Analysis

Do improved pollination services outweigh farm-economic disadvantages of working in small-structured agricultural landscapes? – Development and application of a bio-economic model

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A B S T R A C T

Increases in the size of agricultural fields, the loss of permanent green field edges and other semi-natural habitats have accompanied the intensification of agriculture, and are still ongoing. From a farm economic perspective, an increase in field size increases efficiency mainly due to cost savings. However, recent evidence suggests that increases in field size might lead to the loss of ecosystem services provided by farmland biodiversity, but this trade-off is rarely considered. Here, we aim to quantify the economic and ecological effects of these changes by developing a bio-economic simulation-based land-use modelling framework based on spatially explicit data from an agricultural region in Germany. The results show a substantial decrease in flower visitation in oilseed rape when field sizes increase and permanent green edges are lost. This also leads to a decrease in pollination from wild bees and affects yields and farm economics. However, this loss in agricultural gross margin is overcompensated by economic gains of field enlargement. We conclude that further, more comprehensive evaluations are required and suggest that maintaining fine-grained agricultural landscapes with permanent field margins in the long term may require incentives to farmers, as well as innovations that allow to farm small fields at lower costs.

1. Introduction

Changes in the size of agricultural fields have accompanied technological and socio-economic development in agricultural landscapes for centuries (Skalos et al., 2012). In particular economic aspects are of major importance for field size changes: Increasing field sizes allows managing plots more efficiently and leads to lower production costs per hectare land (Engelhardt, 2005; Rodríguez and Wiegand, 2009). Furthermore, increasing field sizes tend to reduce the length of permanent and – from the agricultural point of view – unproductive ‘green’ field edges and contribute therefore to an extension of productive area. Due to the economic advantages of field size increases the predominant trend over the past 20–30 years has been towards bigger field sizes (White and Roy, 2015). There is still a significant potential to even further increase field sizes, since there remains a large variability in mean field sizes, both across the globe and within Europe, where differences of more than an order of magnitude can be observed between landscapes (Herzog et al., 2006).

However, the increases in field size are not only associated with economic gains, but have been suggested to decrease biodiversity, and ecosystem services to crops, for example by reducing resources for wild pollinators (Fahrig et al., 2015) and increasing distances between crop and service-providing habitats (Boetzl et al., 2018). From an ecological point of view increasing field sizes can affect biodiversity and ecosystem services through several landscape-scale mechanisms that are not mutually exclusive (Dunning et al., 1992). First, landscapes with larger fields have a lower length of field edges. These may be field-field ecotones lacking permanent vegetation, but also permanent field edges in the form of grassy strips, hedges, walls and/or ditches. Permanent field edges in particular provide nesting sites and food resources for many species including wild bees and natural enemies of pests. This has an impact on the biodiversity, the pollination of crops and the natural control of species in the crops. For instance, a higher density of grassy field edges within 1 km has been shown to decrease aphid densities in...
cerals fields (Bosem Baillod et al., 2017). Secondly, landscapes with larger fields are associated with lower diversity of crops at small spatial scales, which can negatively affect mobile species that move between different crops, e.g. where they find complementary resources (Marrec et al., 2017; Smith et al., 2014) and hamper pest control (Redlich et al., 2018). Thirdly, through a sampling effect, less dominant crops might not be represented at all in a given year in landscapes with larger fields, thereby decreasing crop diversity also at larger spatial scales. Landscape configuration (field size) and composition (crop diversity) are thus often correlated dimensions (Fahrig et al., 2011), but their impacts on biodiversity and ecosystem services have been recently disentangled by specially tailored empirical studies (Bosem Baillod et al., 2017; Fahrig et al., 2015; Martin et al., 2016; Sirami et al., 2019).

Large amounts of semi-natural habitat in the landscape can cause significant source-sink relationships that reduce the extent to which changes in agricultural land-use affect species communities within cropland (Tscharntke et al., 2005). Increases in field size can therefore be expected to have a larger deleterious effect on biodiversity and ecosystem services in landscapes dominated by arable land.

Despite all the technical progress during the last decades aiming to decouple agricultural production from its dependence on ecological site conditions in order to improve production stability and profitability (Bateman et al., 2013; Omer et al., 2007), agricultural production still requires a good ecological shape of production sites. In particular, pollination, but also natural control of pests are ecological services of major importance for agriculture (Bianchi et al., 2006). Smaller field sizes have been suggested as a strategy to conserve farmland biodiversity and associated ecosystem services without taking land out of production (Fahrig et al., 2011), but the potential costs of such strategies have been largely ignored (but see Rodríguez and Wiegand, 2009). Despite the overwhelming evidence for the importance of the configuration and composition of farmland mosaics for biodiversity and ecosystem services, joint ecological-economic studies, critically important to inform policymakers, farmers and conservationists seeking to combine agricultural production, an improved flow of ecosystem services and biodiversity conservation, are currently lacking (Bateman et al., 2013; Schönhart et al., 2011a).

With our study, we aim to contribute to closing these knowledge gaps by assessing the economic and ecological effects of increasing field size and decreasing area dedicated to permanent field edges (Fig. 1). The central aim of our paper is to set up a bio-economic model that allows to assess the influence of structural aspects of the landscape, namely field size and landscape elements, on pollination and to estimate the private benefits of these pollination services for agricultural production. We use the model to analyse what happens with these services if the landscape structure in an already intensively and conventionally used arable region is further simplified. We also assess whether it is possible to shape the landscape structure in a more pollinator-friendly way such that increased pollination services compensate for the opportunity costs induced by to work on smaller fields and the loss of agricultural area covered by landscape elements. Finally, we analyse biodiversity effects of the suggested land-use changes in order to demonstrate trade-offs between biodiversity and farm-private gross margins.

In our analysis, we focus on pollination since this is a factor of relevance within conventionally managed agricultural systems. This stands in contrast to other factors such as e.g. natural control of pests, whose positive effects are currently fairly limited in conventional production due to the reliance of farmers on insecticides. Our model, applied to an intensively cultivated agricultural region of Germany, allows, in contrast to other complementary approaches (e.g. Cong et al., 2014), to quantify pollination services for agriculture in a small scale, realistic and spatially explicit manner. Furthermore, it goes beyond other bio-economic pollination modelling approaches (e.g. Brosi et al., 2008) in that it integrates ecosystem-service benefits not only with opportunity costs, but also other costs associated with decreased field size.

The remainder of this paper is structured as follows: in Section 2, we present material and methods of our analysis. This includes the presentation of the model, which is sub-structured in three modules, namely data input, bio-economic simulation and response variables. After giving a brief overview on the overall framework we present the data basis, describe the five sub-models of the simulation, before we present the response variables, the study region and the scenarios. In Section 3, we present our results, which we critically discuss in Section 4. The article closes with concluding remarks in Section 5.

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**Fig. 1.** The overall modelling framework. Source: Own illustration.
2. Material and methods

2.1. Overall modelling framework

The aim of our analysis is to model the impact of a transforming agricultural structure on pollination services, biodiversity and its economic impacts. We assess the effects of a joint increase in field size and a reduction in permanent field edges compared to a baseline situation with small fields and a fine mesh of permanent field edges. We therefore develop and apply a bio-economic simulation modelling framework, which we substructure into three modules, namely the input data module, the bio-economic simulation module and the response variables module (Fig. 1). The input data module organises and rasterizes all input data required for the subsequent modelling calculations, and the response variables module collects and displays economic and ecological key results.

The core module of our model is the bio-economic simulation module (cf. Fig. 1). It consists of the five sub-models LU (land use), POLL (pollination), YLD (yield), ECON (economic) and MULTIDIV (multiple biodiversity), which are closely interconnected: The LU model is of particular importance and delivers information for all other models. Furthermore, also the POLL model, the YLD model and the ECON model are closely linked.

2.2. Data basis and data preparation

We base our calculations on two main types of data sources, namely spatial data sources and production and price data sources (Fig. 1). The spatial data sources consist of three datasets: (1) the German IACS-LPIS (Integrated Administration and Control System – Land Parcel Information System) data, which is available for the period from 2010 to 2015, (2) the CORINE Land-use Cover layer (CLC2012) and (3) the German ‘Bodenschätzung’ (land taxation). Based on these sources we develop for 13 study landscapes spatially explicit GIS layers, which are rasterized into 25 × 25 m grid cells. Each grid cell is considered as homogeneous response units (Kirchner et al., 2016), and therefore belong to a single field, is uniform with regard to site conditions (in particular with regard to the soil type), and shows a uniform land use. In addition, it may either contain or not contain a field edge.

