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Optimizing land-use strategies to improve grassland multifunctionality

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ABSTRACT

We investigate the effect of spatial land-use intensity allocation, policies, and risk on the expected utility derived from grassland multifunctionality (i.e., bundles of ecosystem services) and optimal land-use strategies. The considered policies stipulate various minimum shares of extensive grasslands and can be implemented at the farm or landscape level. Based on comprehensive survey data from Swiss permanent grasslands, we find that risk decreases expected utility from multifunctionality. Using an integer programming approach shows that optimizing land-use strategies at the landscape level would increase expected utility from multifunctionality. Hence, implementing policies at the landscape level can help increase policy effectiveness and multifunctionality.

1. Introduction

The demand for increasing the sustainability of agricultural production is a global priority in policy agendas (Baylis et al., 2022; EBP, 2022; Pannell and Rogers, 2022; Pe'er et al., 2022). When designing policies to influence farmers' land-use decisions, it is crucial to consider a wide range of ecosystem services. This is particularly relevant for managed grasslands, which cover a large proportion of global agricultural land and provide many ecosystem services, such as forage supply, carbon storage, erosion prevention, landscape aesthetics, and wildlife habitats (Bengtsson et al., 2019; Buisson et al., 2022; Sandström et al., 2022; Suttie et al., 2005). The land-use intensity of these grasslands—often assessed via the number of cuts, grazing intensity, and fertilization rates (Blüthgen et al., 2012)—is decisive in the supply of those services (Allan et al., 2015; Le Clec'h et al., 2019; Van Vooren et al., 2018). Therefore, policies influencing grassland management intensity are a crucial entry point to achieving agri-environmental policy goals.

The influence of policies on various ecosystem services can be assessed using multifunctionality indices (hereafter referred to as *multifunctionality*) (Manning et al., 2018), which combine different ecosystem services into one indicator value and account for stakeholders' preferences for different ecosystem services (Allan et al., 2015; Hector and Bagchi, 2007; Linders et al., 2021; Neyret et al., 2021; Neyret et al., 2023; Wolff et al., 2015). From the perspective of policymakers and farmers, multifunctionality is stochastic, for example, due to variability in weather, pest pressure, and responses to land-use changes (Dormann et al., 2008; Le Clec'h et al., 2019; Richter et al., 2021; Socher et al., 2012). This stochasticity can pose risks to policymakers and farmers in realizing agri-environmental goals and influence the expected utility of policies that target farmers' land-use decisions (Brunner et al., 2017; Derissen and Quaas, 2013; Iyer et al., 2020; Polasky et al., 2011). Following the economic literature, we define risk as any outcome that is not known for sure ahead of time, but (some) information about the probabilities of the outcome is known (Chavas, 2004). Thus, risk represents an increased uncertainty of (future) outcomes, and reducing risk can have value for decision makers.[1] Consequently, both the expected level of multifunctionality and the associated risk play a role in designing policies targeting land-use change to improve agri-environmental performance.

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[1] Definitions of risk can deviate from the one we used in our study. For example, in their threat assessment of ecosystem services, Maron et al. (2017) defined risk as "the chance that the level of ecosystem service supply will be inadequate to meet demand or will cease completely within a set time horizon."

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Taking into account both multifunctionality and the associated risk when determining optimal land-use strategies and designing measures to promote ecosystem services related to land-use intensity is important because farmers and policymakers (as well as other stakeholders) are generally risk averse (Boucher and Bramoullé, 2010; Derissen and Quaas, 2013; Falk et al., 2018; Iyer et al., 2020). Thus, they care about increasing expected outcomes and reducing risk.

Risk aversion could lead to the decision to postpone the introduction of policy measures, for example, because the uncertainty of reaching the policy target is too high. Moreover, policymakers want their measures to create value added for stakeholders, implying that stakeholders have an incentive to reduce the risk of the supply of multifunctionality in the area in which they live. Therefore, information on the expected level and the risk of multifunctionality supply of different distributions of land-use intensities can support policymakers in designing and evaluating land-use policies that aim to influence farmers' land-use decisions. To our knowledge, this has been addressed only by one study on forest planning and two ecosystem services using the risk measure of value-at-risk (Eyvindson et al., 2018).

Furthermore, optimizing land use and implementing related policies at the landscape level instead of the farm level can increase multifunctionality (Engel, 2016; Huber et al., 2022) and reduce risks. This is because of the supply and riskiness of single ecosystem services, and thus, multifunctionality can differ in space due to differences in environmental conditions (Allan et al., 2015).

Studies investigating optimal land-use strategies and their responses to different policy and climate scenarios have used various methodological approaches in their simulation models to identify optimal land uses for ecosystem services. Previous studies that focused on managed grassland often relied on repeated random assignment of parcels to different land-use intensities (Huber et al., 2022; Neyret et al., 2021; Neyret et al., 2023), rather than employing an optimization model. However, not using an optimization model might exclude optimal solutions and limit advice to decision makers. By contrast, other studies investigating optimal land use for different ecosystem services of forests and agricultural land (including extensive grasslands) have used optimization models (such as (mixed) integer linear models) to identify optimal land-use strategies (Eyvindson et al., 2018; Eyvindson et al., 2023; Triviño et al., 2017) and their response to different climatic (Karner et al., 2021) or conservation scenarios (Pennington et al., 2017; Uthes et al., 2010). However, these optimization studies considered only a few (usually two to three) ecosystem services in their models (with the exception of Law et al. 2017).[2] This is an important limitation because (i) considering multiple services can change tradeoffs and synergies between services as well as multifunctionality optima (Pennington et al., 2017), and (ii) policymakers need to design measures that can meet the diverse preferences of different stakeholders for different ecosystem services (Peter et al., 2022).

We build on the existing literature and contribute to it by investigating four research questions (RQ). In what follows, we present the questions and how we address them.

RQ1: How much does the expected utility from multifunctionality decrease when accounting for risk? To this end, we initially develop a new risk-adjusted multifunctionality indicator that integrates risk[3] into the multifunctionality assessment based on expected utility theory. We then assess the actual importance of risk in this assessment in our study region.

We parameterize the risk-adjusted multifunctionality for a topographically heterogeneous region in Switzerland, whose agricultural area is dominated by different permanent grassland types, which can be categorized as extensive versus intensive management. Our parameterization uses a comprehensive field survey dataset comprising detailed information on six ecosystem services and agricultural land management. These six ecosystem services belong to all three categories of ecosystem services: provisioning, regulating, and cultural services (Haines-Young and Potschin, 2018).

RQ2: How do varying minimum shares of extensive grassland required at the farm level influence the maximum supply of risk-adjusted multifunctionality? Such required minimum shares of grasslands under extensive land use reflect farm-level cross-compliance regulations that exist in Switzerland and other European countries (Huber et al., 2024; Meyer et al., 2014). Thus, answering this question provides insights into how a change in cross-compliance requirements can influence multifunctionality.

For this analysis, we use farm census data containing information from 17,834 parcels and an integer programming optimization approach, allowing us to identify optimal land-use strategies.

RQ3: What gains in risk-adjusted multifunctionality can be expected when the minimum shares of extensive land-use strategies are implemented at the landscape rather than the farm level? By answering this question, we assess the potential multifunctionality benefits of organizing cross-compliance regulations in the study region at the landscape level instead of the farm level (the latter reflects current practices). We implement this analysis by simulating the scenario of RQ2, both at the farm and landscape levels.

RQ4: What is the optimal share of extensive grassland to maximize risk-adjusted multifunctionality at the landscape level? This provides insights for policymakers regarding the level of extensive grasslands in the study region that would provide the highest risk-adjusted multifunctionality and whether this deviates from current levels.

We address this question following the same approach as in RQ2 but with predefining an extensive grassland share instead of setting a minimum one. We note that our results should be viewed as illustrations of potential outcomes, given the assumptions outlined in the model.

We focus on Switzerland and differentiate the land-use intensity of grasslands by extensive versus intensive management when addressing all four RQs. This research setting is particularly relevant for policymaking for multiple reasons. First, permanent grasslands in Switzerland are highly important for delivering ecosystem services (Le Clec'h et al., 2019). Second, cross-compliance requirements, which require a minimum share of extensive land use, are a key element of Swiss agricultural policy (Huber et al., 2024; Swiss Federal Council, 2023). Third, the differentiation between extensive and intensive land use (i) serves as a binary decision variable in many agricultural policies (e.g., Klaus et al., 2023; Panassiti et al., 2023; Swiss Federal Council, 2023), (ii) is key in predicting ecosystem service supply (Richter et al., 2024), and (iii) is often known to decision makers at large spatial scales.

The rest of the paper is structured as follows. In Section 2, we develop an economic model that describes how to include risk in policymakers' landscape management strategies. Section 3 presents the study area and data. Section 4 lays out our empirical analysis. Section 5 presents the results. We discuss and conclude our findings in Sections 6 and 7.

