale while reassigning crop types over multiple years to existing arable fields. The model implements field-level crop sequence rules and maintains the crop composition of each farm and for each year. We found that a 10% higher crop diversity can be attained on average compared to currently observed diversity; minor changes in crop composition would close this gap. Improved crop allocation can contribute to closing the gap between observed and attainable crop diversity, which in turn can increase biodiversity, improve pollination services, and support pest control.

## 1. Introduction

The increasing similarity of crops grown across regions (Martin *et al* 2019), continuing field enlargement (White and Roy 2015), and declining crop diversity within regions (Aguilar *et al* 2015) have led to more homogenous agricultural landscapes. However, heterogeneous crop mosaics can promote biodiversity (Ronnenberg *et al* 2016, Josefsson *et al* 2017, Sirami *et al* 2019, Strobl 2022) and support key ecosystem services, such as pollination (Hemberger *et al* 2021, Raderschall *et al* 2021) and pest control (Gurr *et al* 2016, Redlich *et al* 2018a, Tschardt *et al* 2021). Crop rotations—that is, cultivation of a diverse crop structure over time—have been shown to generate higher economic returns (Bohan *et al* 2021), and spatial diversification has been identified to lead to an increase in crop yields (Burchfield *et al* 2019, Rosa-Schleich *et al* 2019, Hufnagel *et al* 2020). In recent years, agricultural policies in the United States (US) and the European Union (EU)

have provided incentives to increase crop diversity (European Parliament and Council 2021, USDA FSA 2021, Schaak *et al* 2023). Finding efficient pathways to enhance spatial crop diversity without lowering farm profitability can reduce the mismatch between societally desired and existing crop diversity patterns desired and existing crop diversity patterns.

Viable strategies for crop diversification should consider ecological and economic limitations and potentials (Aramburu Merlos and Hijmans 2022). Trade-offs that arise from the potential disparity between the immediate economic costs incurred by farmers and long-term ecological benefits need to be considered (Rosa-Schleich *et al* 2019). Assessing observed, attainable, and potential crop diversity, as well as crop diversity gaps, i.e. the difference between attainable and potential to observed crop diversity, can shed light on these trade-offs by describing theoretical levels of crop diversity based on location-specific crop suitability and the human demand for crops (Aramburu Merlos and Hijmans 2022).

Potential crop diversity is determined by crop suitability; attainable diversity refers to crop suitability and demand for crops, which is estimated based on the crop's current total production (Aramburu Merlos and Hijmans 2022). Quantifying the characteristics of crop diversity can reveal opportunities for diversification that consider environmental and economic constraints.

Field-level mapping of crop types enables the quantification of observed and attainable spatial crop diversity. Examinations at the field scale are currently lacking for larger areas. The literature on optimizing crop allocations at the farm-level focuses on maximizing yields or profits (Galán-Martín *et al* 2015, Telles *et al* 2021) rather than on spatial crop diversity as an explicit objective function. Studies of larger areas ignore constraints at the level of individual farms (Schönhart *et al* 2011, Capitanescu *et al* 2017, Galán-Martín *et al* 2017). One option to increase crop diversity is to introduce new crops into cropping systems by proposing intercropping, mixed cropping, or companion cropping (Hufnagel *et al* 2020). However, doing so can increase costs and complicate agronomic management (Roesch-McNally *et al* 2018). Here, we suggest a spatial optimization approach and incorporate spatial crop diversity as an objective function for existing farm-level crop portfolios on 470 km<sup>2</sup> of arable land cultivated by 100 farms operating 3008 fields. We address the following research questions: (1) by how much can landscape scale crop diversity be increased without changing yearly farm scale crop compositions and while respecting field-level crop sequence constraints? (2) How can we design a decision-making model that maximizes crop diversity at the landscape scale over multiple years while incorporating field and farm-level constraints?

## 2. Methods

### 2.1. Approach

We developed a spatially explicit, multiscale optimization model based on linear programming (figure 1) that allows to quantify and map observed, attainable, and potential landscape-scale crop diversity as well as crop diversity gaps. The model implements decisions at the field scale and maximizes crop diversity at the landscape scale for multiple years while accounting for farm-level constraints as well as field-level crop sequence rules. We used a 1 × 1 km grid, in which each grid cell represents a landscape; this landscape definition is similar to the approach of Sirami *et al* (2019), Wesemeyer *et al* (2023). Much research on the effect of crop diversity on biodiversity measures spatial compositional crop diversity on the landscape scale, typically defined as a circular or rectangular area with a radius between 250 and 3000 m (Hass *et al* 2018, Redlich *et al* 2018a, Sirami *et al* 2019, Aguilera *et al* 2020). Other approaches use farm-level or municipality level (Ronnenberg *et al* 2016) or

test for scale effects with multiple landscape definitions (Redlich *et al* 2018b, Strobl 2022). We used field-level data from the Integrated Administration and Control System (IACS), the EU-wide dataset that underpins the EU's payments to farmers, for 100 farms in the federal state of Brandenburg, Germany. Our model reassigns crop types to existing arable fields and evaluates crop allocations at the landscape scale; hence, a decision regarding one farm affects the decisions made for farms in their spatial proximity. Farm-level crop composition constraints ensured that the observed crop composition per farm was maintained with crop composition tolerance of 5% per crop and farm. Crop sequence rules ensured feasible crop sequences, by considering for instance minimum return periods and crop incompatibilities. We used the field boundaries from 2018 and assumed the boundaries did not change; we also assumed that the same farm farmed the field for all years.