Based on the IACS-LPIS data set we generate a GIS layer, which describes the field structure. The layer reflects the currently given original field structure and therefore represents the small-scaled field structure.

Furthermore, the IACS-LPIS data is used to define location and length of edges along agriculturally used fields. Therefore, we identify all grid cells overlapping field boundaries and flag them as containing an edge. Edges are classified either as normal field edges or as permanent green edges. Permanent green edges are permanent grassy and not agriculturally used field strips, which are unproductive from the economic point of view but of high value from the ecological point of view. We assume that permanent green edges have a total width of 4 m on given physical boundaries and 1 m on field edges without such boundaries. The influence of these assumptions on our results are explored by a sensitivity analysis, presented in Appendix C. Normal field edges are agriculturally used, but yields are lower and input use is higher, both due to edge effects (Kläre et al., 2005).

We combine IACS-LPIS and the CORINE data to generate for all study regions GIS layers on the current land use. We subdivide land-use data into three classes: arable land, permanent agricultural land and non-agricultural land. Arable land-use is subdivided into eleven land-use types, namely winter wheat, winter barley, summer barley, maize, autumn oilseed rape, peas, sugar beet, potato, alfalfa, set-aside and flower strips. These land-use types are non-permanent and vary over the study period within the cropping system. In contrast, permanent agricultural land is constant over the study period. This class consists of permanent grassland and permanent crops, which are agriculturally negligible within our selected regions. Therefore, this class is ignored for agricultural output calculations but serves as ecological input for our simulation models. Similar to non-agricultural land-use, which is taken from the CORINE data set and considers the following land-use types: settlement area, forest area and area of green infrastructure.

We use the “German Bodenschätzung” data set to derive the given site quality of the agriculturally used fields. As indicator for the site quality we use the “Acker-/Grünländzahl”, which reflects the yield potential based on soil type, water availability, climatic conditions and relief information (Bayerische-Vermessungsverwaltung, 2009; BayLfSt, 2009). Agricultural site quality ranges between 0 and 100, where 0 indicates the less productive soil and 100 the most productive soil in Germany. In case of missing values, we adjust the data and use the site quality value of the adjacent grid-cells.

Furthermore, beyond spatial data sources we apply several non-spatial production and price data sources. Based on KTBL (2018) and LfL (2018) we derive standardized data to define the agricultural production processes. We complement this data with local information in order to adapt the standardized production data to locally given circumstances. Local data is provided by the Landwirtschaftsamt-Würzburg (2017) and consists of local yield information.

2.3. The bio-economic simulation model

The core module of our model is the bio-economic simulation module (Fig. 1). It consists of five sub-models, which we describe and technically specify in the following sub-sections.

2.3.1. Land use model

The LU model combines all spatial information gathered in the data-preparation process and attributes a specific land use to each 25 × 25 m grid raster cell. While permanent land use is kept static over time, we simulate a six-year crop rotation for non-permanent agricultural land-use. Therefore, we randomly select crops based on the relative occurrence of crops in each field. The resulting crop rotations are applied on field level and remain the same in all scenarios as long as field sizes remain the same. In case of changes in field size (cf. Section 2.6), the randomized selection process adapted to account for this, but with the relative occurrence of crops remaining similar though. In order to minimise the stochastic influence of this process on our results, we execute the selection process and all further subsequent modelling steps repeatedly and use average values. We use 20 repetitions, since preceding tests have shown that this number guarantees stable results as well as an acceptable computing time for a model run.

The outcome of LU model calculations directly serves as input for subsequent ecological modelling steps in the POLL as well as in the MULTIDIV model. For the YLD model and the ECON model an average land use is necessary: thus, we calculate for every grid cell the average share of all arable crops within plots or blocks, respectively (cf. Castellazzi et al. (2008); Koschke et al. (2013); Schönhart et al. (2011b) for similar approaches).

2.3.2. Pollination model

Within the POLL model, we use a spatially explicit, process-based approach to model insect-dependent crop pollination. Our focus is on oilseed rape (winter-sown) since among field crops it is the main insect-pollinated crop in the region. Crop pollination depends on both the...
behavioural responses of pollinators to the amount and spatial arrangement of nesting and feeding habitat and on the within- and between-season dynamics of pollinator populations in response to land use. The scenarios investigated in the present study are expected to impact crop pollination through different pathways. Permanent, grassy field borders are nesting sites for wild bees such as bumblebees and solitary bees. These borders also harbour flowering plants, which can provide nectar and pollen to the wild bees. Changes in field border density thus affect the availability of nesting sites, and thus both the total population size of wild bees at the landscape-scale, and the availability of pollinators to insect-pollinated crops. At the same time, field size mediates the aggregation of mass-flowering crops, and thus the variability in availability of pollen and nectar to wild bees across space and time. Changes in food resources may result in concentration/dilution of foraging bees in the short term, and changes in population density in the longer term (Holzschuh et al., 2016). Here, we use a published pollinator model (Häussler et al., 2017) which (1) integrates preferential use of more rewarding floral and nesting resources; (2) considers population growth over time; (3) allows different dispersal distances for workers and reproductive of colonial bee species; (4) provides visitation rates for use in crop pollination models. The model reproduces patterns found in empirical studies of wild bees in agricultural landscapes. It has been parametrized using expert knowledge for Southernmost Sweden.

We input to the model a randomized land use raster and a raster for green edges. The output of the model used in the present study is the spatially explicit percentage share of pollination for winter oilseed rape when winter-oil-seed rape is grown at the respective location. The output is used further in the YLD model.

2.3.3. Yield model

The aim of the YLD model is to calculate the grid-cell specific yield for all crops. Agricultural yield depends on a broad variety of farm- and site-specific factors. As farm size variation tends to be small in our study region, we neglect farm-specific variation and focus exclusively on site-specific and structural aspects. Namely, we consider site quality, pollination effects and field edge effects (De Koeijer et al., 1999; Hoang, 2013; Lobel et al., 2009).

Within a first step we estimate the yield \( (Y_C) \) for all crops (where C can have the following values: 1 = winter wheat, 2 = winter barley, 3 = summer barley, 4 = maize, 5 = autumn oilseed rape, 6 = peas, 7 = sugar beet, 8 = potato, 9 = alfalfa, 10 = set aside, 11 = flowering strips) subject to the site conditions (D). We do this by setting up a linear regression model correlating site quality with crops specific minimal and maximal yield: \( Y_C = f(D) \). Using the grid-cell specific site quality \( (d_i) \), and the coefficients \( \hat{\beta} \) and \( \hat{\beta} \) of the above-mentioned function, we are able to estimate yields in a spatially explicit manner \( (Y_{ci}) \):

\[
y_{ci} = \hat{\alpha} + \hat{\beta} * d_i
\]

The regression analysis is based on minimal and maximal values of yield data for each crop provided by the Landwirtschaftsamt-Würzburg (2017) and on site quality data provided by the Bayerische Vermessungsverwaltung (2009). Since data sets are too small to achieve significant results, we validated the final numbers of our estimations with the knowledge of local experts of the Landwirtschaftsamt-Würzburg (2017).

In the next step, we consider the effect of insect pollination on insect-pollination sensitive crops \( (cp) \). \( cp \) can be a vector or a single crop. In this study this is done for oilseed rape \( (C = 5) \), the only arable crop in our study region, which is sensitive for insect-pollination. Based on this we adjust site-condition-based yields \( (Y_{ci}) \) for the pollination effect by increasing (or respectively decreasing) the calculated oil-seed rape yields. This is done in the following formula:

\[
y_{ci}^* = y_{ci} + y_{ci,cp} * (\delta_{cp} - \delta_0)/\delta_0
\]

where \( y_{ci,cp} \) is the grid-cell-specific pollination-effect-adjusted yield, \( y_{ci} \) the original grid-cell-specific site-condition-based yield for insect-pollination sensitive crops, \( \delta_{cp} \), the grid-cell-specific pollination ratio for these crops calculated in the POLL model and \( \delta_0 \) the average pollination ratio for these crops and the study region. In order to calculate this effect, we assume a base value of missing insect pollination. Comparisons between plants with insect or artificially pollinated flowers and wind-pollinated flowers, from studies conducted in Ireland (Stanley et al., 2013: 0.7), Sweden (Bommarco et al., 2012; Lindström, 2017) and Germany (Hudewenz et al., 2014: 0.81) suggest that non-insect pollinated oilseed rape yield reaches 79% of the yield of well pollinated oilseed rape yield. Consequently, we assume the non-insect-pollinated oilseed-rape yield level \( \delta_0 = 0.79 \). Given the lack of region-wide data on pollination deficits, we assume average pollination values to correspond to the intermediate value \( \delta_0 = 0.86 \), which is a third into the range between the assumed proportional yield in case of no insect pollination \( 0.79 \) and the potential yield in case of full pollination \( 1 \). The consequences of this assumption are explored in the sensitivity analysis on the yield level in case of missing insect pollination (cf. Appendix C). In order to calculate the pure insect-pollination effect, we eliminate insect pollination assuming a total absence of pollinating insects in original grid-cell-specific site-condition-based yield \( (y_{ci}) \). Technically, we do this by replacing the grid-cell specific pollination ratio \( \delta_{cp} \) with a hypothetical pollination ratio without insect pollination \( \delta_0^{cp} \).