2. Economic model

In this section, we present a stylized microeconomic model that (i) highlights the importance of considering risks in ecosystem service supply when policymakers evaluate and design policies to influence farmers' decisions about land-use intensity and (ii) shows how risk can be taken into account in the assessment of multifunctionality, applying an economic concept.

We consider that policymakers are risk-averse and that they maximize utility, U, based on the expected multifunctionality, $\hat{\mu}$, and the variance of the multifunctionality, γ^2, when developing land-use stra-

[2] Law et al. (2017) used an integer programming approach to estimate the production possibility frontiers considering different land management strategies and multiple ecosystem services in Indonesian forest landscapes.

[3] Note that we focus here on risk as defined above, and not on risk that, for example, could lead to the collapse of ecosystems (see, e.g., Maron et al., 2017).

tegies:

$$\max U(\hat{\mu}, \gamma^2) \tag{1}$$

Further, we assume that the functional form of the utility function is lognormal (Hardaker et al., 2015), implying constant relative risk aversion. Thus, *ceteris paribus*, a higher "wealth" (here in terms of multifunctionality per parcel) reduces the risk for a decision maker. Furthermore, we assume that policymakers maximize the expected utility from land use by maximizing the certainty equivalent, *CE* (Binder et al., 2018):

$$\max CE = \max\left(\hat{\mu}\left(1 + \frac{\gamma^2}{\hat{\mu}^2}\right)^{-\frac{r}{2}}\right) \tag{2}$$

where r is the relative risk aversion coefficient.

The certainty equivalent refers to the minimum certain (i.e., guaranteed) amount of money that a decision maker would consider as equally desirable as an uncertain amount of money (Hardaker et al., 2015). Importantly, throughout our study, the certainty equivalent is measured in multifunctionality (rather than in money), and we refer to it later on as *risk-adjusted multifunctionality*.

Furthermore, from the certainty equivalent and the expected multifunctionality supply, we can compute the cost of risk bearing, the so-called risk premium, *RP*, by taking the difference:

$$RP = \hat{\mu} - CE \tag{3}$$

Multifunctionality is an indicator comprising different ecosystem services, y. When computing multifunctionality, policymakers can consider that stakeholders attach ratings, i.e., weights, to different ecosystem services (Peter et al., 2022), representing the demand for the ecosystem services (Neyret et al., 2023). Hence, multifunctionality can be calculated as (Neyret et al., 2023):

$$\mu = \sum_{j=1}^{m} \sum_{i=1}^{n} y_{ji} p_i \tag{4}$$

where μ is the multifunctionality, m and n the number of parcels in a landscape and services, respectively, and y_{ji} is the supply of ecosystem service i on parcel j. p_i is the average weight attributed to ecosystem service i across stakeholder groups. μ allows for substitution between ecosystem services and does not require minimum thresholds for any ecosystem service supply.

To account for the different parcel sizes, a_j, the index needs to be modified to:

$$\mu = \sum_{j=1}^{m} \sum_{i=1}^{n} y_{ji} p_i a_j \tag{5}$$

The expected multifunctionality, $\hat{\mu}$, and its variance (thus its risk), γ^2, depend on the land-use intensity level (i.e., extensive vs. intensive) of the permanent grasslands, z_j, as well as land and other management characteristics (e.g., meadow (predominantly mown) versus pasture (predominantly grazed) and organic vs. conventional farming), X_j. Using this information, we can compute the expected risk-adjusted multifunctionality, M, resulting from land-use strategies:

$$\mathrm{M} = \sum_{j=1}^{m} \sum_{i=1}^{n} \left(\hat{y}_{ji}\left(1 + \frac{\sigma_{ji}^2}{\hat{y}_{ji}^{\,2}}\right)^{-\frac{r}{2}}\right) p_i a_j \tag{6}$$

where $\hat{y}_{ji}$ and σ_{ji}^2 is the expected supply and variance, respectively, of ecosystem service i on parcel j. Thus, the higher the risk-adjusted multifunctionality, the higher the utility for risk-averse policymakers.

Focusing on a binary decision variable of land-use intensity (i.e., extensive or intensive management) is highly attractive for a number of reasons. First, the binary land-use intensity choice is currently a key land-use definition in many agri-environmental policies, such as in Switzerland or Germany (e.g., Klaus et al., 2023; Panassiti et al., 2023; Swiss Federal Council, 2023). Second, if spatially explicit large-scale information on land use intensity is available to policymakers, this information is usually relatively coarse and mainly represents the two above-mentioned levels. Third, extensive versus intensive grassland management (as defined in our study) is decisive for the supply of ecosystem services (Richter et al., 2024). Fourth, we recognize that using a binary choice variable for land-use intensity may overlook the full heterogeneity of grassland management, introducing additional uncertainty for decision makers regarding the supply of multifunctionality. However, our modeling approach considers this by focusing on risk-adjusted multifunctionality.

3. Data

We utilize three different data sources to parametrize and scale up the risk-adjusted multifunctionality: (i) measured plot-level information about ecosystem service supply from field surveys, (ii) spatially explicit farm-level data and parcel-specific management information from agricultural census data, (iii) spatially explicit land characteristics information from geo-referenced administrative data, and (iv) information about ecosystem service relevance from an online stakeholder survey (Fig. 1). In this study, we use *parcel* to refer to the area managed by farmers (which can have different sizes), while we use *plot* to refer to a standardized area used for measuring ecosystem services in the field.

3.1. Study region

Our case study region is the canton of Solothurn (Fig. 2) and is representative of the dominant grassland types and land-use intensities in large parts of Switzerland. Solothurn's agriculture is dominated by permanent grassland, which covers two-thirds of the Swiss agricultural area (Le Clec'h et al., 2019). Moreover, this canton is characterized by a heterogeneous landscape, encompassing intensively managed lowlands (400–550 m a.s.l.) dominated by arable land and permanent grassland in the southwest and a mountainous region (up to 1445 m a.s.l.) dominated by permanent grasslands and large forests in the northeast (Fig. 2).

3.2. Plot-level data for parametrization of ecosystem service supply

In our study, we focus on managed permanent grasslands, defined as grasslands that were not included in a crop rotation for at least six years.[4] Specifically, we study the four most frequent types of permanent grassland: (i) extensively managed unfertilized meadows, (ii) extensively managed unfertilized pastures, (iii) intensively managed meadows, and (iv) intensively managed pastures. Meadows are predominantly mown, whereas pastures are predominately grazed.

This categorization of grassland management covers a wide gradient in land-use intensity, ranging from unfertilized to intensively fertilized and frequently defoliated grasslands, which is representative of other parts of Central Europe (Blüthgen et al., 2012). To receive direct payments in Switzerland, farmers need to have at least 7 % of their utilized agricultural area (i.e., grasslands and arable land) as ecological focus areas, which include, among others, litter meadows, extensive arable habitats, and *extensive grasslands* (Swiss Federal Council, 2023). Areas considered extensive grasslands have restrictions such as no fertilization and a late cut of meadows, which are required by the Swiss direct payment ordinance. For intensive grasslands, farmers are free to choose

[4] The plot-level data have been gathered by Richter et al. (2024).

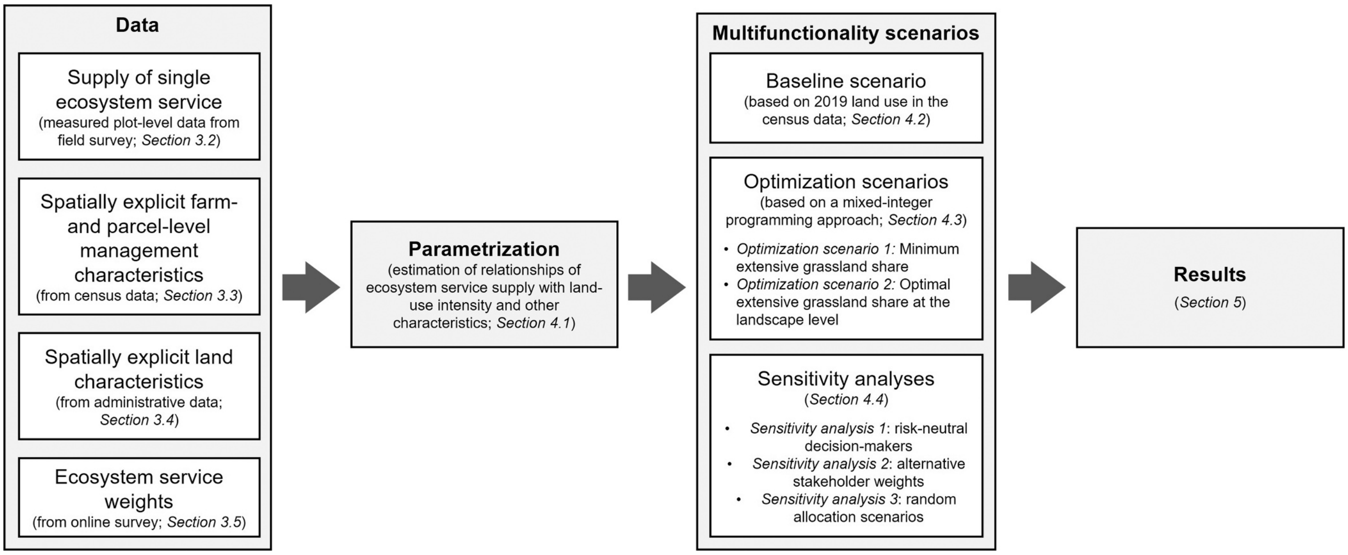

Fig. 1. Schematic overview of our data sources and the empirical analysis.

