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NON TECHNICAL SUMMARY

Conservation of biodiversity can benefit agriculture through its provisioning of supporting ecosystem services. It is therefore argued that ecological intensification—whereby farmers implement measures to boost flows of ecosystem services—could be used to replace environmentally damaging inputs and hence boost yields and incomes while simultaneously reducing environmental degradation.

Evaluating the potential of ecological intensification to meet this challenge is however far from straight-forward. Ecological-economic modelling can be used to investigate the complex interactions between famers' land-use decisions and impacts on ecosystem services. Further it makes it possible to evaluate the cost-effectiveness of different policy responses.

Here we develop an ecological-economic optimization that considers the impacts of farmers' land-use decisions on flows of above- and below-ground ecosystem services, and the concomitant impacts on production and incomes. Further the model has been calibrated to the Liberation project's seven, pan-European, case-study landscapes to reproduce observed production decisions (land-use, crop areas and input use) in each landscape.

The main focus has been on developing and calibrating the optimization model for each landscape to economic data while using preliminary parameter values for the ecosystem-service production functions to generate some exploratory results. Hence the presented results are purely exploratory.

In the next step we will link our models with the multiple production function developed in WP 4 to validate our results and test their sensitivity to changing conditions.

POLICY RELEVANCE

The development of ecological-economic optimization models for seven landscapes across the EU is a key achievement towards quantifying and communicating the expected impacts of ecological intensification on agricultural production and farmers' livelihoods.

Our preliminary results indicate that ecological intensification has the potential to boost future agricultural productivity and farm incomes while reducing environmental degradation, but it will involve potentially substantial short-term costs to achieve higher levels of services in the future. Consequently, the time lag between implementing measures to benefit biodiversity and realizing higher flows of ecosystem services is likely to hinder ecological intensification under the current policy framework.

Liberation Deliverable 5.2

Report on Economic Models Calibrated to Case-Study Landscapes

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Contents

1 Introduction

Conservation of biodiversity can benefit agriculture through its provisioning of supporting ecosystem services such as soil fertility, biological control of crop pests and pollination of flowering crops by insects. It is therefore argued that ecological intensification—whereby farmers implement measures to boost flows of ecosystem services—could be used to replace environmentally damaging inputs such as mineral fertilizers and chemical pesticides. In this way farmers could meet a major future challenge for agriculture: boost yields and incomes while simultaneously reducing environmental degradation.

Evaluating the potential of ecological intensification to meet this challenge is however far from straight-forward. Ecological-economic modelling is an approach that can handle the complex interactions between famers' optimizing behavior, resultant land-use and management choices, and impacts on ecosystem services of potential benefit to agriculture and society. Further it makes it possible to explore the efficacy of different management strategies through simulation and evaluate the cost-effectiveness of potential policy responses.

The main aim of this deliverable is to document the development and calibration an ecological-economic optimization model that will be used in Liberation to examine the potential of ecological intensification to boost agricultural productivity and support farmers' incomes in seven pan European case-study landscapes. This work is closely related to the development of the multiple production function (multi-PF) in WP4 which will be used to quantify the effects of changes in flows of *supporting*[1] ecosystem services (henceforth ESS or simply services) on crop yields and associated external inputs such as fertilizers and pesticides (Clough et al., 2015).The focus here therefore has been on developing and calibrating the optimization model for each landscape to local economic and agronomic data while using preliminary parameter values for the ecosystem-service production functions which is sufficient to meet the aim of this paper. For this reason we also focus on an illustrative above-ground ecosystem service, pollination, however bio-control will be modelled using similar principles. Below-ground services are on the other hand modelled in their entirety as will be explained below. In a forthcoming step we will link the calibrated economic models with WP 4's multi-PF.

Nevertheless we perform test simulations to ensure that the optimization models reproduce observed yields, fertilizer application rates and crop areas, and conclude by generating some highly exploratory results (i.e. based on the preliminary parameratizations of the ecosystem service production functions that need to be validated in WP 4).