Finally, we consider field-edge effects in our yield model. As literature shows, yield expectations along field edges are significantly lower (Brunotte et al., 2000; De Snoo, 1994; Kapfer, 2007; Keymer et al., 1988; Klare et al., 2005; Lebert et al., 2003; Schneider et al., 2015). Therefore, we reduce the grid-cell-specific site-condition-based yield \( y_{ci} \) with field edge effects and achieve the field-edge-adapted grid-cell-specific (pollination-effect-adjusted) site-condition-based yield \( y_{ci,fe} \). The yield reduction is calculated by multiplying the yield with the field edge yield depression factor \( \epsilon_{fe} \). The same approach is applied to the yield with no insect-pollination resulting in the field-edge-adapted grid-cell-specific site-condition-based yield \( (y_{ci,fe}) \). These can be depicted as

\[
y_{ci,fe} = y_{ci} * \epsilon_{fe}
\]

In order to calculate the cell-grid individual field edge factor \( \epsilon_{fe} \), we differentiate between headlands and normal field edges. As the literature indicates a broad range of yield reductions on field edges with respect to different crops, we follow the assumptions of Kapfer (2007) and use an average yield depression on headlands of 30%, whereas the yield reduction of field edges is with 15% significantly lower. Literature shows that this value can have a broad range. Therefore, we analyse the impact of this assumption on the results in a sensitivity analysis, presented in Appendix C. However, the negative influence of headlands on yields is even more extensive, since the negatively influenced area of headlands is twice as wide (8 m) as this of normal field edges (4 m). Since we do not have any information enabling us to differentiate spatially explicit between headlands and normal field edges, we simplifying assume that all grid cells with field edges contain headlands and normal field edges. On basis of the standard field shape, we assume a ratio of headlands to normal field edges of one to two. Applying these

\[2\]
assumptions to our 25 × 25 m grid cells, we calculate a standard yield depression for a grid cell affected by edge effects of 4.8% and a field edge factor of 0.952. The field edge factor is slightly reduced on grid-cells with permanent green edges as they include less agricultural area then normal grid-cells (0.948 for broad and 0.951 for narrow permanent green edges; cf. Section 2.2).

2.3.4. Economic model

The aim of the ECON model is to calculate the economic consequences for farmers of a loss of pollination-friendly infrastructure. As economic indicator, we use the gross margin farmers receive for the cultivation of their arable land. The gross margin is a major decision criterion for farmers’ production planning and widely used in agricultural economic landscape modelling (Parra-López et al., 2008). In comparison to a full cost accounting, the gross margin does not require to calculate fixed costs, which is very data demanding and not needed in this study since the analysed land-use changes do not change the production structure and thus mainly affect variable production costs.

In order to calculate the gross margin, we subtracted variable production costs from revenues. Following Cong et al. (2014), Kennedy et al. (2016) and Polasky et al. (2008) the calculation of the gross margin (\( \pi_i \)) for each grid-cell \( i \) is expressed as

\[
\pi_i = r_i - c_i = (c_f + c_v + c_o) \]

where \( r_i \) are the revenues per grid cell and \( c_i \) the total variable costs. The total variable costs can be subdivided into fertilizer cost \( (c_f) \), in yield-dependent variable costs \( (c_v) \) and in further variable costs \( (c_o) \). Revenues and costs are expressed in Euro per hectare and their calculation is explained in the following paragraphs:

We calculate revenues by multiplying crop yields \( (y^{**}_{i,c}) \) with respective sales prices \( (p_{y,c}) \). Furthermore, we consider governmental payments \( (q_{g,c}) \), which are directly bound to the culmination of a respective crop \( (c) \). In our study we include agro-environment payments for flowering strips \( (C = 11) \). We execute this calculation for all crops considered in the grid-cell-specific crop rotation and multiply the results with the respective shares of the crops \( (s_{i,c}) \). Finally, we calculate the grid-cell-specific revenues by summing up all proportional crop-specific revenues. Crop yields are derived from the YLD model, sales prices from LfL database (LfL, 2018) and governmental payments from StMELF (2017). The overall revenue calculation is depicted as

\[
\eta = \sum_{i=1}^{C} (y^{**}_{i,c} \cdot p_{y,c} + q_{g,c}) \cdot s_{i,c}
\]

The fertilizer costs \( (c_f) \) are the most complex cost factor in our model. For simplification, we focus our calculations of fertilizer costs on nitrogen, phosphorous and potassium. We base the calculation of the required fertilizer quantities on farmers’ crop-specific yield expectations and the according nutrient removal with the harvest. The calculation of farmers’ yield expectations \( y^{O75}_{j,c} \) is based on the results of the YLD model. Thereby we assume that farmers determine their fertilizer demand on field level and not on grid-cell level and we compile all grid-cell specific yields within each single field \( (j) \). We hypothesize that farmers tend to not orient the required amount of fertilizers on median yields, but rather try to realise higher yields and assume the farmer orient their fertilization strategy at the 75%-quantile of the observed grid-cell specific yields \( (y^{75}_{i,c}) \) within a field. Thus, we write

\[
y^{O75}_{j,c} = Q_{0.75}(y^{75}_{i,c})
\]

We furthermore consider nitrogen fixation by rhizobia on pea plants in our fertilizer demand calculation. Nitrogen fixation decreases the required fertilizer amount and costs. Cost decreases can be calculated by multiplying the fixed nitrogen amount per unit with the estimated actual yield and the nitrogen price. This is done for every pea crop and the result is multiplied with its respective share.

Furthermore, we account for increased fertilizer demand due to edge effects. Again, we follow Kappfer (2007) and assume that -due to double treatments- fertilizer applications on headlands increase by 30% and on normal field borders by 15% (Keymer et al., 1989; Klare et al., 2005). Using the same procedure as in the yield model for yield depression on field edges (cf. Section 2.3.3) we receive an edge factor for input enhancement \( (e_x) \) of 1.048, which is applied in each grid cell with edge effects. The field edge factor is slightly increased on grid-cells with permanent green edges as they include less agricultural area then normal grid-cells (1.052 for broad and 1.048 for narrow permanent green edges; cf. Section 2.2).

Overall, the grid-cell specific fertilizer amount calculation \( (f_{n,c}^{*}) \) for each nutrient \( n \) \((1 = nitrogen, 2 = phosphorus, 3 = potassium)\) is depicted as

\[
f_{n,c}^{*} = \sum_{i=1}^{C} y^{O75}_{j,c} \cdot m_{n,c} \cdot e_x \cdot s_{i,c}
\]

where \( y^{O75}_{j,c} \) is the estimated yield for each crop \( c \) and field \( j \), \( m_{n,c} \) the nutrient removal through harvest for each crop \( c \) and nutrient \( n \). This is multiplied with the edge factor \( e_x \) and the share of each crop within the cell-grid \( (s_{i,c}) \).