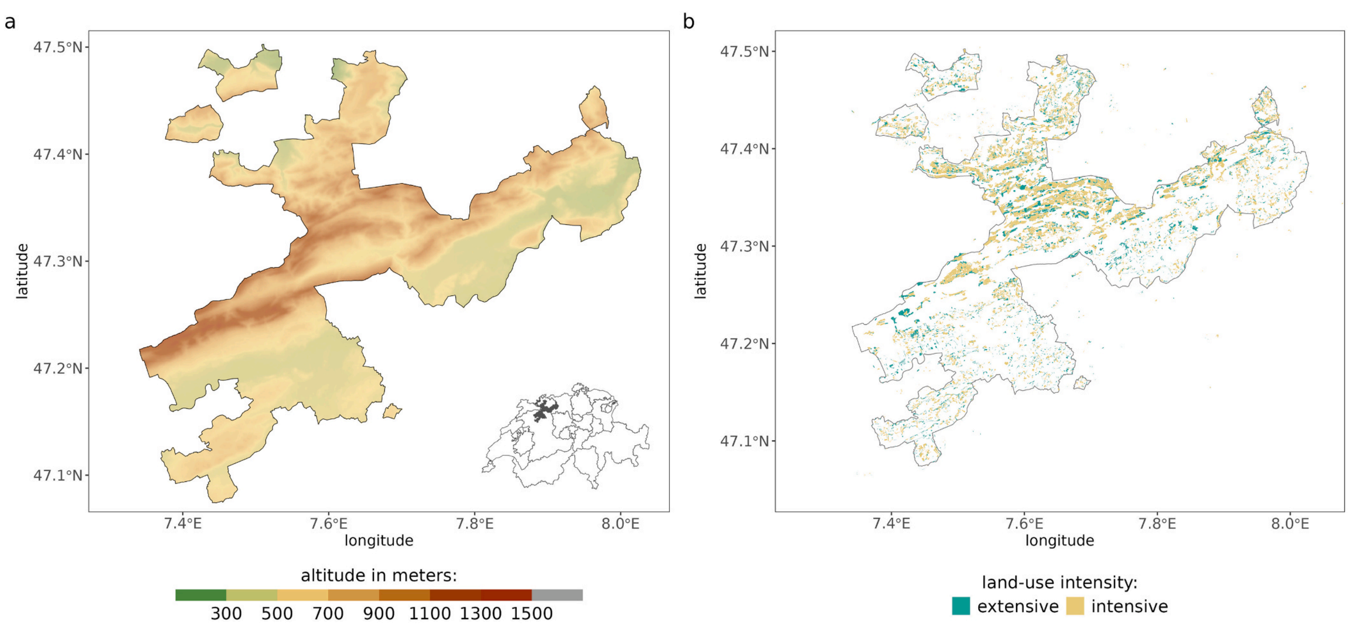

Fig. 2. Relief map (panel a) and baseline land use map (panel b) of the study area (i.e., the Swiss canton of Solothurn). The location of Solothurn is indicated by the dark gray shaded area in the map of Switzerland on the bottom left of panel a. The relief map is based on swisstopo (2023) and Royé (2022). The land use map represents two intensity levels: extensive grassland management and intensive grassland management.

the type and timing of harvest and, within legal constraints, the intensity of fertilization[5] (Klaus et al., 2023; Swiss Federal Council, 2023). For additional details on grassland management type and definition, see Text S1 in Appendix A.

To select a sample of plots for the field survey, farm-level agricultural census data was used to first select all cattle farms (dairy, suckler, and mixed) with at least 30 % of the farm agricultural area managed as grassland, and second identify possible grassland plots on these farms (see Text S2 in Appendix A for details farm and plot selection). The focus on farms with cattle is because cattle is the most frequent type of livestock in the region and Switzerland as a whole (Swiss Federal Office for Agriculture, 2020). The final set of plots for field assessments of ecosystem services contains 92 grassland plots of different types—12 extensive pastures, 22 extensive meadows, 34 intensive meadows, and 24 intensive pastures—on 36 farms. Regarding grassland type, half of the plots were managed organically, and the other half were managed conventionally (Text S1 in Appendix A).

On the 92 plots, we assess the following six ecosystem services, whose supply is evaluated using different well-established indicators (Richter et al., 2021):

(i) annual protein yield (kg per ha) as an indicator of forage production (provisioning service),
(ii) vascular plant species richness (number of species on 8 m^2) as an indicator of biodiversity and gene pool protection (henceforth *biodiversity*; regulating service),

[5] For example, the legal constraints across all intensive meadows of a conventional farm at low elevations is a maximum *average* of 162 kg available nitrogen per hectare and year (Klaus et al., 2023; Swiss Federal Council, 2023).

(iii) soil organic carbon stock in the top 20 cm of the soil (g 100 cm^{-3}) as an indicator of carbon storage (regulating service),
(iv) root biomass in upper 5 cm topsoil (g per soil sampling core, i.e., 98.175 cm^{-3}) as an indicator of erosion prevention (regulating service),
(v) nectar produced by the grassland plant community (kg ha^{-1} $year^{-1}$) as an indicator of a pollination service (regulating service), and
(vi) the aesthetics of the grassland plant community as cultural ecosystem service (Likert scale).

The detailed measurement of all six ecosystem service indicators is described in Text S3 in Appendix A and Richter et al. (2024). In brief, feed production is estimated by calculating the annual protein yield, which is the raw protein in the first harvest multiplied with the annual grassland yield estimates from the official Swiss fertilization guideless (Huguenin-Elie et al., 2017) that have been corrected by field measurements of aboveground biomass (details are in (i) of Text S3 in Appendix A). Plant species richness is captured as the cumulative number of plant species found in two 2 m × 2 m vegetation records per grassland (details are in (ii) of Text S3 in Appendix A). Soil carbon storage is assessed as the organic carbon stock in the top 20 cm of soil (details are in (iii) of Text S3 in Appendix A). Erosion prevention is assessed via the root biomass in the top 5 cm of the soil, with more roots providing higher soil stability (details are in (iv) of Text S3 in Appendix A). The pollination service is approximated by the amount of nectar provided by the plant community of the respective grassland, based on vegetation information on species composition and abundance and databank information of nectar provision per species (details are in (v) of Text S3 in Appendix A). Finally, the aesthetics of each grassland plant community are assessed through an online questionnaire survey, resulting in averaged Likert-scale preference data. The participants rated their aesthetic appreciation of grasslands based on a photo showing a close-up of the plant community without any aspects of the local environmental setting or grazing animals visible. Scores from 1 to 5 represent the gradient from unattractive to attractive (details are in (vi) of Text S3 in Appendix A).

3.3. Spatially explicit census data for upscaling ecosystem service provision

We use detailed and spatially explicit agricultural census data from 2019 to upscale the plot to the parcel and to the whole study region, provided by official agricultural statistics. In particular, the data contain information on all parcels in the study region, that is, their location, the corresponding farm, and the individual land use covering the intensity level (extensive vs. intensive), the type of harvesting (meadow vs. pasture), and the farming system (organic vs. conventional).

We include the 17,834 parcels managed as one of the four permanent grassland types on which this study is focused (i.e., intensive meadows, intensive pastures, extensive meadows, and extensive pastures). We classify grasslands as extensively managed when declared an ecological focus area (i.e., fertilization not allowed) and as intensively managed otherwise (i.e., fertilization allowed). This is the same classification we used for plot-level data in the parametrization. We include all farms with some permanent grassland area but only considered their permanent grassland parcels, excluding other types of land use. Including all farms with some permanent grassland allows the identification of the overall benefits of land-use strategies at a wider spatial level than the farm levels, as it allows for "trading" extensive grassland across the landscape (e.g., to meet cross-compliance regulations).