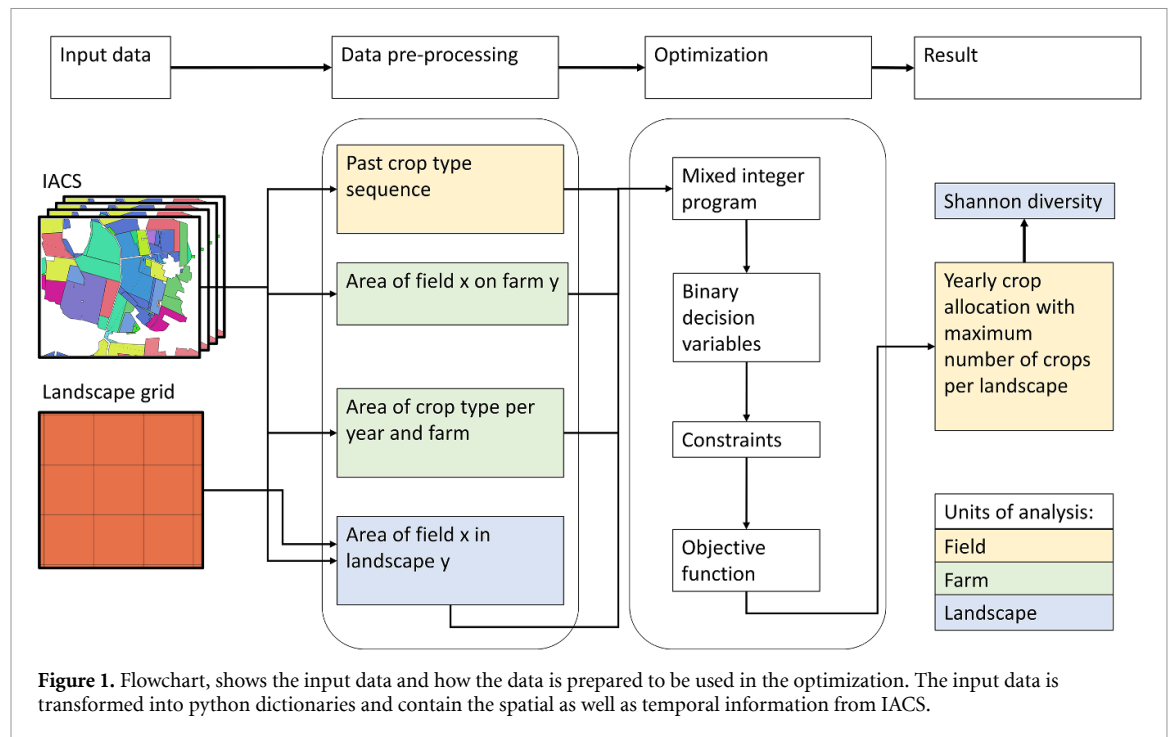
### 2.2. Study area

We choose 20 case studies within our study area—the federal state of Brandenburg (29 479 km<sup>2</sup>) in former East Germany. The state is characterized by large farms (average farm size of 242 ha) with large fields (average field size of 10 ha<sup>4</sup>) (Amt für Statistik Berlin-Brandenburg 2023). Brandenburg's agricultural landscape is increasingly dominated by homogeneous land use and the intensification of production, both of which are arguably associated with a decrease in biodiversity (Kamp *et al* 2021, Wolff *et al* 2021). According to the IACS, the state contained 13 000 km<sup>2</sup> of arable land in 2018. The four main crop types are winter cereals (48%), maize (22%), winter rapeseed (13%), and legumes (6%). To reduce computational complexity, we randomly selected 20 case studies, with each case study containing five farms in spatial proximity to be optimized as well as the surrounding other farms taken as static. A description of the sampling procedure can be found in the supplementary material (A1).

### 2.3. Data

We used IACS data from 2012 to 2018 to extract field and farm boundaries, crop types on each field, and the farms' crop compositions. For each field, we extracted the crop type sequence for a seven-year period. Furthermore, we aggregated the original IACS crops into ten crop types, following Jänicke *et al* (2022), Josefsson *et al* (2017), Stein and Steinmann (2018). The aggregated crop types are maize, winter cereals, beets (mainly sugar beet), winter rapeseed, potato, spring cereals, legumes, arable grass, sunflowers and others, and unknown

<sup>4</sup> According to IACS 2018 the size of agricultural fields in Brandenburg is 10.7 ha. This excludes grasslands, but includes e.g. vegetable fields, landscape elements, flowering strips, permanent cultures.



(a very small class with unknown crop type codes). By using these aggregated classes, we reduced computational demand and represented the structural diversity (structure refers to similar management and vegetation structure) of crops in a landscape, which has been shown to be a more meaningful metric for biodiversity than crop diversity of single crop species (Josefsson *et al* 2017, Frank *et al* 2024). However, some crop type classes contain only single species (e.g. maize and rapeseed) because either their management or vegetation structure is not similar to any other class. We excluded permanent grassland because no crops are grown on it (these fields represent 50% of the original data set). We removed fields smaller than 1 ha to decrease computational demand (these fields represent 6.7% of the original data set).

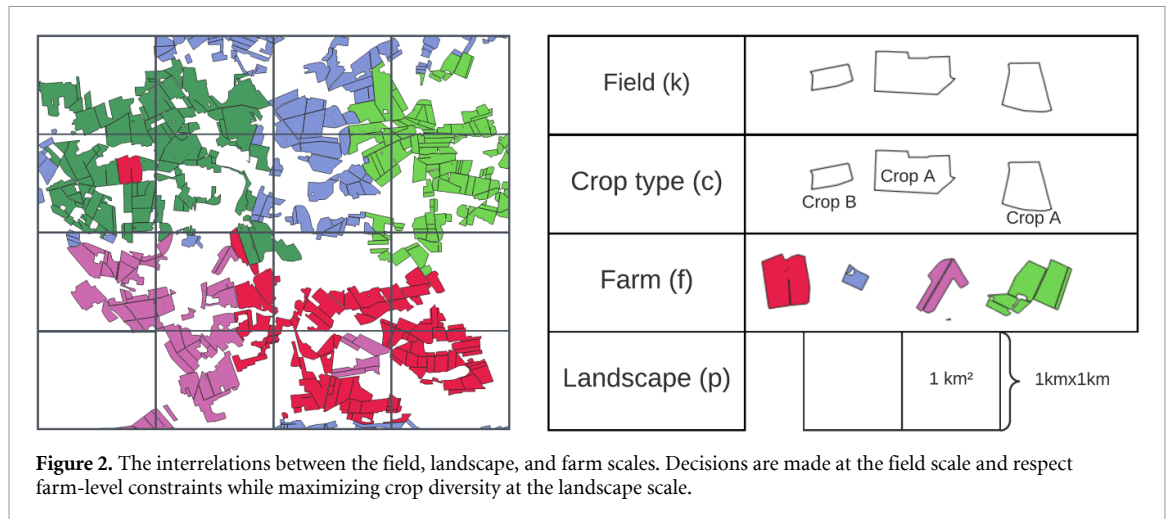
#### 2.4. Definition of attainable and potential diversity