In the next step the nitrogen surplus through biological nitrogen fixation \( (n = 1) \) fixation is included in the calculation. Therefore the yield \( y^{**}_{j,c,n} \) of each crop which fixes nitrogen \( (cn) \) is multiplied with the nitrogen surplus rate \( sur_{n-1,cn} \) the share of each crop within the cell-grid \( (s_{i,c}) \) and subtracted from the fertilizer amounts \( f_{n,c}^{*} \) calculated above. In our study the nitrogen fixation only occurs for peas \( (cn = 6) \).

\[
f_{1,n,i} = f_{1,n}^{*} - y^{**}_{j,c,n} \cdot sur_{n-1,cn} \cdot s_{i,c}
\]

Finally, we multiply the calculated nutrient-specific fertilizer quantities \( (f_{n,c}^{*}) \) with the nutrient-specific prices \( p_{n} \) per unit (LfL, 2018) and add up the costs of all three nutrients in order to achieve the total fertilizer costs for each crop. This is depicted as

\[
c_f = \sum_{n=1}^{N} f_{n,c}^{*} \cdot p_{n}
\]

Beyond fertilizer costs we consider also further yield-dependent variable costs, namely costs for drying and cleaning of the harvest as well as for its transportation. The calculation of these costs \( (c_v) \) per grid-cell are based on crop-specific standardized values by LfL (2018), which are multiplied with the yield data from the YLD model and the crop rotation shares from the LU model. Further variable costs \( c_o \) include costs for seeds, pesticides, machinery and other costs such as insurances. This group of variable costs can be considered as variable costs only depending on the cultivated area as well as an increase on field edges due to overlaps. In our calculations, we use crop specific standardized values per hectare land of each of these costs (LfL, 2018) and multiply it with land use shares from the LU model. Furthermore, a top up on field edges is added following the procedure of fertilizer costs. Our model does not account for natural pest control on field edges next to permanent green edges. The impact of integrating this aspect into our model is displayed in the sensitivity analysis in Appendix C.

2.3.5. Multiple diversity model

Within our multiple diversity (MULTIDIV) model we assess the effects of the different scenarios on biodiversity. Therefore, we use a statistical model derived in a previous study from a dataset from the BiodivERsA project Farmland comprising biodiversity data for multiple species groups collected in 1 × 1 km agricultural landscapes chosen to span uncorrelated gradients of field size, crop diversity and semi-natural habitat (Sirami et al., 2019). The study covered multiple regions across Europe and North America, including Germany. The gradients in field size, crop diversity and semi-natural habitat covered in the present study in the different scenarios are within the range of the observed gradients in the empirical data. An integrative biodiversity indicator, multi-diversity, was calculated as follows: For each taxonomic group
(plants, bees, butterflies, hoverflies, carabid beetles, spiders and birds), species richness was calculated at the landscape level, i.e. across all sampling sites and across all visits when multiple survey visits were conducted. Species richness was standardized for each taxonomic group by centering species richness on its mean and scaling it based on its standard deviation across all regions. The average standardized species richness across all seven taxonomic groups was then computed. The biodiversity data was recorded within crops, both at the centre and the edge of the crops (but not in permanent field borders). The multi-diversity index used here, while being highly integrative, does not consider habitat diversity (see Discussion). Here, to generate multi-diversity predictions we use a model with three explanatory landscape variables that are computed from the land-use and edge rasters in a similar way as they were computed in Sirami et al. (2019). The landscape variables include the crop diversity, computed using the Shannon diversity index, the crop mean field size in hectares and the proportion semi-natural habitat cover in the landscape. Three covariates were set to fixed values. The categorical variable region was set to “Germany”, and the covariates number of crops sampled and the year of sampling, which differed among datasets in the Farmland project, were set to two and 2013, respectively.

2.4. Response variables

In order to present the results of our application on multiple subject areas, we have chosen the following response variables: Firstly, we model the variable multi-diversity score reflecting one of the major ecological effect dimension of the analysed land-use changes. Technically, we derived the variable by calculating the Z-score, representing the standardized species richness across all seven taxonomic groups (plants, bees, butterflies, hoverflies, carabid beetles, spiders and birds). Furthermore, we integrate two variables reflecting farm-private impacts of the analysed land-use changes, namely the agronomic variable oilseed rape (OSR) yield and the economic variable gross margin. The OSR yield is calculated as a total of all OSR fields per landscape as well as per hectare OSR area within the landscape. Similar to this we calculate the total gross margin of all arable area per landscape as well as per hectare arable land. Costs for cultivation of green strips and other semi natural habitats as well as cost and benefits of permanent crops are ignored. In order to calculate the ecological contribution to the agronomic and economic response variables, we furthermore estimate the contribution of insect pollination to OSR yield and gross margins per landscape and hectare repetitively. The description of all variables is presented in Table 1.

2.5. Study region and study landscapes

We execute our analysis in a region with excellent conditions for arable farming. The region is located in northern Bavaria in the surroundings of the city of Würzburg (Germany). From the agricultural point of view the region is characterized by a low precipitation rate (about 600 mm per year), calcareous soils based on Muschelkalk (shell-bearing limestone), comparatively high temperatures (average temperature of 9–10 °C per year) and a for German circumstances long vegetation period (LiU, 2018). Arable land use is predominating, covering approximately 90% of total UAA, with the most ubiquitous crops being winter wheat, sugar beet and barley are cultivated. Farms have an average size of 45 ha and the average field size is approximately 1.5 ha. Animal production consists mostly in fattening pigs. Dairy production is of marginal importance due to the high productivity of arable land and due to the corresponding minor relevance of grassland (StiMELF, 2018). Semi-natural habitats consist mainly of dry calcareous grasslands, abandoned vineyards and (often deciduous) forests.

Natural site conditions and density of permanent semi-natural area vary significantly within the study region. In order to reflect this in our study, we conduct our analysis in 13 study landscapes with a standardized size of 2 × 2 km. As Fig. A-1 in Appendix A shows, the landscapes are broadly spread all over the study region and represent the different site conditions.

The average characteristics of the 13 study landscapes underline the diversity of the landscapes (cf. Table 2): The mean site qualities range from 25 to 63 points, with an average of 47 points and standard deviations between 12 and 21 points. The landscapes’ mean field size ranges from 0.91 to 2.71 ha. Mean field size correlates with the length of field edges, which reach from 57 to 85 km per landscape. The landscapes show diverging shares of arable land, ranging from 60 to 84%. On arable land, mainly cash crops are cultivated, whereas ecological focus areas and legumes have minor importance (both classes altogether between 9 and 29%). Permanent grassland covers between zero and 5%, while cover of permanent crops (in particular vineyards) ranges from zero to 3%. Permanent semi-natural cover differs significantly between landscapes and ranges from 16 to 58%.

2.6. Definition of scenarios

The aim of our study is to measure the impact of green infrastructure density and average field sizes on selected economic and ecological indicators. In order to tease apart effects of increasing field sizes and decreasing permanent edge density we use the concept of counterfactuals.

In order to calculate the effects of increasing field sizes, we simulated a land consolidation process in a manner that is practically applicable and realistic. As consolidation principle, we decided to aim formerging all neighbouring fields, which are not separated by natural or artificial borderlines such as streets, watercourses or ditches, into single large fields. The applied land consolidation approach allows us to consider regional specifications and to shape a fairly realistic land consolidation result. By comparing the resulting structure with the original smaller scaled structure we are able to estimate ecological and economic consequences of a field size increase (cf. Fig. 2).

Beside average field sizes we also vary permanent green edge density. We distinguish three grades, namely high, low and zero permanent

| Table 1 | Description of response variables. |
|---------|-----------------------------------|
| Response variable | Unit(s) | Description of response variable |
| Multi-diversity | Z-score/landscape | Average standardized species richness across all seven taxonomic groups (plants, bees, butterflies, hoverflies, carabid beetles, spiders and birds) |
| OSR yield | €/landscape | The sum (average) of grid-cell specific actual yield of all OSR fields. |
| Gross margin | €/ha arable land | The sum (average) of cell-grid specific gross margins (revenues minus variable costs) of all arable land. |
| Contribution of insect-pollination to OSR yield | dt/ha OSR | The difference between the simulated OSR yield with pollinators and a counterfactual yield with no pollinators. |
| Contribution of insect-pollination to gross margin | €/landscape | The difference between the simulated gross margin with pollinators and a counterfactual gross margin assuming no pollinators. |
edges. In the high-density scenario, all field edges are permanent and green. In the low-density scenario, permanent green edges are restricted alongside block boundaries. And in the zero density scenarios permanent green edges are removed completely.

By combining the two structural changes, we derive five scenarios, reaching from a small-structured landscape with a high density of permanent green edges to a large-structured landscape with no permanent green edges at all (Fig. 3).

Large-structured landscapes have an average field size of 2.93 ha and are therefore twice as large as the original small-structured landscapes (with an average field size of 1.54 ha, Table 3). However, average field sizes in landscapes vary substantially throughout both scenarios: in large-scaled structured scenarios average field size range from 1.61 to 6.56 ha, whereas in small-scaled structured scenarios field sizes range from 0.91 to 2.71.