We begin by extending the standard theoretical farm-economic optimization model to consider the effects of below- and above-ground ground ecosystem services on crop yields and fertilizer input rates. To build the empirical ecological-economic model we have extended the positive mathematical programming model developed by Brady (2003) to include ESS. Since the effects of different landscape structures on ESS and yields will be quantified using the landscape specific multi-PFs developed in WP4, spatial aspects are not considered

[1] In this report we define supporting ecosystem services as those ecosystem functions that need to be managed to deliver the final ecosystem services, crop yields (cf. Haines-Young and Potschin 2009; see also Fischer et al. 2009).

explicitly in the economic model. To calibrate the landscape specific models we have used regional agricultural statistics from EUROSTAT, and agronomic and ecological data from WP 2 and WP 3, as well as information from agricultural experts in relevant partner countries (i.e., Italy, Hungary, Sweden, Poland, Germany, Netherlands and UK). The primary agricultural data we used are typical crop rotations, areas of major crops, and normal yields and input levels per ha by crop (primarily NPK fertilizers).

The resulting ecological-economic optimization models will allow us to study the effects of different degrees of ecological intensification (e.g., low, high or optimal) and landscape structures on supporting ecosystem services, yields, external input use and farm incomes in each of the case-study landscapes. In the exploratory results we quantify the (marginal) natural-capital value of above and below ground biodiversity and attendant supporting ecosystem services to farmers given a particular landscape structure and degree of ecological intensification. We also illustrate the potential of ecological intensification to support farmers' incomes through optimization of ecosystem services. This will make it possible in conjunction with the Multi-PF from WP 4 to assess the desirability of investing in natural capital and for determining the optimal level of ecological intensification in each of the case-study landscapes (from either the farmers' perspective or society's goals).

2 Theoretical economic optimization model

In this section we develop the economic optimization model that will be used to evaluate the impacts of ecological agriculture on farm incomes in interaction with multi-PF (WP4) in each study landscape. Accordingly the model is driven by the behavioural assumption that farmers aim to maximize farm income or profit. We begin by presenting a standard agricultural-economic model with endogenous yield and thereafter show how this model can be extended to consider the influence of farmers' land-use decisions (crop and management choices) on supporting ecosystem services and, in turn, of changes in these services on agricultural production (yield and input use).

2.1 Standard agricultural economic model

To begin with note that farmers allocate crops to their arable area and apply fertilizer to maximize profit (excluding annual sunk costs) subject to resources constraints:

$$\max_{\mathbf{X},\mathbf{N}} \pi = \sum_{j=1}^{J} \left[p_j Y_j(N_j) - w_j N_j \right] X_j - G_j\left(X_j\right) \tag{2.1}$$

subject to

$$\sum_{j=1}^{J} X_j \leq \overline{A} \tag{2.2}$$

$$X_j, N_j \geq 0 \qquad\qquad \forall\, j.$$

where the choice variable X_j (ha) is the area allocated to crop or land-use $j \in J$ and N_j is the rate of nitrogen fertilizer input (N kg/ha) to crop j. The parameter p_j is the market price of crop j, and w_j the unit price of applying N-fertilizer to crop j; all in €/kg. Note that either nitrogen input or yield can be construed as a proxy for external input intensity since other variable inputs such as the nutrients phosphorous and potassium, pesticides and energy (e,g., for drying) tend to vary linearly with N input or yield. Consequently it is not necessary to model other input decisions explicitly here, but instead interpret the prices p_j and w_j to be net of or including associated variable costs, whichever the case might be. For tractability we therefore focus on N input as the only variable cost.