Theoretical levels of crop diversity can reveal opportunities for diversification under environmental and economic constraints. We build on the concepts of observed, attainable, and potential diversity proposed by Aramburu Merlos and Hijmans (2022) and adapt these to the landscape scale. We define observed crop diversity as the average Shannon diversity over our study period at the landscape scale ( $1 \times 1$  km) by using the crop allocation derived from the IACS data. We define attainable crop diversity as average Shannon diversity over our study period at the landscape scale based on the crop allocation that maximizes the number of unique crops at the landscape scale while respecting the crop choices of farmers for a field,

their crop sequential rules, and the crop composition of a farm per year. We define the farmer's crop choice as all crop types that have been cultivated in a given field in the past seven years based on IACS data from 2012 to 2018. We derived the farm-specific crop compositions from IACS data for each of the seven years. We define potential crop diversity as Shannon diversity at the landscape scale based on a crop allocation that maximizes the number of unique crops at the landscape scale while considering the farmer's crop choices for a field. Thus, the yearly farm crop compositions are not considered for potential crop diversity. We use linear programming to find crop allocations with maximum crop diversity at the landscape scale in order to determine the attainable and potential landscape crop diversity.

#### 2.5. Problem definition

Spatial optimization involves the systematic allocation of resources or the arrangement of spatial elements to maximize or minimize an objective function, considering geographic or spatial constraints (Cao 2018). The objective function is either maximized or minimized by changing decision variables that represent decisions such as planting a crop on a field. Lastly, constraints prevent undesired solutions. We aimed to find a crop type allocation that maximizes the number of unique crop types per agricultural landscape per year, given a set of cropland fields, the farms these fields belong to, the agricultural landscapes the fields are located in, and the number of occurrences per crop type per field over the seven-year period (figure 2).



### 2.5.1. Constraints

The allocation is subject to the following constraints (all rules including references can be found in the appendices A2 and A3):

- (1) Only one crop type can be allocated to each field per year.
- (2) Only crops that have been cultivated in the previous seven years on a given field can be allocated to that field to respect the precious crop allocation decisions of farmers. We keep the field-specific frequency of each crop in the crop sequence constant. However, if crops appeared more than one time in the sequence, the crop must appear at least  $n-1$  times to allow some flexibility.
- (3) The farm-specific crop composition derived from IACS data for a given year has to remain similar for each farm, within a tolerance of 5% of the crop allocation in that year. The tolerance is needed as fields have different sizes, which prevents satisfying exactly the crop composition for each year (except for the observed situation in the IACS).
- (4) Crop sequence constraints have to be respected such as minimum return periods (e.g. 4 years for sugar beet), crop incompatibilities (e.g. no sunflowers after rapeseed), and within year cycles, referring to harvest and sowing dates that must be compatible (e.g. no rapeseed after maize) (Leteinturier *et al* 2006, Castellazzi *et al* 2008, Schönhart *et al* 2011). When farmers violated some of those rules, we did not enforce the crop sequence rule on that field during the optimization.

### 2.5.2. Objective function

To capture crop diversity, we maximize the number of unique crops per landscape for all years. We used the optimized crop allocation to calculate Shannon diversity as an indicator for biodiversity. A detailed

mathematical formulation of the model including the objective function can be found in the supplementary material A2 and A3.