This distribution of field sizes is presented in Fig. 4, for the small-scaled as well as for the large-scaled scenario. The comparison of the frequency of field sizes between scenarios shows that the simulated field size increase clearly shifts the distribution to the right-hand side. However, also in the large-field scenario most fields are small.

The differences between scenarios are also shown in Table 4 where the length of permanent green edges is displayed for each landscape and permanent green edge density scenario. In the high-density scenario, the average length of permanent field edges is 68 km per landscape. This value drops in the low-density scenario to an average of 49 km per landscape. In the zero density scenario, by definition, permanent green field edges disappear completely.

### 2.7. Sensitivity analysis

Uncertainty is of relevance with regard to several of our assumptions. In order to show the impact of uncertain assumptions on our results we establish a sensitivity analysis on several main parameters. Main criteria for the selection of parameters for sensitivity analysis is, of course, their general importance for the model and the quality of data assumptions based on given literature findings (but where we do not dispose of a sufficient literature basis to make unequivocal assumptions). We selected four parameters, namely the magnitude of yield depression on headlands, the zero yield level in case of missing insect pollination, the width of green edges and a possible influence of natural pest control. All four parameters fundamentally shape our model, but literature basis did not allow to make unequivocal assumptions. The results of this sensitivity analysis are presented in Appendix C.

### 3. Results

#### 3.1. Average results per landscape and hectare UAA

In Figs. 5 and 6 we present the average results of all 13 study landscapes, both at landscape level (respectively the upper parts of the figures) and per-hectare UAA (respectively the lower part of the figures). On landscape level, all results are summed up to the total regional effect and therefore related to the overall area in the respective region. The results per-hectare UAA are obtained by dividing the calculated effects by the area, considering only agriculturally used areas.

### Table 2

Descriptive statistics of selected landscapes.

Source: Own calculations based on IACS-LPIS data.

| Landscape ID | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    | Ø     |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Site quality (pts.) | Mean  | 53    | 44    | 55    | 63    | 50    | 48    | 51    | 43    | 33    | 54    | 44    | 25    | 48    |
|               | SD    | 12    | 19    | 13    | 16    | 15    | 21    | 20    | 19    | 14    | 21    | 15    | 13    | 17    |
| Field size (ha) | Mean  | 2.71  | 1.53  | 0.91  | 1.77  | 1.69  | 1.01  | 1.05  | 1.37  | 1.96  | 1.31  | 1.33  | 2.13  | 1.22  |
|               | SD    | 2.21  | 1.91  | 1.00  | 1.93  | 1.19  | 0.98  | 1.44  | 1.00  | 1.96  | 1.84  | 1.30  | 2.21  | 1.16  |
| Length of field edges (km) | Total | 57    | 72    | 67    | 65    | 67    | 74    | 84    | 66    | 60    | 75    | 85    | 60    | 58    |
| Arable land (%) | Total | 71    | 78    | 62    | 79    | 77    | 68    | 84    | 68    | 68    | 83    | 83    | 74    | 60    |
| Ecological focus area (%) | Total | 9     | 29    | 19    | 12    | 27    | 27    | 18    | 17    | 21    | 16    | 15    | 24    | 23    |
| Perm. grassland (%) | Total | 0     | 2     | 4     | 5     | 1     | 3     | 4     | 1     | 3     | 5     | 1     | 0     | 1     |
| Perm. crops (%) | Total | 0     | 0     | 1     | 0     | 3     | 0     | 1     | 0     | 0     | 0     | 0     | 1     | 1     |
| Perm. semi-nat. cover (%) | Total | 14    | 15    | 20    | 9     | 13    | 16    | 6     | 25    | 21    | 2     | 15    | 6     | 29    |

Fig. 2. Small-scaled structure (left) versus large-scaled structure (right).

Source: Own illustration based on IACS-LPIS data.
In Fig. 5, which shows the absolute values for the scenarios, we further differentiate the overall effect into an insect-pollination induced effect (light grey areas) and into a non-insect-pollination induced effect (dark grey areas).

On landscape level, scenario 1 (S1) results in a biodiversity score of 0.37, an oilseed rape yield of nearly 1200 decitons and a total gross margin of about 92,000 euro (cf. Fig. 5). When the mesh of green edges is reduced (S2) or abolished (S3), biodiversity and oilseed rape yields are slightly smaller, whereas gross margins are higher. The scenario with large fields and a wide mesh of green edges (S4) indicates that field enlargement is widely responsible for biodiversity loss, as its score drops down to 0.22. With regard to oilseed rape yield and gross margins, we find similar results as in S3. The abolishment of green edges in S5 shows again a further small decline of biodiversity, no differences in oilseed rape yield and a further small increase in total gross margins. Furthermore, our results demonstrate that the yield attributable to pollination drops with decreasing permanent green edge density, particularly if permanent green edge density drops to zero as in the scenarios S3 and S5. However, at the landscape scale, the pollination-induced losses are overcompensated by the respective increases of non-pollination-induced oilseed rape yield and gross margins due to the increase in total arable land and field sizes.

On the lower part of Fig. 5 we present our results per hectare UAA. The absolute values of the results are - as expected - generally lower, but the relative differences of the five scenarios for the three output factors show the same tendencies: gross margins are higher in case of large field sizes (S3 and S5), since larger fields allow a more efficient plot cultivation. In addition, the contribution of insect pollination to oilseed rape yield and gross margins are comparatively small in case of zero permanent green edge density. However, in contrast to landscape results this loss of insect-pollination effect is not compensated by an increase of non-pollination induced effects, since the release of arable land due to the reduction of permanent green edge density does not occur on hectare level. This results in higher oilseed rape yields and similar gross margins in scenarios with green edges (S1, S2 and S4).

In Fig. 6 we directly calculate and visualize the effects of a variety of changes in land-use, namely, the reduction of green edges, the enlargement of fields and the combination of both. Again, we firstly present the results on landscape level: The decrease of green edge density from high to low (S1 → S2) shows no effect with regard to all three indicators. The effects become slightly more relevant in case of a total loss of permanent green edges (S1 → S3), in this case biodiversity decreases by 0.03 pts. and oilseed rape yields by 1.5 decitons (dt). In contrast, gross margins clearly increase by almost 2950 euro. However, the main driver of changes is the enlargement of fields (S2 → S4 and S3 → S5). This applies in particular to biodiversity scores, which decrease dramatically. Contrary, oilseed rape yields and gross margins are positively affected by larger field sizes. Whereas the increase in total oilseed rape yields is of lower relevance, total gross margins increase clearly. The two comparisons (S2 → S4 and S3 → S5)
allows us to differentiate between field enlargement effects with and without green edges. The differences between the effects of these two changes are small for biodiversity (−0.15 and −0.17) and gross margins (2600 and 2570 euro) but make a relatively big difference for oilseed rape yields per landscape (4.3 and 7.3 dt).

The final comparison (S1 → S5) summarises the overall results for the complete shift from a small-structured and highly permanent green edge equipped landscape to a comparably large-structured landscape with a total loss of permanent green edges. The total effect on landscape level sums up to a loss of 0.2 biodiversity scores, a small gain of two decitons oilseed rape and an additional gross margin of 5550 Euro.

The lower part of Fig. 6 again demonstrates the effects per hectare UAA. Due to the non-consideration of the increase in arable land released by the elimination of permanent green edges, the resulting effects change in several respects. Oilseed rape yields now clearly decrease by 1.2 dt per ha, which is mainly triggered by the loss of permanent green edges and the concomitant loss of insect pollination. In contrast, overall gross margins slightly increase by eight Euro per ha, which is in particular caused by increasing field sizes.

### 3.2. Case-study specific results

We further analyse our results on case-study level. We focus this analysis on the complete change from a small-structured landscape with a high cover of green edges to a comparatively large-structured landscape with no permanent green edges (S1 → S5, cf. Fig. 3), and analyse the influence of the share of semi-natural habitat on our three main

| Landscape ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | Ø |
|-------------|---|---|---|---|---|---|---|---|---|----|----|----|----|---|
| Length of field edges (km) – high-density scenario | Total | 57 | 72 | 67 | 65 | 67 | 74 | 84 | 66 | 60 | 75 | 85 | 60 | 58 | 68 |
| Length of field edges (km) – low density scenario | Total | 31 | 43 | 46 | 46 | 56 | 52 | 62 | 48 | 46 | 55 | 55 | 47 | 49 | 49 |
| Length of field edges (km) – zero density scenario | Total | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

### Table 4

Total length of permanent green edges in high-, low- and zero-permanent green edge density scenarios.