3.4. Land characteristics

We obtain the following biophysical information about plot and parcel-specific land characteristics for parametrization (*Section 3.2*) and upscaling (*Section 3.3*): the slope (in degree), altitude (in m), orientation (in degree), rootable soil depth (quasi-metric gradient), potential waterlogging of the soil (quasi-metric gradient), and permeability of the soil (quasi-metric gradient). We use the (i) digital elevation model of Switzerland (25 m grid resolution) (swisstopo, 2023) to obtain altitude and calculate slope and orientation using QGIS (version 3.22) and (ii) soil suitability maps of Switzerland to obtain the aforementioned soil characteristics (Swiss Federal Office of Agriculture, 2023). We match all land characteristics to the center of each parcel (see Fig. S1 in Appendix A for a statistical descriptive overview of the data).

3.5. Ecosystem service weights

To parametrize the weights of the six ecosystem services to compute multifunctionality (i.e., p_i of Eq. 6), we use a stakeholder survey conducted with Swiss agricultural stakeholders (Klaus et al., 2022) (for a description of the survey, see Text S4 in Appendix A). The parametrization leads to almost equal weights, i.e., equal relevance of the different ecosystem services (forage production = 0.181, biodiversity = 0.177, carbon storage = 0.152, erosion prevention = 0.187, pollination service = 0.168, and aesthetics = 0.136).

The six ecosystem services include both public and private goods and cover all three categories of ecosystem services: provisioning, regulating, and cultural services (following the widely used *Common International Classification of Ecosystem Services* typology) (Haines-Young and Potschin, 2018). Including forage production, which is a private good, in a social welfare function is important, given its contribution to human well-being and the fact that the production of food is often a policy objective (Huber et al., 2024).

4. Empirical analysis

We present our empirical analysis in four steps. We begin by presenting how we parametrize and predict risk-adjusted multifunctionality (4.1). This is followed by a description of the baseline scenario analysis (4.2), the two optimization scenario analyses (4.3), and the sensitivity analyses (4.4).

4.1. Parametrization and prediction of risk-adjusted multifunctionality

To estimate the relationship between land-use intensity and the supply of ecosystem services, we use the following model:

$$y_{ji} = \beta_1 + \beta_2 z_j + \beta_3 X_j + \beta_4 z_j X_j + e_{ji} \tag{7}$$

where z_j represents the land-use intensity level (i.e., extensive management = 0 and intensive management = 1), X_j is a vector including variables about land characteristics (i.e., slope, altitude, orientation, rootable soil depth, potential waterlogging of the soil, and permeability of the soil), and whether a parcel is used as a meadow or pasture and is organically or conventionally managed. e_{ji} is the error term. In our model, we consider management and land characteristics that potentially affect the supply of ecosystem services and are readily available to policymakers.

The exact model specification varies between ecosystem services (for detailed model specifications, see Table S1 in Appendix A). Specifically, for each ecosystem service, we develop a model that contains the drivers relevant to the respective services, using available parcel-level data over the whole study region. To select the relevant drivers per ecosystem service (i.e., the explanatory variables of the models), the models with the lowest AIC value are selected (using the stepAIC function of the R package MASS) (Venables and Ripley, 2002). The starting point of selection is for each ecosystem service the full model presented in Eq. 7, including information about parcel-level land-use intensity (z_j) and other management and land characteristics (X_j). Additionally, all these other management and land characteristics are allowed to interact with land-use intensity. Further, prior to the model specification, we take the log of nectar produced and the square root of the protein yield, given the non-normal distribution of the error terms.

Although we use this estimation primarily for the parametrization of the different scenarios (*Sections 4.2* and *4.3*) and do not discuss the single-service results in detail, we point out that some services are positively and others negatively associated with land-use intensity. Thus, we observe tradeoffs as well as synergies when deciding on land-use intensity among the six services included in our analysis (detailed results can be seen in Table S1 in Appendix A).

Furthermore, to assess the risk of providing the different ecosystem services resulting from the two land-use intensity levels, we compute the prediction variance, $\widehat{\sigma}^2$ (Greene, 2003; Olive, 2007) for each parcel and ecosystem service as:

$$\widehat{\sigma}^2_{ji} = \left(\sqrt{MSE_i}\sqrt{1+\omega_j'(\Omega'\Omega)^{-1}\omega_j}\right)^2 \tag{8}$$

where *MSE* is the mean squared error, ω a vector of the characteristics of the predicted parcel including an intercept, and Ω a matrix of the characteristics of all parcels used to estimate the model (i.e., Eq. 7) including the intercept.[6]

Finally, using the prediction of the expected value of each service, $\widehat{y}$, and the prediction variance, $\widehat{\sigma}^2_{ji}$, of Eqs. 7 and 8, we can compute both multifunctionality and risk-adjusted multifunctionality following Eqs. 5 and 6.[7] Here, we follow Neyret et al. (2023) in our analysis and scale the risk-adjusted service supply, $\overline{v}$, of each ecosystem service between zero and one. For example: $\overline{v}_{ji} = \left(\widehat{v}_{ji} - \min\left(\widehat{v}_{ji}\right)\right)\left(\max\left(\widehat{v}_{ji}\right) - \min\left(\widehat{v}_{ji}\right)\right)$, where $\overline{v}_{ji}$ is the scaled risk-adjusted supply of service i on plot j. Moreover, before scaling the variables, we reverse the log-transformed or square root-transformed nectar and protein yields, respectively. Thus, we compute the scaled risk-adjusted multifunctionally as follows:

$$\overline{\mathrm{M}} = \sum_{j=1}^{m}\sum_{i=1}^{n}\overline{v}_{ji}p_i a_j = \sum_{j=1}^{m}\sum_{i=1}^{n}\overline{\left(\widehat{y}_{ji}\left(1+\frac{\widehat{\sigma}^2_{ji}}{\widehat{y}_{ji}^{\,2}}\right)^{-\frac{r}{2}}\right)}p_i a_j \tag{9}$$

where the bars over expressions indicate scaling. We also scale the expected ecosystem service provision using the scaling parameters of the risk-adjusted service supply.

4.2. Baseline scenario

In the *baseline scenario*, we compute risk-adjusted multifunctionality (see Eq. 9) using the predicted ecosystem services of each parcel in our study region and their prediction variance, considering the actual land-use intensity (from the census data of 2019), other management (i.e., organic vs. conventional and pasture vs. meadow; from the census data of 2019), and land characteristics (*Section 4.1* for the parametrization). Moreover, in all our analyses, we assume that decision makers are rather risk averse, thus, $r = 2$ (Hardaker et al., 2015). Thus, the baseline scenario depicts the status quo of risk-adjusted multifunctionality, given the current land-use intensities.

4.3. Optimization model and scenarios

We run two different optimization scenarios according to which our model optimizes land-use decisions (see Table 1 for an overview). In both cases, the objective function is to maximize risk-adjusted multifunctionality:

$$\max_{z}\ \overline{\mathrm{M}} = \max_{z}\sum_{j=1}^{m}\sum_{i=1}^{n}\overline{v}_{ji}p_i a_j = \max_{z}\sum_{j=1}^{m}\sum_{i=1}^{n}\overline{\left(\widehat{y}_{ji}\left(1+\frac{\widehat{\sigma}^2_{ji}}{\widehat{y}_{ji}^{\,2}}\right)^{-\frac{r}{2}}\right)}p_i a_j \tag{10}$$

See Table 1 for a summary of the variable and index definitions. Important for the optimization is that (i) while the supply of some ecosystem services increases when management is extensive, it decreases for other services, revealing synergies and tradeoffs, and (ii) the relationship of ecosystem services with land-use intensity can vary depending on the land and other management characteristics (see Table S1 in Appendix A).

Further, all optimization scenarios are subjected to at least the following three constraints (Table 1): (i) all of the total grassland area, A, is continued to be used as grassland; (ii) land and management characteristics other than land-use intensity, X_j, remain fixed; and (iii) the land-use intensity decision is either intensive management ($z = 1$) or extensive management ($z = 0$).[8]

Table 1
Overview of optimization scenarios and variable definitions.

Optimization scenarios	Level	Objective function (see also Eq. 10)	Constraints
All optimization scenarios	Farm & Landscape	$\max_{z}\ \overline{\mathrm{M}}$	$\sum_{j=1}^{m} a_j = A^1 \quad X_i = X_i \quad z \in \{0,1\}$
Optimization scenarios	Level	Additional constraints	
Optimization scenario 1: Minimum extensive grassland share	Farm	$\left(1 - \frac{\sum_{l=1}^{L} a_l \quad z_l}{A^2}\right) \times 100 \geq \quad \mathrm{H}^2$	
	Landscape	$\left(1 - \frac{\sum_{j=1}^{m} a_j \quad z_j}{A^1}\right) \times 100 \geq \quad \mathrm{H}^1$	
Optimization scenario 2: Optimal extensive grassland share at the landscape level*	Landscape	$\Phi \times 0.999 \geq \sum_{j=1}^{m} a_j(1 - z_j) \geq \Phi \times 1.001$	
Variables and indices	Definitions		
$\overline{\mathrm{M}}$	Risk adjusted multifunctionality (standardized)		
z	Land-use intensity level (i.e., extensive management $= 0$ and intensive management $= 1$)		
a	Parcel sizes		
A^1	Total grassland area of a landscape		
A^2	Total grassland area of a farm		
X_i	Vector of other land and management characteristics than land-use intensity		
H^2	Minimum share of extensive grassland at the farm level in percent.		
H^1	Minimum share of extensive grassland at the landscape level in percent.		
Φ	Predefined extensive grassland share		
i	Indicates the ecosystem service supply		
j	Indicates the parcel		
l	Indicates a specific parcel of a farm		
n	The number of ecosystem services		
m	The number of parcels in a landscape		
L	The number of parcels of a farm		

Remark: *We allow a small deviation from predefined extensive grassland share, as matching the exact share can be extremely constraining, given that we consider that parcels have different sizes. Specifically, we consider a relative deviation of 0.1 % from the grassland area.