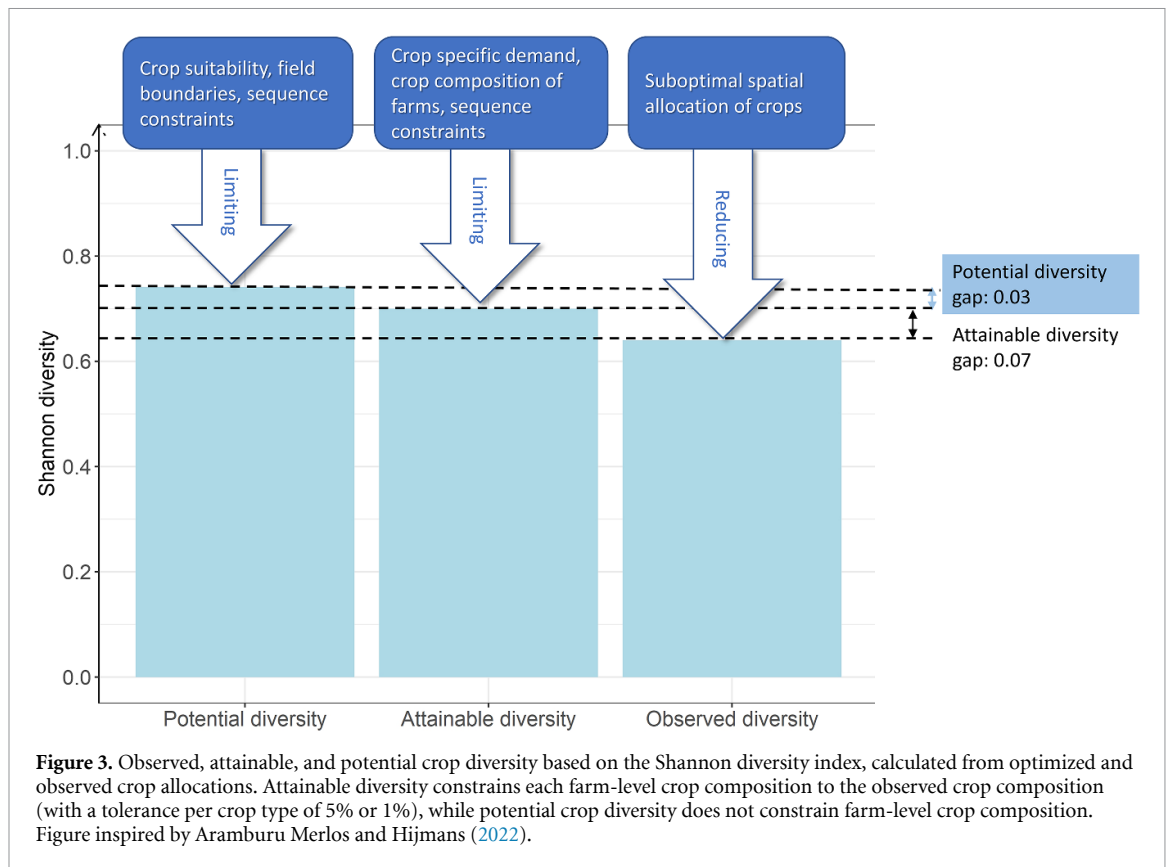
## 2.6. Implementation

In each case study we optimized the crop allocation for the five selected farms including all their fields. The surrounding farms and their fields were included in the calculation when they shared a landscape with any of the selected farms. All fields of the unselected farms were set as static, so each field was assigned the respective crop sequence from IACS. We present two final model runs. The first model run with a threshold value of 5% was performed to estimate the attainable crop diversity. The run without farm crop composition constraints (as described rule 3), was conducted to estimate the potential crop diversity. The model was implemented in Gurobi optimization software v11.0 (Gurobi Optimization LLC 2023) and each of the 20 case studies was executed independently. Finding an optimal solution took between a few minutes up to 12 h on a server utilizing up to 20 GB of RAM and 32 threads. We provide all code (Wesemeyer 2024) with a small example data set (IACS geometries with random farm ID), since we are not allowed to share the original farm ID of the IACS data.

## 2.7. Analysis of results

We calculated landscape crop diversity as Shannon diversity and the number of unique crops per landscape for all observed crop allocations from 2012 until 2018 and for the optimized crop allocations. We used the Shannon diversity as it is frequently used when studying the effects of crop diversity on biodiversity (Ronnberg *et al* 2016, Josefsson *et al* 2017, Raderschall *et al* 2021). We calculated Shannon diversity  $H$  within each landscape by summing the area of each crop per landscape, dividing it by the total area of all crops ( $C$ ) in that landscape to get probabilities ( $p$ ) and using the probabilities to calculate Shannon Diversity according to equation (1):





$$H = - \sum_{i=1}^C p_i \ln(p_i). \quad (1)$$

We then calculated the attainable diversity gap by subtracting the observed Shannon diversity from the attainable Shannon diversity. We also calculated the potential diversity gap by subtracting the attainable diversity from the potential diversity. Since the tolerance value only limits crop composition at the farm-level (enforced only for the attainable diversity), we also verified how much each crop proportion changed for the entire study region because we did not prohibit changes in the overall crop composition. Therefore, we calculated the proportion per crop for all optimized farms for the observed situation (IACS) and the optimized solution to identify the difference for each year. Crop sequence rules ensured economically feasible crop sequences. We therefore analyzed the resulting crop sequences by monitoring the pre- and succeeding crop after each crop on each field.

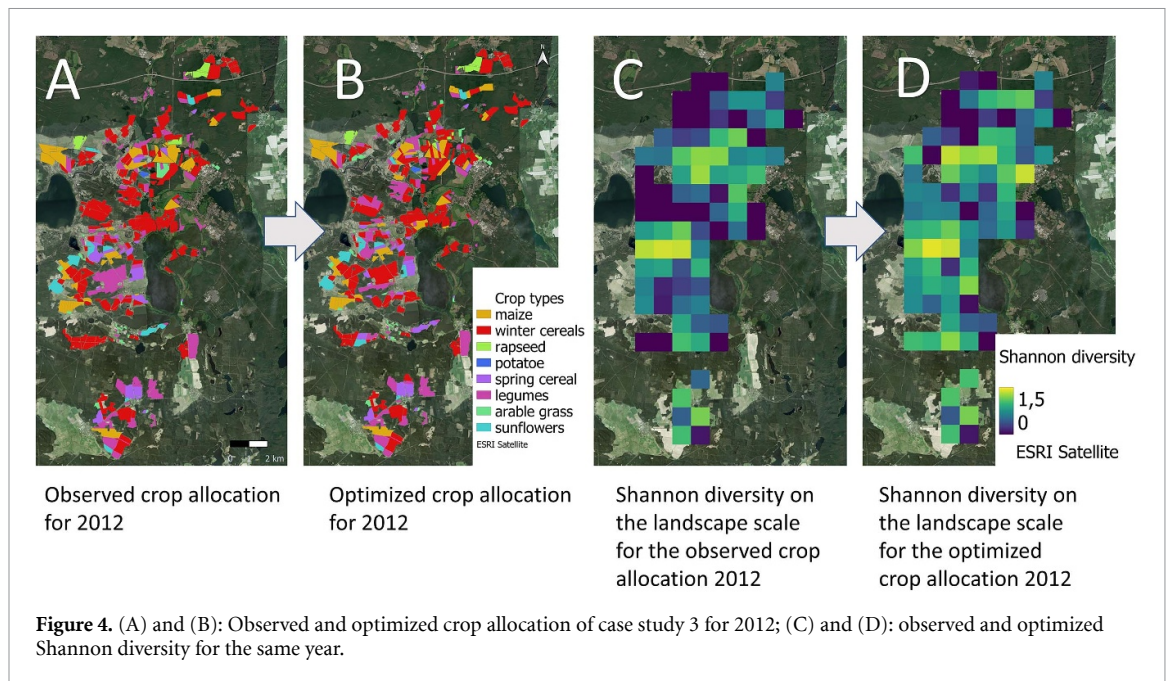
### 3. Results

#### 3.1. Observed, attainable, and potential crop diversity

With a crop composition tolerance of 5% as the allowed deviation from the observed crop type distribution within each farm, the attainable landscape-scale average Shannon crop diversity for all years was 10.5% (0.07) higher than the observed crop diversity

of 0.64; hence, the attainable diversity gap amounted to 0.07 (figure 3). The attainable crop allocation increased the average number of crop types per landscape from 2.8 to 3.0, an increase of 8.5%. The variability in crop diversity differences between case studies was quite large. While case study 11 increased from 0.41 to 0.58 (+40%), other regions increased only by 2% (case study 5). The selected farms in case studies with lower attainable diversity gaps seem to have less fields and cover less area (see supplementary material A4.1). Other factors that could lead to small attainable diversity gaps are areas that are dominated by monocultures and where the crop allocation is close to the optimum already. Case studies where crop sequences are synchronous within the landscapes (i.e. when the same crop at the same time is cultivated on fields within a landscape) offer potential to desynchronize the sequences (e.g. in case study 1) (Bohan *et al* 2021).