Source: Own calculations based on IACS-LPIS data.
Fig. 6. Estimation of the effects of simulated land use change (see Fig. 3) on biodiversity (a), oilseed rape yield (b, d) and gross margin (c, e) per landscape (a, b, c) and hectare arable land (d, e): green infrastructure reduction effect (bars 1 and 2), field size increase effect (bars 3 and 4) and overall effects (bar 5).
Source: Own calculations cf. Table A-7.

Fig. 7. The overall effect (comparing scenario 1 with 5, cf. Fig. 3) for biodiversity (a), oilseed rape (osr) yield (b) and gross margin (c) per landscape with regard to share of semi-natural habitat (% of total landscape area). Regression formula and a bold regression line is displayed within the plot, when statistical significant.
Source: Own calculations.
output indicators (biodiversity, oilseed rape yield and gross margins). The influences are analysed by applying bivariate linear regression for each factor and output indicator. Furthermore, we plot a regression line, which is bold when statistical significance is given (Fig. 7).

The case study specific analysis demonstrates that our results are not uniform across case studies, but show a broad variance with regard to all three output-indicators. We observe that the cover of semi-natural habitats in the landscape reduces the effect of agricultural landscape simplification on biodiversity, with similar, but non-significant results being observed for oilseed rape yields. Cover of semi-natural habitats seems to have a negative effect on the change in overall gross margins, a trend that is not significant.

4. Discussion

We conducted the first ecological and economic study of changes in field size and green infrastructure, integrating the economic effects on ecosystem services to the crop and effects on farmland biodiversity. Our results show that green infrastructure, in the form of a network of permanent green edges, plays an important role in supporting wild pollinators that contribute to the yields of mass-flowering crops such as oilseed rape, and increase the farmer’s gross margins. Smaller fields decrease the variability in availability of flower resources from mass-flowering crops, and thus benefit wild pollinators and crop pollination. Economically, however, under current conditions these provided beneficial effects of maintaining smaller fields and permanent green edges are not enough to by themselves outweigh the cost-reducing effects of simulated increased in field sizes and reduction of field margins. Opportunity costs for maintaining small fields are about 19 euro per hectare arable land and therefore fairly small but result in high ecological benefits. This means that a payment of 19 euro per hectare for ecosystem service delivery could make farming in such landscapes with small fields as profitable as with larger fields. Agri-environmental schemes for flowering strips cost about 30 euro per hectare arable land.

Wild pollinators are of substantial economic importance for crops that are dependent fully or partially on insects for pollination (Perrot et al., 2018). High abundances of wild pollinators are conditional on the presence of non-cultivated areas that harbour nesting sites and, when the crops are not flowering, complementary food resources (pollen and nectar). Our results help explain why, in spite of this evidence, measures to mitigate pollinator declines are rarely taken in arable landscapes. In the case-study, as in many other regions, the insect pollinated crops account for ~10% of the agricultural area. These crops are often break crops grown in a rotation with cereals that are not dependent on insect pollination. This means that the benefits of managing the landscape to increase wild pollinators are limited to a small portion of the cropped area at any given point in time. The opportunity costs of having larger areas of the agricultural land devoted to permanent green edges applies to the whole rotation. Of course, our findings may have been different had the mixture of crops grown in the study region been a different one. Indeed, Pywell et al. (2015) find that agri-environmental measures cause yield increases offsetting the costs of setting aside land. However, the effect is largely mediated by the increase in yield of field beans, not of oilseed rape. Grain legume crops, of which several species are dependent on pollinators, cover a large area worldwide (14.5% of arable land) but account for a small percentage of arable land in Europe (1.5%), with common pollinator dependent species such as field beans being concentrated in certain regions, such as the UK or Poland (Watson et al., 2017).

Our simulation study takes as a starting point the current farming system and management patterns, and is not representative of what could be achieved with wider changes in agricultural management and input use. As highlighted above, our results are dependent on the current crop mix, and future increases in the share of field beans or other protein-rich pollinator-dependent crops (Röös et al., 2017) means that conserving landscapes that maintain wild pollinators is important to ensure high future yields. Also, currently, the dependence of arable crop production on ecosystem services is reduced through the high use of inputs. Changes in input use in response to either agri-environmental policy, changes in prices or shortages may substantially increase the need to substitute ecosystem services for inputs. For instance, we may have been underestimating the potential of wild pollinators to contribute to the gross margins, since it has been shown in experiments that reduction in nitrogen fertilization can at least partly be compensated by increased effects of pollination on yield (Marini et al., 2015). Similarly, we chose to ignore the effects of natural control of crop pests, another yield-supporting ecosystem service that benefits from green infrastructure and small field sizes (Bosem Baillod et al., 2017). We motivate this by the current widespread use of insecticides, making natural pest control less relevant, and the very low cost currently associated with pesticide use. Finally, we did not consider technical progress with regard to agricultural mechanisation. Future development in this field might be twofold: On the one hand, future technical development might drive changes towards even larger fields and therefore might be an important factor for further land consolidation. On the other hand, innovations in the field of small unmanned autonomous vehicles might increase the competitiveness of small fields (Aravind et al., 2017; Duckett et al., 2018).

Our simulation study clearly shows the economic-ecological trade-offs in changing agricultural landscapes. Despite positive pollination effects small fields are from an economic point of view unfavourable for farmers. However, simulating increases in field sizes and reductions in permanent green edges that caused increases in gross margins, we could show that such changes would cause large parallel declines in biodiversity at the landscape scale. Maintaining small field structures and permanent green edges is thus of utter relevance from the point of view of society in general, since mitigating the past severe declines of biodiversity, and preventing any further declines, is of public interest and a target of public policy (EC, 2011). We note here that the largest biodiversity effects of the simulated land-use changes were observed with the reduction in field sizes, irrespective of edge structures, while the largest economic opportunity costs lie in the area under permanent green edges, despite these being particularly important for supporting pollination of the crops (Fig. Sb and d). Further aspects, not considered here, are effects of green infrastructure and field size on other environmental and social aspects, such as water quality or the aesthetics of cultural landscapes, as well as social consequences both within the farming communities and at the interface of farming and the wider society.

Integrating public good effects into our economic calculations would shift results towards a more positive balance with regard to maintaining small structured landscapes. However, in this case we have to consider that our calculations would clearly go beyond private considerations. Farmers’ willingness to accept such changes despite a positive economic balance would be small. Consequently, our results confirm that the maintenance of small-structured and well-endowed landscapes cannot be based on private incentives solely, even when taking into account biodiversity-based ecosystem services to crops. Policy is necessary to bridge this gap. This may take the form of regulations obliging farmers to maintain green infrastructure and small field sizes. However, such an approach will reduce economic margins of farmers and may subsequently lead to abandonment in areas where the land-use is too fragmented for farming to be economical. Thus, policy measures for maintaining biodiversity in agricultural areas clearly have to consider local socio-economic conditions and should motivate farmers to contribute and to actively bring in their local knowledge. Consequently, it is advisable to use economic incentives or other

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3 Division of the average overall effect (comparing scenario 1 with 5) for gross margin (5500 Euro) by the average extent of arable land per landscape (292 ha). The latter is calculated as the average share of arable land (73%) of the landscape size (440 ha) (cf. Table 2).

4 It is assumed that flowering strips cover about 5% of arable land.
instruments actively involving and motivating farmers in maintaining green infrastructure and small field sizes. A potential caveat is that while the simulated landscape changes we conducted were assumed to be not only achievable, but also at no costs to the farmers, reality is different. While it might be straightforward in many cases to physically increase the scale of fields, this may be less easy in practice where the reason for small field sizes is the fragmentation of land ownership. Indeed, land consolidation projects are time-consuming processes that can take 10 years or more, and the land market, through which farmers could in principle constantly consolidate the land, is imperfect. While we do not have land ownership data for the landscapes on which we applied the simulations, high fragmentation of land ownership is the rule in the region, and likely a major reason for the small current field sizes. The extent of past changes in field sizes globally, including Europe (White and Roy, 2015), does suggest that over longer time periods field sizes can be expected to increase, despite such obstacles, and that our findings are therefore relevant to ongoing processes.