[6] Note that for computing the *RSS* of the services that we initially log-transformed or square root-transformed (i.e., nectar and protein yield), we reverse transformations to reflect the uncertainty of the service supply for policymakers.

[7] We note that while we do not account directly for spatial interaction when predicting the expected outcomes and variance, we use spatially explicit data at the parcel level for it and account for a set of land characteristics.

[8] In *Section 2*, we described the attractiveness of modelling land-use intensity as a binary choice.

To solve the optimization problems, we use an integer programming approach given the binary nature of land-use intensity decisions. The optimization problem presented in Table 1 can be computationally simplified from a non-linear to a linear integer programming problem (see Text S5 in Appendix A). We implement the optimization in R using the *ompr* package (Schumacher, 2022).

4.3.1. Optimization scenario 1: minimum extensive grassland share

In *optimization scenario 1*, we consider that decision makers define minimum shares of extensive grasslands. This scenario adds an additional constraint to the general optimization problem defined in *Section 4.3* (see Table 1). We run this scenario for a range of different minimum shares of extensive grasslands, from 0 % to 100 % in steps of 1 %.

A minimum share of extensively managed grasslands could, for example, be introduced as part of the cross-compliance requirements. In Switzerland, the cross-compliance requirements currently encompass a minimum share of ecological focus areas (including mostly extensive grasslands) of 7 % of the total utilized agricultural area of any grassland or arable farm (Swiss Federal Council, 2023). We conduct this scenario so that one time the minimum share is set at the farm level and one time at the landscape level. This helps us identify potential gains from implementing policies at the landscape level compared to the farm level. The landscape level represents the entire study region.

4.3.2. Optimization scenario 2: optimal extensive grassland share at the landscape level

In *optimization scenario 2*, we consider a policy that predefines an exact share of extensive grassland instead of a minimum share at the landscape level. Hence, a different constraint applies in this scenario (Table 1). We consider a gradient of *predefined* extensive grassland share from 0 % to 100 % in steps of 1 %, where a share of extensive grassland always implies a share of intensive grassland (i.e., 100% − extensive grassland share). The optimal predefined extensive grassland share that a policymaker can set (given optimal land use allocation) is therefore the predefined share with the maximum risk-adjusted multifunctionality.

We conduct this scenario only for the landscape level for two reasons. First, defining an optimal share of extensive grassland at the farm level would require identifying the optimal share for each individual farm. This, in turn, would preclude the development of a uniform policy applicable to all farms, given the specificity required for each farm's optimal share. Second, at the farm level, not every predefined share of extensive grassland can be reached, given the fixed number of parcels per farm and their fixed size. By contrast, at the landscape level, we have over 17,000 parcels to realize the exact share of extensive grasslands; thus, this limitation is not a concern. Moreover, to avoid not finding a solution in the optimization model and to account for differences in parcel sizes, we allow the realized extensive grassland share to deviate from the predefined grassland share by 0.1 % (Table 1).

4.4. Sensitivity analyses

In addition to our main analysis, we run three sensitivity analyses. In the first sensitivity analysis, we check how our results change when the objective is to maximize multifunctionality without risk adjustments, assuming a risk-neutral decision maker. Therefore, this analysis does not require making assumptions about the level of risk aversion (i.e., the relative risk aversion coefficient, r).

Second, we check the sensitivity of our results to changes in ecosystem service weights, which approximate "equal weight multifunctionality" (Allan et al., 2015) in our main analysis. Therefore, two additional sensitivity analyses are conducted with increased and decreased weights given to forage production, similar to Allan et al. (2015). The rationale behind this is that farmers often show high priorities for forage production (Neyret et al., 2021) and that forage production is known to benefit from intensive land use; thus, increasing and decreasing its importance provides a production- and conservation-oriented perspective, respectively. Therefore, in the first specification, called the "production-oriented perspective," we double the weight of forage production (resulting in the following scaled weights: forage production = 0.306, biodiversity = 0.150, carbon storage = 0.129, erosion prevention = 0.159, pollination service = 0.142, and aesthetics = 0.115). In the second specification, the "conservation-oriented perspective," we halve the weight of forage production (resulting in the following scaled weights: forage production = 0.099, biodiversity = 0.194, carbon storage = 0.167, erosion prevention = 0.206, pollination service = 0.184, and aesthetics = 0.149).

In the third sensitivity analysis, we compare the baseline to a hypothetical scenario in which land use is randomly allocated. Thus, the resulting land-use allocation in this scenario is independent of farmers' current allocation decisions and not the result of an optimization model. Conducting this analysis provides a statistical reference point to (i) compare the land-use decision in the baseline scenario against and (ii) understand the magnitude of the change in risk-adjusted multifunctionality gained in the optimization scenarios. In detail, the random allocation scenario depicts the supply of risk-adjusted multifunctionality when the existing land-use intensity across parcels is randomly redistributed either at the farm or landscape level. To this end, we consider redistribution across the number of parcels under extensive and intensive management and not the area of extensive and intensive grassland, as the latter would reduce the degree of freedom given the different and fixed sizes of parcels. We run the random redistribution 500 times (separately at the farm and landscape levels) and compute the average multifunctionality, risk premium, and risk-adjusted multifunctionality.

5. Results

The presentation of our results is separated into three parts: (i) the baseline scenario, (ii) the optimization scenarios, and (iii) the sensitivity analyses.

5.1. Baseline scenario

The baseline scenario represents the currently implemented land-use intensities and, thus, the status quo. The mean share of the extensive grassland area of the total permanent grassland area in the baseline scenario is 31 % (Fig. S2 in Appendix A).[9] The expected risk-adjusted multifunctionality across our study area is 0.37, which is 12 % lower than the non-adjusted multifunctionality (i.e., 0.42), indicating that considering risk is important when estimating the supply of multifunctionality (Fig. S3 in Appendix A). In particular, considering risk matters for the design of policy measures when the difference between non-risk-adjusted and risk-adjusted service supplies varies between services. Indeed, we find differences in risk between the different services. For example, the reductions resulting from risk-adjusted compared to the non-risk-adjusted supply of carbon stock, soil quality, biodiversity, and forage provision are −5 %, −36 %, −10 %, and −11 %, respectively (Table S2 and Fig. S4 to S9 in Appendix A).

5.2. Optimization scenarios results

5.2.1. Optimization scenario 1 results: minimum extensive grassland share

We first present the results of the scenario in which we optimize land-use intensity to maximize the risk-adjusted multifunctionality over a range of minimum shares of extensive grassland at the farm or landscape level (*optimization scenario 1*). Fig. 3a and b show the relative changes in

[9] The relatively high share of 31 % can be explained because we consider all grassland parcels and, therefore, the extensive grassland parcels used to meet cross-compliance requirements in mainly crop production-oriented arable farms.