The potential crop diversity averaged 0.74 per landscape, which was 16% higher than the observed crop diversity and 0.03 higher than the attainable crop diversity. The latter refers to the potential diversity gap—that is, the difference between potential and attainable diversity (figure 3). The number of crops increased from 2.8 at observed levels to 3.2 in the potential situation, an increase of 14%. The attainable diversity gap (0.07) resulted from suboptimal spatiotemporal crop allocation, while the loosening the constraint to satisfy farm-level crop compositions of individual farms for individual years determined a



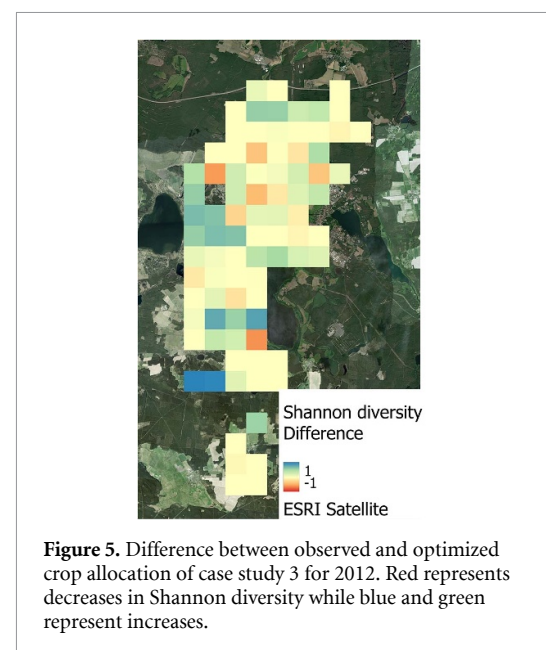
**Figure 4.** (A) and (B): Observed and optimized crop allocation of case study 3 for 2012; (C) and (D): observed and optimized Shannon diversity for the same year.

potential diversity gap value of 0.03 (figure 3). Figures describing the statistical distribution of diversity values for the observed and optimized landscapes can be found in the supplementary material A5.

Figure 4 shows the observed crop allocation for the case study three in 2012 according to IACS (panel A), the optimized allocation with the maximum number of crops per landscape (panel B), the corresponding observed average Shannon diversity in 2012 and the optimized allocation in 2012 for case study 3 (panels C and D; supplementary material A4.1). Note that the values slightly deviate from those in supplementary material A4.1, which contains average values across all years. Figure 5 shows the difference between C and D in figure 4. Red represents decreases in Shannon diversity while blue and green represent increases.

### 3.2. Crop sequence and composition differences

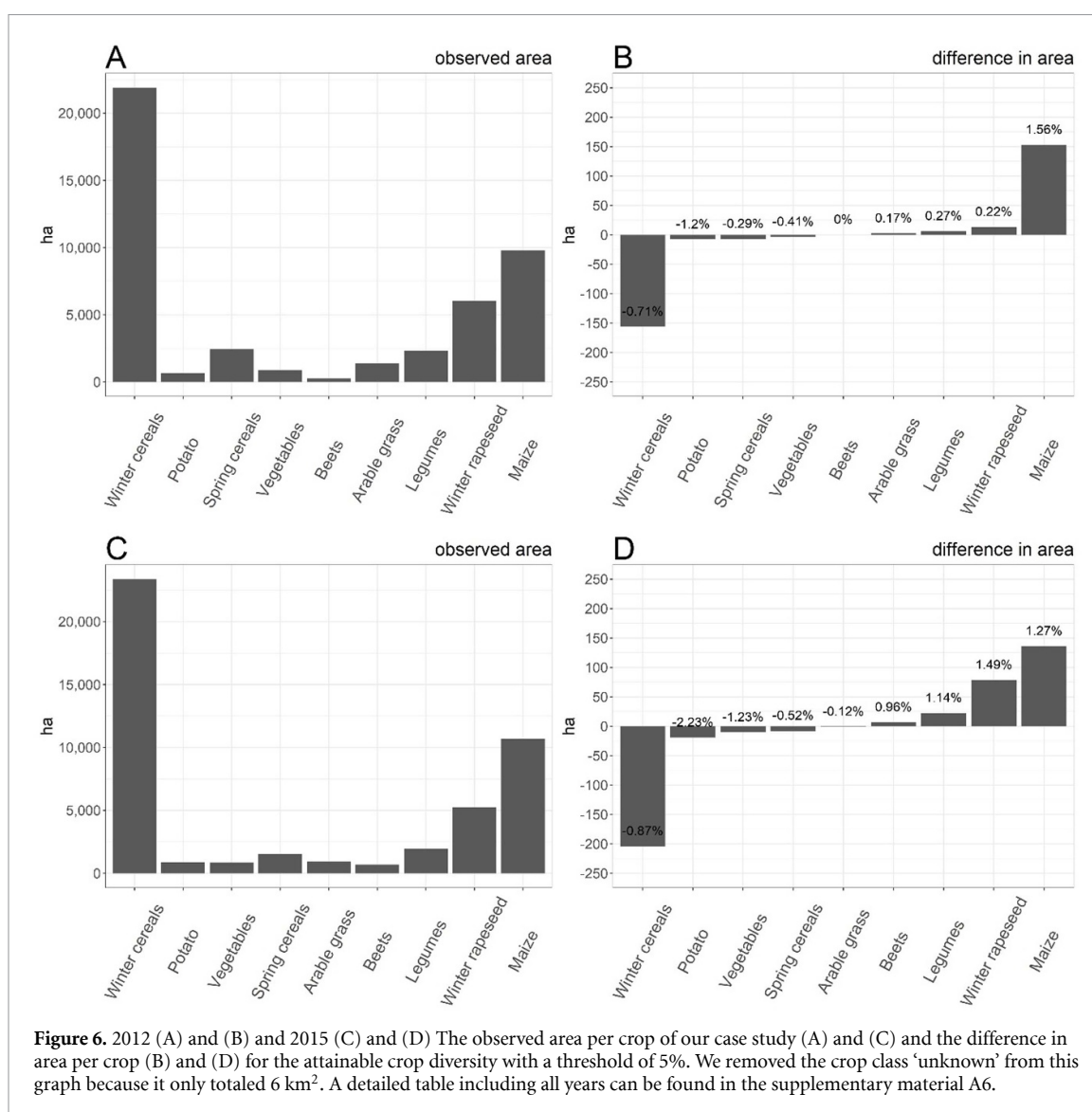
The overall area under winter cereals cultivation for the attainable crop allocation decreased by 200 ha in 2015 with a crop composition tolerance of 5% compared to the observed crop allocation (0.87% of the observed winter cereals area in that year), which was the largest absolute decrease (figure 6). The area under maize cultivation increased by about 150 ha in 2012 (1.56%), the largest absolute increase. The largest relative decrease was 2.25% in potato area in 2015. Whereas the largest relative increase was 3.25% of potato area in 2013. For all years, the area under winter cereal cultivation slightly decreased and the area under maize cultivation slightly increased for the optimized crop allocations. We should note that the farm-level differences in crop composition were limited to  $\pm 5\%$  for each year of the observed area per crop due to the crop composition tolerance; changes