Further developments of the model have the potential to further increase its applicability for decision-making. Firstly, it is to recommend to integrate stochasticity into the model in order to improve the ability of the model to deal with uncertainties, which are obviously given in such complex economic and ecological interrelations. Secondly, it is to aim to set up the model as a multi-periodic dynamic model; this would allow to model changeover steps of farms in a realistic manner and would thus allow to develop the model as a concrete decision-support tool for farmers and policy. Furthermore, it is to recommend to broaden in future studies the analysis of private benefits of farmers gained from small-scaled landscapes well-endowed with permanent green edges by taking into account further ecological services beyond pollination, e.g. by considering natural pest control effects of predation.

5. Conclusions

Maintaining small fields and permanent green edges in arable-dominated landscapes are essential for supporting biodiversity in farmland. The significance of small fields, not only for biodiversity, but also for ecosystem services to the crop emerges from our results based on a mechanistic model for pollinators and pollination services to the crops. However, we find major economic-ecological trade-offs in conserve field margins and fine-grained arable landscapes, trade-offs that are not resolved by considering biodiversity-based ecosystem services to arable crops. This is because currently, both in the study region and in Europe more generally, insect-pollinated crops often contribute small fractions of the overall margin in arable farming. Field size is an underestimated mediator of ecological-economic trade-offs between biodiversity and gross margins that is currently to little considered within agri-environmental policy. The main driver of the trade-offs is costs, both in terms of opportunity costs of not taking permanent green edges into production, and in terms of increased inputs required to farm small fields. This suggests that to maintain fine-grained agricultural landscapes with permanent green edges, incentives to farmers are necessary, as well as innovations that allow to farm small fields at lower costs. Our findings are conditional on other ecosystem services mediated by the landscape-scale land-use playing a minor role. We thus expect that for production systems that rely mainly on natural pest control, such as organic crop production, the ecological-economic trade-offs implied by changes in field sizes and density of permanent edges would be different.

Declaration of competing interest

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

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Appendix A. Study region

![Fig. A-1. Location of the selected landscapes around the city of Würzburg (Germany). Source: Own illustration based on Apple map © Apple Inc.](image)
# Appendix B. Result tables

Table A-1  
Results and descriptive variables of the multidiversity model for different Scenarios.  
Source: Own calculations.  

| Scenario | Average Z-score | Crop_SHDI$^1$ | Crop_MFS$^2$ | Seminatural habitat (% of total landscape area) | Length of permanent green edges (m) |
|----------|-----------------|---------------|--------------|-----------------------------------------------|-----------------------------------|
| S1       | 0.37            | 1.47          | 1.54         | 17.50                                         | 68,432                            |
| S2       | 0.37            | 1.47          | 1.54         | 17.26                                         | 48,942                            |
| S3       | 0.34            | 1.47          | 1.54         | 14.81                                         | 0                                 |
| S4       | 0.22            | 1.44          | 2.93         | 17.26                                         | 48,942                            |
| S5       | 0.17            | 1.44          | 2.93         | 14.81                                         | 0                                 |

Table A-2  
Average oilseed rape yield per landscape and hectare arable land model for different Scenarios (in decitons).  
Source: Own calculations.  

| Scenario | Total | Contribution of insect-pollination |
|----------|-------|-----------------------------------|
|          | Per landscape | Per hectare oilseed rape | Per landscape | Per hectare oilseed rape |
| S1       | 1105.26     | 32.62                          | 102.99        | 3.2                     |
| S2       | 1105.08     | 32.50                          | 99.48         | 3.08                    |
| S3       | 1103.79     | 31.41                          | 62.99         | 1.94                    |
| S4       | 1109.34     | 32.51                          | 81.68         | 2.33                    |
| S5       | 1111.12     | 31.53                          | 47.38         | 1.3                     |

Table A-3  
Average economic results per landscape model for different Scenarios (in euro).  
Source: Own calculations.  

| Scenario | Revenues | Fertilizer costs | Yield-depending variable costs | Other variable costs | Gross margin |
|----------|----------|-----------------|-------------------------------|----------------------|--------------|
| S1       | 375,770  | 82,808          | 25,696                        | 175,325              | 91,941       |
| S2       | 376,955  | 83,053          | 25,781                        | 175,899              | 92,222       |
| S3       | 388,666  | 85,504          | 26,617                        | 181,654              | 94,892       |
| S4       | 378,120  | 83,056          | 25,907                        | 174,329              | 94,828       |
| S5       | 389,854  | 85,544          | 26,744                        | 180,105              | 97,462       |

Table A-4  
Average economic results per hectare arable land (in euro).  
Source: Own calculations.  

| Scenario | Revenues | Fertilizer costs | Yield-depending variable costs | Other variable costs | Gross margin |
|----------|----------|-----------------|-------------------------------|----------------------|--------------|
| S1       | 1320     | 291             | 90                            | 618                  | 321          |
| S2       | 1320     | 291             | 90                            | 617                  | 321          |
| S3       | 1317     | 290             | 90                            | 616                  | 321          |
| S4       | 1323     | 291             | 90                            | 612                  | 330          |
| S5       | 1321     | 290             | 90                            | 611                  | 330          |
**Table A-5**
Contribution of insect-pollination to the average economic results per landscape model for different Scenarios (in euro).
Source: Own calculations.

| Scenario | Revenues | Fertilizer costs | Yield-depending variable costs | Other variable costs | Gross margin |
|----------|----------|------------------|-------------------------------|----------------------|--------------|
| S1       | 3843     | 833              | 196                           | 0                    | 2813         |
| S2       | 3712     | 805              | 190                           | 0                    | 2716         |
| S3       | 2350     | 518              | 121                           | 0                    | 1712         |
| S4       | 3047     | 660              | 156                           | 0                    | 2232         |
| S5       | 1767     | 388              | 91                            | 0                    | 1290         |

**Table A-6**
Contribution of insect-pollination to the average economic results per hectare arable land model for different Scenarios (in euro).
Source: Own calculations.

| Scenario | Revenues | Fertilizer costs | Yield-depending variable costs | Other variable costs | Gross margin |
|----------|----------|------------------|-------------------------------|----------------------|--------------|
| S1       | 14       | 3                | 1                             | 0                    | 10           |
| S2       | 14       | 3                | 1                             | 0                    | 10           |
| S3       | 9        | 2                | 0                             | 0                    | 6            |
| S4       | 11       | 2                | 0                             | 0                    | 9            |
| S5       | 7        | 2                | 0                             | 0                    | 5            |

**Table A-7**
Estimation of the effects of simulated land use change (cf. Fig. 3) on biodiversity (1), oilseed rape-yield (2,3) and gross margin (4,5) per landscape (1,2,4) and hectare arable land (3,5); green infrastructure reduction effect (comparing S1 with S2; S1 with S3), field size increase effect (Comparing S2 with S4; S3 with S5) and overall effects (Comparing S1 with S5).
Source: Own calculations.

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Average Z-score | Oilseed rape yield (in decitons) | Gross margin (in euro) |
| Per landscape | Per hectare oilseed rape | Per landscape | Per hectare arable land |
| Comparing S1 with S2 | 0.00 | −0.18 | −0.11 | 280.49 | −0.03 |
| Comparing S1 with S3 | −0.03 | −1.47 | −1.21 | 2950.68 | −0.08 |
| Comparing S2 with S4 | −0.15 | 4.26 | 0.01 | 2606.13 | 8.58 |
| Comparing S3 with S5 | −0.17 | 7.32 | 0.12 | 2570.00 | 8.73 |
| Comparing S1 with S5 | −0.20 | 5.65 | −1.09 | 5520.68 | 8.66 |

**Appendix C. Sensitivity analysis**

As a final step in the result section, we establish a sensitivity analysis with regard to four major parameters, which are of central importance in our model. These factors are the magnitude of yield depression on headlands, the zero yield level in case of missing insect pollination, the width of green edges and a possible influence of natural pest control. Fig. A-2 presents the effect of the variation of the four factors on the calculated extent of our three output indicators. Again, we focus our analysis on our main research question, the complete change from a small-structured and highly permanent green edge equipped landscape to a comparably large-structured landscape with no permanent green edges (S1 → S5, cf. Fig. 3) and analyse the impact of a variation of the three parameters on the modelled differences between these two scenarios.