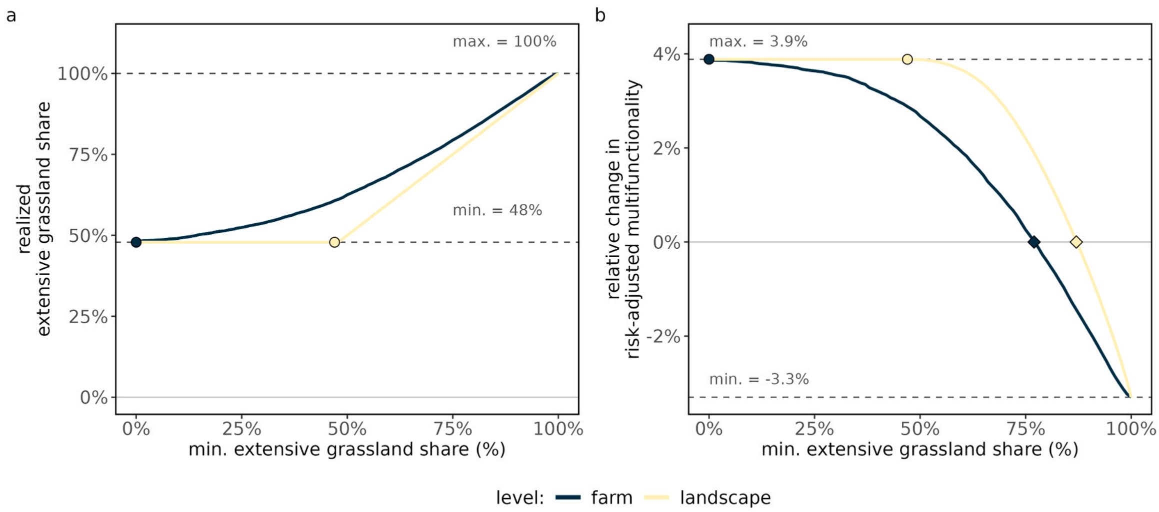

Fig. 3. Results of *optimization scenario 1* (minimum extensive grassland share). The y-axes of panels a and b show the extensive grassland share and relative change in risk-adjusted multifunctionality, respectively, in *optimization scenario 1* compared to the baseline scenario over all parcels. The x-axes show in both panels the minimum share of extensive grassland required in *optimization scenario 1*. Dark blue and light yellow indicate the farm level and landscape level, respectively. The dots indicate inflection points, and the diamonds in panel b indicate when the lines cross the zero of the y-axis. The current share of extensive grassland across the landscape is 31 % (baseline scenario). The results for multifunctionality and risk premium for *optimization scenario 1* can be found in Fig. S10 in Appendix A.

extensive grassland share and the resulting risk-adjusted multifunctionality, respectively, compared to the baseline scenario. When the minimum extensive grassland share is 0 % (no constraints on land use are imposed), the maximum increase in risk-adjusted multifunctionality is + 3.9 %, and it does not matter whether risk-adjusted multifunctionality is maximized at the farm or landscape level. This increase can be attributed to an increase in the non-risk-adjusted multifunctionality by + 3.2 % and a decrease in the risk premium by −1.9 % in the same optimization (Fig. S10 in Appendix A).

When the required minimum share of extensive grassland is increased at farm level, the risk-adjusted multifunctionality decreases immediately (i.e., minimum extensive grassland share > 0 %; dark blue dot in Fig. 3b) compared to the maximum obtainable one (i.e., +3.9 %; Fig. 3b). This can be attributed to the fact that with a 0 % minimum share, some farms do not have any extensive grasslands in the optimization given the other management (i.e., conventional vs. organic and meadow vs. pasture) and land characteristics of their parcels, and despite the overall high realized share of 47.9 %. This highlights the inherent loss in effectiveness when imposing farm-level regulations for extensive management. The results of the analysis at the landscape level show decreases in the risk-adjusted multifunctionality compared to the maximum obtainable one only when the minimum share of extensive grassland exceeds 47 % (considering 1 %-stepwise increases; at which point the realized extensive grassland is 47.9 %; light yellow dot in Fig. 3b). When the *minimum* share of extensive grassland is set to 47 % at the farm level, the risk-adjusted multifunctionality increases by + 2.9 % compared to the baseline scenario, a gain that is 1 % lower than the gain observed when the same minimum share is set at the landscape level (i.e., +3.9 %).[10]

Furthermore, we can separate the total increase in risk-adjusted multifunctionality into (i) changes in the allocation of parcels under extensive and intensive management *given* the extensive grassland share of the baseline scenario (i.e., *re-allocation gains*) and (ii) changes in the extensive grassland share (Fig. S11 in Appendix A illustrates this separation; see also Text S6 in Appendix A for more details). We observe that of the + 3.9 % gain in risk-adjusted multifunctionality, 2.0 % and 3.6 % at the farm and landscape levels, respectively, is due to changing the land-use re-allocation of parcels and the rest due to changing the extensive grassland share.

Furthermore, the highest minimum share of extensive grassland at which we still observe an increase in risk-adjusted multifunctionality in this optimization scenario compared to the baseline scenario is 77 % for the farm level and 87 % for the landscape level (indicated, respectively, by the dark blue and light yellow diamonds in Fig. 3b). If these notably high values are exceeded, the risk-adjusted multifunctionality falls below the baseline scenario.

Fig. 4 presents the changes in the risk-adjusted supply of each of the six considered single ecosystem services compared to the baseline scenario and the realized extensive grassland share when the minimum shares of extensive grassland (*optimization scenario 1*) is 25 %, 50 %, and 75 %. Including the assessment of single services in the study reveals tradeoffs and synergies in the scenarios. We find that the risk-adjusted supplies of aesthetics, biodiversity, erosion prevention, and pollination service increase in this optimization scenario, while the risk-adjusted supply of carbon storage and forage production are reduced. Moreover, we observe that when setting land-use strategies at the landscape level compared to the farm level, all services that are reduced tend to reduce less, and many that are increased tend to have a lower increase. This suggests a more balanced supply of ecosystem services when strategies are organized at the landscape level.

5.2.2. *Optimization scenario 2 results: optimal extensive grassland share at the landscape level*

When the land-use strategy is optimized over a given gradient of *predefined* extensive grassland shares at the landscape level (*optimization scenario 2*), the optimal share is 48 % (considering 1 % steps; light yellow dot; Fig. 5). Thus, policymakers aiming at maximizing risk-adjusted multifunctionality should set the predefined share of extensive grassland at the landscape level to 48 %, given an optimal land-use allocation and the multifunctionality considered here, consisting of six ecosystem services.

5.3. *Sensitivity analysis results*

In the first sensitivity analysis, we explore how the results change

[10] When the *minimum* share of extensive grassland is set to 31 % (currently observed extensive grassland share) the difference in the gain in risk-adjusted multifunctionality between the farm and landscape level is 0.3 %. The maximum difference in the gain in risk-adjusted multifunctionality (i.e., 2 %) is observed when the minimum share of extensive grassland is set to 67 %.