**Figure 5.** Difference between observed and optimized crop allocation of case study 3 for 2012. Red represents decreases in Shannon diversity while blue and green represent increases.

in the overall crop composition were not additionally constrained. In contrast, potential crop diversity was estimated without yearly farm-level crop composition constraints; overall and farm crop composition changed considerably.

Crop sequence rules ensured economically feasible crop sequences. We therefore analyzed the resulting crop sequences by monitoring the pre- and succeeding crop after each crop. In general, there were no larger changes in the distribution of pre and succeeding crops after each crop. Larger changes were also constrained by the fact that we aimed to reproduce the frequency per crop in the sequence (see rule (2)). Detailed figures can be found in the supplementary material A7.



## 4. Discussion

We used spatially explicit optimization to maximize crop diversity at the landscape scale over multiple years. The optimization allowed for the allocation of crops at the field scale for multiple years, while respecting crop sequence constraints and crop composition constraints at the farm-level. Our findings revealed that the average attainable landscape crop diversity over seven years with given field boundaries, farm crop compositions, and crop sequence constraints is 10% higher than the observed crop diversity. Minor changes in the spatial allocation of crop compositions within the farms can close this diversity gap (figure 4). We ensured crop sequences remain feasible due to our crop sequential constraints. We found a high variability in crop diversity gaps between the case studies, which implies that the potential to close these gaps differs across space.

The literature suggests that farm-scale crop diversity cannot be increased without a drastic

reduction in the area cultivated with the dominant crops, which would arguably result in financial losses, at least in the short term (Aramburu Merlos and Hijmans 2020, 2022). However, we found that landscape-scale crop diversity can be higher without major alterations in crop composition at the farm-level and study-area level.

Our approach identified gaps between the actual situation and what is possible if farms would cooperate in crop allocation decisions. For instance, a single farm can reduce the diversity gap but would need spatial information about what the other farms cultivate. Closing the attainable diversity gap can have positive impacts on avian biodiversity (Strobl 2022, Frank *et al* 2024), particularly in landscapes with low crop diversity (Ronnenberg *et al* 2016) and high amounts of seminatural cover (Sirami *et al* 2019). However, the effect of increased crop diversity on bird abundance varies between bird species groups and also depends on the presence of small woody features in a landscape (Frank *et al* 2024). Higher landscape-scale crop diversity can benefit crop pollinators and pest control



(Gurr *et al* 2016, Redlich *et al* 2018a, Aguilera *et al* 2020, Hemberger *et al* 2021, Raderschall *et al* 2021, Tschardt *et al* 2021), and crop-crop boundaries help pollinator dispersal (Hass *et al* 2018). Therefore, closing the attainable diversity gap can be seen as a form of sustainable intensification that promotes biodiversity and the provision of ecosystem services while sustaining or even enhancing crop productivity and reducing dependence on synthetic inputs (Pretty 2007, Charles *et al* 2014). Incorporating our model into a framework proposed by Hernández-Ochoa *et al* (2022) would allow to translate the increased crop diversity into e.g. improvements in biodiversity or other ecosystem services. As the effect of higher crop diversity on biodiversity and economic benefits might be nonlinear, this would need additional models (e.g. a regression with input crop diversity and output biodiversity).

While low landscape diversity can be associated with high rotational crop diversity in Brandenburg (Schiller *et al* 2024), the latter does not stand for higher spatial diversity. If all fields rotate in a synchronized manner in an area, rotational diversity can be very high while spatial crop diversity can be low. Our approach increased the spatiotemporal asynchrony of crops in our landscapes. This means that instead of all fields in a landscape having a synchronous rotation, our approach desynchronized the fields, which leads to an increase in spatial crop diversity on average over all years. Thus, using our approach might identify larger crop diversity gaps in areas where rotational diversity is high and landscape diversity is low. Farmers often steer toward more specialized cropping systems with lower crop diversity but higher profits (Klasen *et al* 2016, Roesch-McNally *et al* 2018, van Zonneveld *et al* 2020). Our results suggest that increasing crop diversity at the landscape scale can provide societal benefits without changing the yearly crop composition per farm. However, larger farms with more fields have a higher probability that crops will need to be spatially rearranged since alternative crop allocations that satisfy the farm's crop composition are more likely when more fields are available. This underlines that larger farms have a greater potential to achieve diversification (Schaak *et al* 2023).

Our study comes with some limitations. We assumed that all farmers decided about their cropping plans at the same time and that these decisions were static. However, farmers make cropping plan decisions throughout the year (Dury *et al* 2012) due to factors such as weather and market uncertainty and because there may be multiple sowing seasons per year. Additionally, the optimized crop allocations in this study might lead to larger distances between fields of a certain crop and the farmstead or to larger distances among crops of the same type, which can increase operating costs. Further, we were unable

to use Shannon diversity as an objective function, however, maximizing the number of crop types per landscape yielded good results. While using Shannon diversity as an objective function might reveal larger diversity gaps, doing so is too expensive computationally. Our approach did not introduce any crops that were not cultivated on a field before. However, introducing new crops to the cropping system, such as legumes, could generate higher economic and environmental benefits (Reckling *et al* 2016). Introducing new crops would increase landscape scale crop diversity on farms where those were not present before. Accounting for the suitability of a particular field provides additional opportunities to enhance diversity through a larger portfolio of crops and impacts the calculation of the potential diversity (Aramburu Merlos and Hijmans 2022). However, doing so would result in larger changes to management schemes at the farm-level, which we wanted to avoid. Finally, the aggregation of single crops into crop type makes our crop sequence constraints sometimes problematic. For instance, within our legumes class peas would have other minimum return times than lupines. Lastly, we assumed that field boundaries as well as field ownership did not change within our study period. However, in reality, field boundaries may change and farms may change what fields they cultivate.