The first sensitivity analysis concerns the yield depression on headlands. Literature shows a broad agreement on the existence of such an effect, but also underlines the broad range from 5 to 50% of yield depression the effect can take (Brunotte et al., 2000; Keymer et al., 1989; Klare et al., 2005). The sensitivity analysis shows that variation of our 30% yield depression assumption does partly influence our overall results (cf. Table A-8). The assumption has no effect on biodiversity scores, but it slightly influences oilseed rape yields: an increasing headland yield-depression factor causes an increasing oilseed rape yield effect per landscape. Appropriately, a decreasing headland yield-depression factor leads to a decreasing oilseed rape yield effect, which even shifts an initially positive oilseed-rape yield effect to a negative one. However, taking into account the total absolute yield level of more than 1.000 decitons per landscape it gets clear that these variations are of minor importance. With regard to gross margins we observe a similar pattern. Increasing headland yield depressions leads to increasing gross-margin effects and vice versa. Nevertheless, the detected gross-margin difference stays positive within the analysed range of variation. Again, we have to consider that total gross margins per landscape are about 100,000€. Therefore, we can conclude that the identified variations are of significant importance, but are not fundamentally challenging our results.
Fig. A-2. Changes in overall effect (comparing scenario 1 with 5, cf. Fig. 3) on biodiversity (a, d, g, j), oilseed rape yield (b, e, h, k) and gross margin (c, f, i, l) per landscape when the parameters edge effect (a, b, c), zero pollination (d, e, f), permanent green edge width (g, h, i) and the pest control costs on field edges are changed. The scale for edge effect ranges from 0% to 50%, for zero insect pollination from 70 to 85% (intermediate pollination values are changed simultaneously), for permanent green edge width from 0 to 10 m and for pest control costs from 0 to −80%.

Source: Own illustrations.

The second sensitivity analysis concerns the zero insect-pollination rate. In our model calculations we assumed that the zero insect-pollination yield level reaches 79% of a perfectly insect-pollinated oilseed rape. However, literature also discusses higher and lower zero pollination rates (Hudewenz et al., 2014). However, our sensitivity analysis shows that the variation of this factor is of minor importance for our results (cf. Table A-9): As expected, we do not observe any impact on biodiversity scores. But also the impact on oilseed rape yield (where we observe a slight decrease) and achieved gross margin is very small and largely negligible, so that we consider our results with regard to this factor as robust.

The third sensitivity analysis deals with the assumed width of the green edges. In our study we assumed a standardized edge width of 4 m for broad permanent green edges (1 m for narrow permanent edges). Within the sensitivity analysis this parameter is altered in 2 m steps towards 10 and 0 m. The results show that these changes have an impact on all three output indicators (cf. Table A-10): Green edge width variation also has an impact on the negative biodiversity score effect, which rises when green edges are broadened and drops when it is narrowed. With regard to oilseed rape yield, the results of the sensitivity analysis show that a variation of green-edge width leads to an increase irrespective of the variation direction. This makes clear that our assumption of a 4 m green-edge width leads to the smallest effects on oilseed rape yield possible. However, again it is to note that detected changes are in comparison to the absolute yield level of minor importance. With regard to total gross margin, as expected we observe increasing effects with increasing green-edge width and decreasing effects with decreasing green-edge width.

As our model does not account for the ecosystem services of natural pest control, we apply another sensitivity analysis to analyse this topic. As natural pest control most probably occurs next to permanent green field edges, we decrease the costs for chemical pest control on edge grid-cells from 0% to −80% (cf. Table A-11). As expected, this variation does not influence the biodiversity score nor the oilseed rape yield, but it shows a high impact on gross margin results. The positive gross margin per landscape effect is reduced towards zero with a reduction of 64% in pest control costs and below zero at 80%. Thus, the results of this sensitivity analysis indicates a high economic potential of natural pest control for farming within small-structured landscapes.

Table A-8
Changes in overall effect (comparing scenario S1 with S5, cf. Fig. 3) on biodiversity, oilseed rape yield and gross margin per landscape when the parameter edge effect is altered.

Source: Own calculations.

| Yield depression on headlands (%) | Average Z-score | Oilseed rape yield per landscape (in decitons) | Gross margin per landscape (in euro) |
|----------------------------------|----------------|-----------------------------------------------|-----------------------------------|
| 0                               | −0.20          | −3.58                                         | 506.92                            |
| 10                              | −0.20          | −0.43                                         | 2178.17                           |
| 20                              | −0.20          | 2.71                                          | 3849.43                           |
| 30                              | −0.20          | 5.85                                          | 5520.68                           |
| 40                              | −0.20          | 9.00                                          | 7191.93                           |
| 50                              | −0.20          | 12.14                                         | 8863.19                           |

Table A-9
Changes in overall effect (comparing scenario S1 with S5, cf. Fig. 3) on biodiversity, oilseed rape yield and gross margin per landscape when the parameter zero-pollination value is altered.

Source: Own calculations.

| Zero-pollination value (%) | Average Z-score | Oilseed rape yield per landscape (in decitons) | Gross margin per landscape (in euro) |
|----------------------------|----------------|-----------------------------------------------|-----------------------------------|
| 0.7                        | −0.20          | 6.29                                          | 5532.79                           |
| 0.73                       | −0.20          | 6.14                                          | 5528.56                           |
| 0.76                       | −0.20          | 5.99                                          | 5524.52                           |
| 0.79                       | −0.20          | 5.85                                          | 5520.68                           |
| 0.82                       | −0.20          | 5.72                                          | 5517.01                           |
| 0.85                       | −0.20          | 5.59                                          | 5513.50                           |

5 The width of narrow permanent edges is altered simultaneously in half-meter steps.
Table A-10
Changes in overall effect (comparing scenario S1 with S5, cf. Fig. 3) on biodiversity, oilseed rape-yield and gross margin per landscape when the parameters permanent green edge width is altered.

Source: Own calculations.

| Permanent green edge width (m) | Average Z-score | Oilseed rape yield per landscape (in decitons) | Gross margin per landscape (in euro) |
|-------------------------------|----------------|---------------------------------------------|----------------------------------|
| 0                             | –0.17          | 0.11                                        | 8.73                             |
| 2                             | –0.18          | –0.49                                       | 8.65                             |
| 4                             | –0.20          | –1.09                                       | 8.66                             |
| 6                             | –0.21          | –1.66                                       | 8.89                             |
| 8                             | –0.22          | –2.17                                       | 9.49                             |
| 10                            | –0.24          | –2.64                                       | 10.44                            |

Table A-11
Changes in overall effect (comparing scenario S1 with S5, cf. Fig. 3) on biodiversity, oilseed rape-yield and gross margin per landscape when the parameter variable costs due to lower pest control applications is altered.

Source: Own calculations.

| Change in pest control costs (%) | Average Z-score | Oilseed rape yield per landscape (in decitons) | Gross margin per landscape (in euro) |
|---------------------------------|----------------|---------------------------------------------|----------------------------------|
| 0                               | –0.2           | 5.85                                        | 5528.16                           |
| –16                             | –0.2           | 5.85                                        | 4175.71                           |
| –32                             | –0.2           | 5.85                                        | 2823.26                           |
| –48                             | –0.2           | 5.85                                        | 1470.81                           |
| –64                             | –0.2           | 5.85                                        | 118.36                            |
| –80                             | –0.2           | 5.85                                        | –1234.09                          |

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Source: Own calculations.

| Change in pest control costs (%) | Average Z-score | Oilseed rape yield per landscape (in decitons) | Gross margin per landscape (in euro) |
|---------------------------------|----------------|---------------------------------------------|----------------------------------|
| 0                               | –0.2           | 5.85                                        | 5528.16                           |
| –16                             | –0.2           | 5.85                                        | 4175.71                           |
| –32                             | –0.2           | 5.85                                        | 2823.26                           |
| –48                             | –0.2           | 5.85                                        | 1470.81                           |
| –64                             | –0.2           | 5.85                                        | 118.36                            |
| –80                             | –0.2           | 5.85                                        | –1234.09                          |

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Source: Own calculations.

| Change in pest control costs (%) | Average Z-score | Oilseed rape yield per landscape (in decitons) | Gross margin per landscape (in euro) |
|---------------------------------|----------------|---------------------------------------------|----------------------------------|
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| –16                             | –0.2           | 5.85                                        | 4175.71                           |
| –32                             | –0.2           | 5.85                                        | 2823.26                           |
| –48                             | –0.2           | 5.85                                        | 1470.81                           |
| –64                             | –0.2           | 5.85                                        | 118.36                            |
| –80                             | –0.2           | 5.85                                        | –1234.09                          |