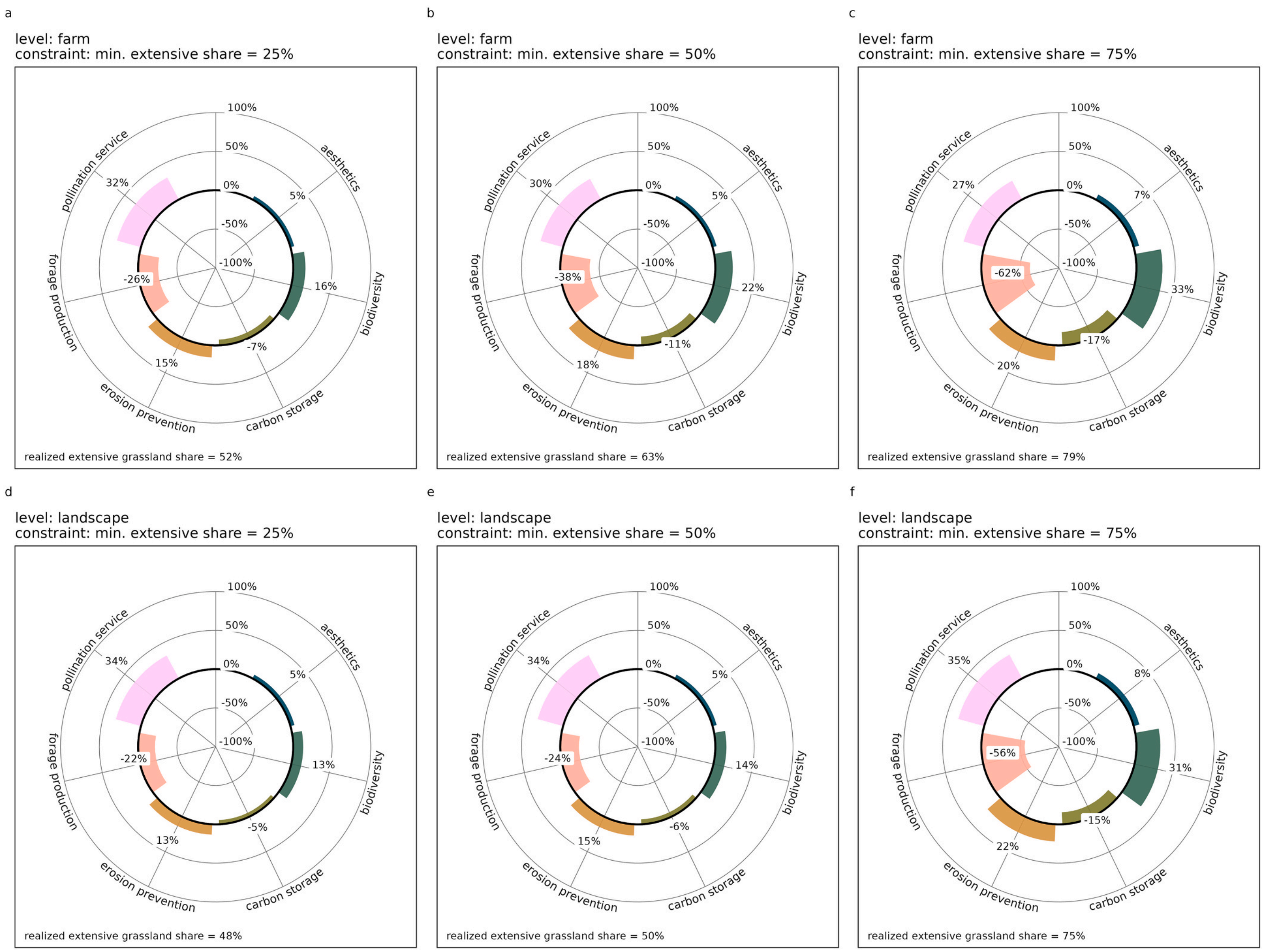

Fig. 4. Response of single, scaled, and risk-adjusted ecosystem services in *optimization scenario 1* (minimum extensive grassland share) at the farm (panels a to c) and landscape levels (panels d to f) along a gradient of minimum extensive grassland share of 25 %, 50 %, and 75 %. The responses are indicated as relative changes compared to the baseline scenario; thus, values above the bold black line at 0 % indicate an increase compared to the baseline scenario, and values below it indicate a decrease. The services are scaled between zero and one; thus, a change of, for example, −100 % does not imply no service provision but a scaled value close to zero, depicting supply close to the minimum observed in our dataset. The changes in forage production are largely due to the strong impact of land-use intensity on this service (Table S1 in Appendix A).

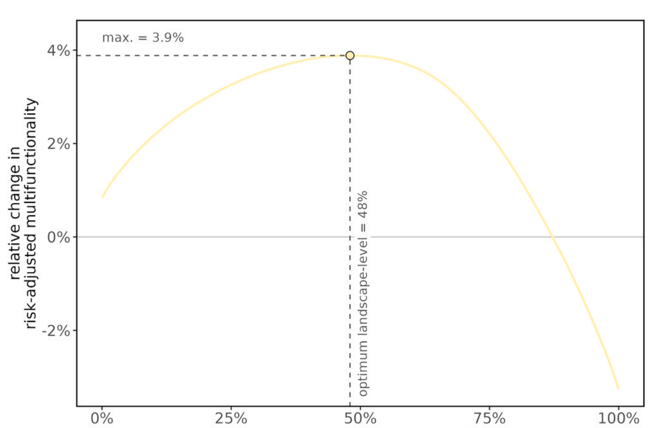

Fig. 5. Results of *optimization scenario 2* (optimal extensive grassland share). The y-axis shows the relative change in the risk-adjusted multifunctionality in *optimization scenario 2* compared to the baseline scenario over all parcels. The x-axis shows the predefined extensive grassland share. Light yellow indicates the landscape level. The dot indicates the inflection point.

when considering risk-neutral instead of risk-averse decision makers, thus optimizing non-risk-adjusted multifunctionality (Fig. 6a and b). When decision makers are risk-neutral, we observe three key outcomes: (i) the same maximum gain in multifunctionality as under risk aversion in the risk-adjusted multifunctionality, (ii) lower reductions in multifunctionality compared to the main analysis when the minimum extensive share is 100 %, and (iii) a slightly higher optimal predefined extensive grassland share at the landscape level (50 % instead of 48 %). These findings, combined with our main results, indicate that when both riskier and less risky ecosystem services are promoted under extensive or intensive grassland management (as shown in Table S2 in Appendix A), the effects of risk on optimal land-use strategies tend to balance out across multiple ecosystem services. Nevertheless, considering risk is still relevant when designing land-use strategies, as we showed that it affects the optimal land-use strategy and considerably reduces multifunctionality (see also *Section 5.1*).

The second sensitivity analysis considers a change in the stakeholder weights of ecosystem services, either toward a more production-oriented perspective (Fig. 6c and d) or a conservation-oriented perspective (Fig. 6e and f). The analysis gives policymakers a range of how optima change over alternative priority setting. The production-oriented perspective favors intensive grasslands almost exclusively. The

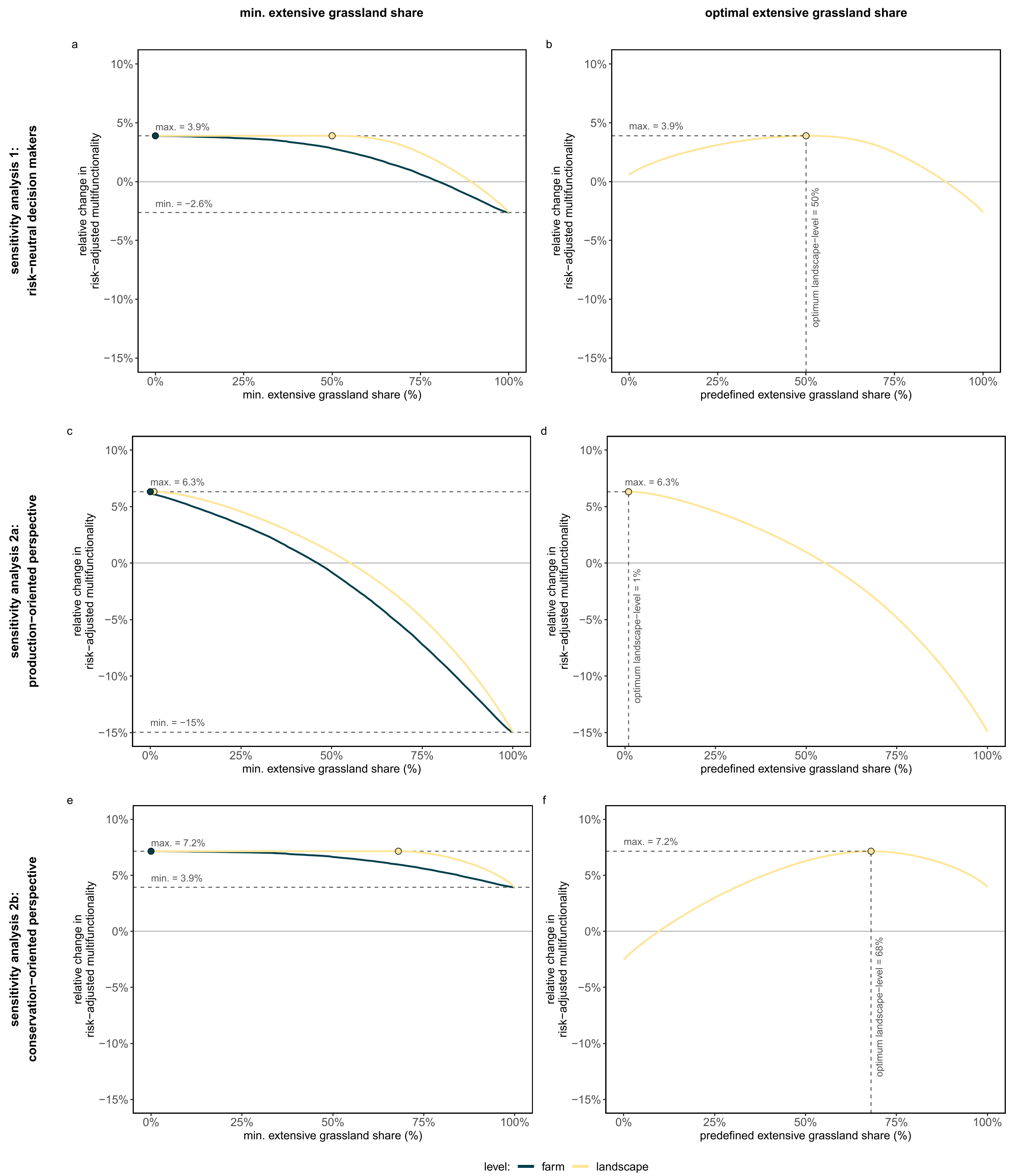

Fig. 6. Results of the sensitivity analyses. Panels a and b show the results for sensitivity analysis 1, omitting the risk adjustment (i.e., risk-neutral decision makers), panels c and d show the results for sensitivity analysis 2a (production-oriented perspective), and panels e and f show the results for sensitivity analysis 2b (conservation-oriented perspective). The left column shows the results over a range of minimum extensive grassland shares (i.e., setting of *optimization scenario 1*), and the right column shows the results over a range of predefined extensive grassland shares (i.e., setting of *optimization scenario 2*). All y-axes show the relative change in risk-adjusted multifunctionality in the respective scenario compared to the baseline scenario over all parcels. Dark blue and light yellow indicate the farm level and landscape level, respectively. The dots indicate inflection points. Detailed results for the sensitivity analysis of *optimization scenarios 1* and *2* can be found in Fig. S14 to S16 in Appendix A.

optimal predefined extensive grassland share is 1 % at the landscape level (Fig. 6d), the proportion at which the risk-adjusted multifunctionally is + 6.32 % higher in the optimization scenario than in the baseline scenario. In the analysis of the conservation-oriented perspective, we find that risk-adjusted multifunctionality at the landscape level begins to decline at a higher minimum share of extensive grassland compared to our main analysis. Moreover, the optimal predefined extensive grassland share is 68 %, which is considerably higher than in the main analysis (48 %; Fig. 6f). The maximum attainable risk-adjusted multifunctionality is higher in both the production- and conservation-oriented perspectives than in our main analysis. This is a consequence of higher weights assigned to either ecosystem services that are favored or disfavored under intensive land use, hence reducing tradeoffs and increasing attainable multifunctionality. Moreover, although in those two sensitivity scenarios the service weights were only moderately modified, the suggested predefined shares of extensive grasslands to optimize multifunctionality change considerably to 1 % and 68 %, respectively (48 % in the main analysis). This highlights how changes in priority setting can have relevant consequences for optimal land-use strategies.