A unique feature of our modeling approach is that we integrate the field, farm, and landscape-level over time. Our contribution hence marries spatial scales usually found in agricultural economics with the landscape scale often found in ecology. Our approach relies on IACS data only, which makes it transferable to other regions in the EU, where IACS data is used to allocate farm subsidies. All code is openly accessible to permit replication and subsequent analysis, including on topics such as mitigating regional decreases in crop diversity or assessing the potential impact of agricultural policies on crop diversity. For instance, a recent study optimized the allocation of crops at the county level and found that GHG emissions could be reduced by 20% and reactive nitrogen losses by 18%, while county-level crop diversity would decrease by 19% (Burchfield 2022, Wang *et al* 2022). Our approach could help to mitigate crop diversity losses at the regional level and potentially even increase crop diversity at the landscape scale. Our model can also help to evaluate eco-schemes that deliver EU payments to farms for the cultivation of certain proportions of the land with cereals and legumes. Different national requirements for the implementation of the eco-schemes could serve as constraints in an optimization framework. Our model could support the estimation of the potential impact of the subsidies on landscape-scale crop diversity (European Parliament and Council 2021, Regulation of the BMEL 2022).

## 5. Conclusion

The observed spatial crop allocation in our study fell short of the attainable landscape-scale crop diversity with prevailing field boundaries, farm constraints, and crop sequence constraints. We found that a reallocation of crops while maintaining field boundaries, crop composition per farm, and crop sequence rules would raise the average attainable landscape crop diversity by 10%. The diversity gaps varied considerably between our case studies, suggesting that some regions would benefit more than others from closing the attainable diversity gap. Closing the attainable diversity gap might simultaneously increase biodiversity and create benefits for farmers by enhancing pest control and crop pollination with minimal profit reductions.

## Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

## Acknowledgments

Funding: This work was supported by the Deutsche Forschungsgemeinschaft as part of Research Unit 2569, 'Agricultural Land Markets—Efficiency and Regulation'. We are grateful for the valuable suggestions and feedback from the reviewers, which helped to improve the manuscript.

## ORCID iDs

Maximilian Wesemeyer  <https://orcid.org/0000-0002-5939-8354>

Daniel Müller  <https://orcid.org/0000-0001-8988-0718>

Tobia Lakes  <https://orcid.org/0000-0001-8443-7899>

## References

- Aguilar J, Gramig G G, Hendrickson J R, Archer D W, Forcella F and Liebig M A 2015 Crop species diversity changes in the United States: 1978–2012 *PLoS One* **10** e0136580
- Aguilera G et al 2020 Crop diversity benefits carabid and pollinator communities in landscapes with semi-natural habitats *J. Appl. Ecol.* **57** 2170–9
- Amt für Statistik Berlin-Brandenburg 2023 *Brandenburger Betriebe durchschnittlich 242 Hektar groß* (available at: [www.statistik-berlin-brandenburg.de/008-2024](http://www.statistik-berlin-brandenburg.de/008-2024))
- Aramburu Merlos F and Hijmans R J 2020 The scale dependency of spatial crop species diversity and its relation to temporal diversity *Proc. Natl Acad. Sci. USA* **117** 26176–82
- Aramburu Merlos F and Hijmans R J 2022 Potential, attainable, and current levels of global crop diversity *Environ. Res. Lett.* **17** 044071
- Bohan D A et al 2021 Designing farmer-acceptable rotations that assure ecosystem service provision in the face of climate change *Adv. Ecol. Res.* **65** 169–244
- Burchfield E K 2022 Where and how to grow food *Nat. Food* **3** 985
- Burchfield E K, Nelson K S and Spangler K 2019 The impact of agricultural landscape diversification on U.S. crop production *Agric. Ecosyst. Environ.* **285** 106615
- Cao K 2018 Spatial optimization for sustainable land use planning *Comprehensive Geographic Information Systems* (Elsevier) (<https://doi.org/10.1016/B978-0-12-409548-9.09603-2>)
- Capitanescu F, Marvuglia A, Navarrete Gutiérrez T and Benetto E 2017 Multi-stage farm management optimization under environmental and crop rotation constraints *J. Clean. Prod.* **147** 197–205
- Castellazzi M S, Wood G A, Burgess P J, Morris J, Conrad K F and Perry J N 2008 A systematic representation of crop rotations *Agric. Syst.* **97** 26–33
- Charles H, Godfray H and Garnett T 2014 Food security and sustainable intensification *Phil. Trans. R. Soc. B* **369** 20120273
- Dury J, Schaller N, Garcia F, Reynaud A and Bergez J E 2012 Models to support cropping plan and crop rotation decisions. A review *Agron. Sustain. Dev.* **32** 567–80
- European Parliament and Council 2021 Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013
- Frank C et al 2024 Woody semi-natural habitats modulate the effects of field size and functional crop diversity on farmland birds *J. Appl. Ecol.* **61** 987–99
- Galán-Martín Á, Pozo C, Guillén-Gosálbez G, Antón Vallejo A and Jiménez Esteller L 2015 Multi-stage linear programming model for optimizing cropping plan decisions under the new common agricultural policy *Land Use Policy* **48** 515–24
- Galán-Martín Á, Vaskan P, Antón A, Esteller L J and Guillén-Gosálbez G 2017 Multi-objective optimization of rainfed and irrigated agricultural areas considering production and environmental criteria: a case study of wheat production in Spain *J. Clean. Prod.* **140** 816–30
- Gurobi Optimization LLC 2023 *Gurobi Optimizer Reference Manual* (available at: [www.gurobi.com](http://www.gurobi.com))
- Gurr G M et al 2016 Multi-country evidence that crop diversification promotes ecological intensification of agriculture *Nat. Plants* **2** 1–4
- Hass A L et al 2018 Landscape configurational heterogeneity by small-scale agriculture, not crop diversity, maintains pollinators and plant reproduction in western Europe *Proc. R. Soc. B* **285** 20172242
- Hemberger J, Crossley M S and Gratton C 2021 Historical decrease in agricultural landscape diversity is associated with shifts in bumble bee species occurrence *Ecol. Lett.* **24** 1800–13
- Hernández-Ochoa I M, Gaiser T, Kersebaum K C, Webber H, Seidel S J, Grahmann K and Ewert F 2022 Model-based design of crop diversification through new field arrangements in spatially heterogeneous landscapes. A review *Agron. Sustain. Dev.* **42** 1–25
- Hufnagel J, Reckling M and Ewert F 2020 Diverse approaches to crop diversification in agricultural research. A review *Agron. Sustain. Dev.* **40** 1–17
- Jänicke C, Goddard A, Stein S, Steinmann H H, Lakes T, Nendel C and Müller D 2022 Field-level land-use data reveal heterogeneous crop sequences with distinct regional differences in Germany *Eur. J. Agron.* **141** 126632

- Josefsson J, Berg Å, Hiron M, Pärt T and Eggers S 2017 Sensitivity of the farmland bird community to crop diversification in Sweden: does the CAP fit? *J. Appl. Ecol.* **54** 518–26
- Kamp J et al 2021 Population trends of common breeding birds in Germany 1990–2018 *J. Ornithol.* **162** 1–15
- Klasen S et al 2016 Economic and ecological trade-offs of agricultural specialization at different spatial scales *Ecol. Econ.* **122** 111–20
- Leteinturier B, Herman J L, De Longueville F, Quintin L and Oger R 2006 Adaptation of a crop sequence indicator based on a land parcel management system *Agric. Ecosyst. Environ.* **112** 324–34
- Martin A R, Cadotte M W, Isaac M E, Milla R, Vile D and Violle C 2019 Regional and global shifts in crop diversity through the Anthropocene *PLoS One* **14** e0209788
- Pretty J 2007 Agricultural sustainability: concepts, principles and evidence *Phil. Trans. R. Soc. B* **363** 447–65
- Raderschall C A, Bommarco R, Lindström S A M and Lundin O 2021 Landscape crop diversity and semi-natural habitat affect crop pollinators, pollination benefit and yield *Agric. Ecosyst. Environ.* **306** 107189
- Reckling M, Bergkvist G, Watson C A, Stoddard F L, Zander P M, Walker R L, Pristeri A, Toncea I and Bachinger J 2016 Trade-offs between economic and environmental impacts of introducing legumes into cropping systems *Front. Plant Sci.* **7** 202846
- Redlich S, Martin E A and Steffan-Dewenter I 2018a Landscape-level crop diversity benefits biological pest control *J. Appl. Ecol.* **55** 2419–28
- Redlich S, Martin E A, Wende B and Steffan-Dewenter I 2018b Landscape heterogeneity rather than crop diversity mediates bird diversity in agricultural landscapes *PLoS One* **13** e0200438
- Regulation of the BMEL 2022 *Anlage 5—GAP-Direktzahlungen-Verordnung (GAPDZV)* (available at: [www.buzer.de/Anlage\\_5\\_GAPDZV.htm](http://www.buzer.de/Anlage_5_GAPDZV.htm))
- Roesch-McNally G E, Arbuckle J G and Tyndall J C 2018 Barriers to implementing climate resilient agricultural strategies: the case of crop diversification in the U.S. Corn Belt *Glob. Environ. Change* **48** 206–15
- Ronnenberg K, Strauß E and Siebert U 2016 Crop diversity loss as primary cause of grey partridge and common pheasant decline in Lower Saxony, Germany *BMC Ecol.* **16** 1–15
- Rosa-Schleich J, Loos J, Mußhoff O and Tschardt T 2019 Ecological-economic trade-offs of diversified farming systems—a review *Ecol. Econ.* **160** 251–63
- Schaak H, Bommarco R, Hansson H, Kuns B and Nilsson P 2023 Long-term trends in functional crop diversity across Swedish farms *Agric. Ecosyst. Environ.* **343** 108269
- Schiller J, Jänicke C, Reckling M and Ryo M 2024 Higher crop rotational diversity in more simplified agricultural landscapes in Northeastern Germany *Landscape Ecol.* **39** 1–18
- Schönhart M, Schmid E and Schneider U A 2011 CropRota—a crop rotation model to support integrated land use assessments *Eur. J. Agron.* **34** 263–77
- Sirami C et al 2019 Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions *Proc. Natl Acad. Sci. USA* **116** 16442–7
- Stein S and Steinmann H H 2018 Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems—a case study from Central Europe *Eur. J. Agron.* **92** 30–40
- Strobl E 2022 Preserving local biodiversity through crop diversification *Am. J. Agric. Environ.* **104** 1140–74
- Telles L A D A et al 2021 When, where and what cultivate: an optimization model for rural property planning *J. Clean. Prod.* **290** 125741
- Tscharntke T, Grass I, Wanger T C, Westphal C and Batáry P 2021 Beyond organic farming—harnessing biodiversity-friendly landscapes *Trends Ecol. Evol.* **36** 919–30
- USDA FSA 2021 *Conservation Reserve Program* (available at: [www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/index](http://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/index))
- van Zonneveld M, Turmel M S and Hellin J 2020 Decision-making to diversify farm systems for climate change adaptation *Front. Sustain. Food Syst.* **4** 32
- Wang Z et al 2022 Integrating crop redistribution and improved management towards meeting China's food demand with lower environmental costs *Nat. Food* **3** 1031–9
- Wesemeyer M 2024 maxwesemeyer/MaxNCrops: maxNCrops Zenodo (<https://doi.org/10.5281/zenodo.11474389>)
- Wesemeyer M, Kamp J, Schmitz T, Müller D and Lakes T 2023 Multi-objective spatial optimization to balance trade-offs between farmland bird diversity and potential agricultural net returns *Agric. Ecosyst. Environ.* **345** 108316
- White E V and Roy D P 2015 A contemporary decennial examination of changing agricultural field sizes using Landsat time series data *Geo* **2** 33
- Wolff S, Hüttel S, Nendel C and Lakes T 2021 Agricultural landscapes in Brandenburg, Germany: an analysis of characteristics and spatial patterns *Int. J. Environ. Agric. Res.* **15** 487–507