In the third sensitivity analysis, we check the difference between (i) a hypothetical scenario where land use is randomly allocated and (ii) the baseline scenario to provide a reference point for comparing the changes in risk-adjusted multifunctionality following the optimization scenarios. We find a higher risk-adjusted multifunctionality in the baseline compared to the random allocation scenario, both at the farm and landscape levels, highlighting the relevance of the targeted selection of which parcels are extensively versus intensively managed by farmers (Table S3 in Appendix A, Fig. S12 and S13 in Appendix A). Specifically, the risk-adjusted multifunctionality in the baseline scenario compared to the random allocation scenarios is 0.7 % higher at the farm level and 0.9 % higher at the landscape level compared to the baseline scenario. The magnitude of those gains is approximately six to four times lower than the gains we show in *optimization scenario 1* (i.e., 3.9 %/0.7 % and 3.9 %/0.9 %). Moreover, these gains of land-use allocation in the baseline compared to the random allocation (i.e., 0.7 % and 0.9 %) are similar to the gains when implementing policies at the landscape level instead of the farm level (i.e., +1 % when the minimum extensive grassland share is set to 47 %). These results indicate policy-relevant potential for increasing multifunctionality through optimal spatial land-use intensity allocation based on the regional biophysical characteristics of the parcels.

6. Future research and limitations

Our study is not without limitations and highlights important future research areas. First, we assume that ecosystem services respond immediately to land-use changes, and we neglect interactions in space. However, services often need time to respond to management changes (Isbell et al., 2013; Seabloom et al., 2021) and are interconnected in space as well as affected by neighboring land uses (Duarte et al., 2018; Le Provost et al., 2023). Incorporating these aspects into the analyses requires multi-year data collection and additional data across space, which are not available in our case. In addition, although increasing attention is being paid to spatial interactions among ecosystem service supply and in interaction with neighboring land use (e.g., Boesing et al., 2024), knowledge of the actual net increase or decrease due to such multifactorial interactions is still limited and, as such, cannot be integrated into our model. Thus, they depict important future tasks for data collection and extensions of our modeling approach, especially considering that these aspects could cause additional risks for decision makers when introducing policies.

Second, in our survey, to calibrate the weights of ecosystem services, we asked about the relevance of each ecosystem service and not about the relative priorities of each service. Thus, the participants rated each service according to its individual importance without being asked to consider that an increase in one service might result in a decrease in another. Therefore, using relative priorities or prices (which are only available for a limited number of ecosystem services) can advance future research (Huber et al., 2022; Neyret et al., 2023). Thus, in this context, it is important our analysis should be viewed as a case study, given the absolute weights from our survey. These weights might also change across space and time (e.g., Richter et al., 2021). We have addressed these limitations by altering the service weights in our sensitivity analysis, which highlights the importance of choosing and surveying weights. Thus, given that surveys are costly and it is difficult to survey all relevant stakeholders, providing online interactive tools for decision makers could be an attractive way forward (see Neyret et al., 2021 as an example).

Finally, we focus on permanent grasslands and the supply of six ecosystem services. While we acknowledge that our results are influenced by the identity of the selected services and results should be interpreted in light of this selection, we are convinced that this outcome is relevant and informative because we included ecosystem services from all three domains – provisioning, regulating, and cultural (Haines-Young and Potschin, 2018). Including all three domains assured that our analysis accounts for important tradeoffs and synergies among services, especially since provisioning services have been shown to conflict with regulating and cultural ones(e.g., Allan et al., 2015; Lavorel et al., 2011; Richter et al., 2024). Additionally, the number of services considerably exceeds what has been considered in most studies using optimization models to identify optimal land-use strategies (e.g., Eyvindson et al., 2018; Eyvindson et al., 2023; Triviño et al., 2017). Furthermore, extending our modeling approach to other land uses (e.g., crop land and forests) (Law et al., 2015; Law et al., 2017) or even more or other sets of ecosystem services (Neyret et al., 2023; Zasada, 2011), cost of supply (Huber et al., 2021; Schaub et al., 2021; Uthes et al., 2010), or whole-farm ecosystem service supply (Klaus et al., 2024; Rotz et al., 2005) would add valuable extra dimensions and remain important areas for future research. Despite these limitations, our study highlights important pathways and improvements for policymakers and provides a layout for further developing the assessment of multifunctionality, such as accounting for risk and using spatially explicit optimization approaches.

7. Concluding remarks

We analyze how land-use intensity allocation (i.e., spatial land-use intensity distribution), policies that mandate varying minimum shares of extensive land use (as found in cross-compliance regulations), and risk (following an economic concept) impact the expected utility derived from grassland multifunctionality and resulting optimal land-use strategies. Additionally, we consider that the policies can be implemented at either the farm or landscape level. Our analysis utilizes integer programming and relies on rich, spatially explicit data from a heterogeneous Swiss agricultural region (> 17,000 grassland parcels). Moreover, it considers six ecosystem services belonging to all three categories of ecosystem services (provisioning, regulating, and cultural services).

Our main findings and policy implications are as follows and add to the literature on land-use strategies and the spatial targeting of conservation actions (e.g., Huber et al., 2022; Neyret et al., 2023; Polasky et al., 2014; Wünscher et al., 2008). We find that considering risk decreases expected utility from multifunctionality and optimizing land-use strategies under different policies can increase the supply of risk-adjusted multifunctionality at both the farm and landscape levels (up to +3.9 % compared to the status quo). Furthermore, implementing policies at the landscape level, as opposed to the farm level, can enhance policy efficiency, as it reduces stringent policy requirements for individual farms and allows the exploitation of favorable environmental production conditions across space. We show that these increases can be practically meaningful in terms of magnitude (i.e., *Section 5.3*). Yet, currently, most agri-environmental policies remain to be implemented at the farm level (Huber et al., 2022; Nguyen et al., 2022), forgoing these gains from improved spatial targeting.

Furthermore, we identify that the optimal share of extensive grassland is 48 % at the landscape level, given the considered six ecosystem services and stated stakeholder preferences. This share is quite above the currently observed level of 31 %. Additionally, our results differ from Huber et al. (2022), who found an optimum of around 25 %, considering three grassland ecosystem services (i.e., forage provision, carbon storage, and habitat maintenance) and prices.

We show that when decision makers have a production-oriented perspective, this can lead to predominately intensive grassland use. However, in the case of grasslands, such a production-oriented perspective does not reveal the preferences for a range of ecosystem services of diverse stakeholder groups (Peter et al., 2022; Thiemann et al., 2022). Hence, if policymakers aim to satisfy a wide range of stakeholders, policies need to adapt to those stakeholders' preferences (Manning et al., 2018; Uthes et al., 2010). Furthermore, we recommend including risk in future ecosystem service and multifunctionality assessments, given our results regarding the importance of risk in the evaluation of multifunctionality, as well as previous extensive use of quite coarse ecosystem service proxies resulting in high supply uncertainty, i.e., risk (Eigenbrod et al., 2010; Lavorel et al., 2017).

Finally, our study highlights that agri-environmental policies can improve multifunctionality and, hence, the sustainability of agricultural production. However, these improvements depend on thought-through policies that can benefit from implementation at the landscape level instead of at the farm level and steering the land-use decision process by farmers (i.e., targeting areas or parcels).

Code availability statement

All R-codes for the reproduction of this study is available online on Github (https://github.com/seschaub/multi).

CRediT authorship contribution statement

Schaub Sergei: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Huguenin-Elie Olivier:** Writing – review & editing, Writing – original draft, Conceptualization. **Richter Franziska:** Writing – review & editing, Data curation. **El Benni Nadja:** Writing – review & editing, Writing – original draft, Conceptualization. **Jan Pierrick:** Writing – review & editing, Writing – original draft, Conceptualization. **Klaus Valentin H.:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2025.107548.

Data availability

All survey data will be made available upon request. Land characteristics are available online. The agricultural census data need to be requested from the Swiss Federal Office for Agriculture.

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