The production function Y_j is the yield of crop j (kg/ha) resulting from fertilization rate N_j. This function is assumed to be concave, i.e., increasing at a decreasing rate in N. The cost function G_j represents nonmonetary and hence unobservable opportunity costs of increasing the area of crop j, e.g., own labour and risk. The cost function is assumed to be convex or increasing in X. Since agricultural land is a limited resource, Eq. (2.2) constrains the total area of land used in production to the area of land available on the farm or region, $\bar{A}$ (ha). Note that other potential resource or technological constraints such as the amount of family labour or financial constraints might also exist but for simplicity we do not consider them here, but these can be easily modelled in the same way and added to the empirical model if relevant. Finally, the choice variables X_j and N_j cannot be negative.

The solution to this problem can be found using the Lagrangean method

$$L(\mathbf{X},\mathbf{N}) = \sum_{j=1}^{J}\left[p_j Y_j(N_j) - w_j N_j \right] X_j - G_j\left(X_j\right) - \lambda\left(\sum_{j=1}^{J} X_j - \bar{A} \right) \tag{2.3}$$

where λ is the Lagrangean multiplier associated with the area constraint which , from an economic perspective, is interpreted as the shadow price of land or the marginal economic value of arable land to the farmer.

Since the problem is convex, the first order necessary conditions for profit maximization are also sufficient to guarantee an optimal solution, which are

$$\frac{\partial L}{\partial N_j} = 0 \quad \Rightarrow \quad p_j \frac{\partial Y_j}{\partial N_j} = w_j \quad \forall\, j \tag{2.4}$$

$$\frac{\partial L}{\partial X_j} = 0 \quad \Rightarrow \quad p_j Y_j(N_j) - w_j N_j - \frac{\partial G_j}{\partial X_j} = \lambda \quad \forall\, j. \tag{2.5}$$

Eq. (2.4) implies that fertilizer should be applied until the revenue from applying the last unit of fertilizer equals the cost. Solving Eq. (2.5) simultaneously with Eq. (2.4) implies that the farmer should increase the area of crop j until the additional profit (i.e., crop revenues minus the cost of fertilizer and unobservable costs) is equal to the implicit cost (or shadow price λ) of using an additional unit of land in the production of j. If λ= 0 it implies that it is not profitable to use all land in production, in which case some area will be left idle.

2.2 Incorporating supporting ecosystem services into the model

Introducing the influence of ESS on agricultural production is, conceptually, quite straightforward. In instances where services can be mediated via a market, such as (in principle) pollination of crops by commercial honey bees, there is no principal difference to modelling other purchased inputs such as fertilizer, since the farmer can simply hire in as many hives as they desire. More problematic, and our concern here, are the services provided by wild organisms, because these can only be managed indirectly through farmers' maintaining suitable habitat. Habitat though is likely to come at a cost, either by reducing the area of arable land available for commercial crop production or reducing the intensity of production. Consequently we focus on the management of ESS that are provided by wild organisms.

In the standard model, Eqs. (2.1) and (2.2), it is assumed that environmental conditions, such as flows of ESS, are constant; hence it is not necessary to represent them in the model. However if farmers' land-use decisions have consequences for flows of services that influence crop production then these can be captured by extending the standard crop production function Y_j to include ESS. In this case the rate of flow of a particular service $i \in I$, denoted E_i (and measured using a relevant indicator), can be considered an unpriced input.

We single out the land use $j=H$ to represent habitat and hence the area of habitat is denoted X_H. Since the rate of flow of each service i is influenced indirectly through the area of habitat, we need to express E_i as a function of habitat area, thus $E_i = E_i(X_H)$ or in vector notation $\mathbf{E}(X_H)$. Consequently if the yield of a particular crop j is influenced by ESS, then the crop production function can be written as

$$Y_j = \left(N_j, \mathbf{E}\left(X_H\right)\right). \tag{2.6}$$

We assume that even this production function complies with common sense, meaning that higher levels of services will be associated with higher yield ($\partial Y_j / \partial E_i \geq 0$ for all i) but the effect is diminishing ($\partial^2 Y_j / \partial E_i^2 \geq 0$ for all i).

The farmer's optimization problem when considering ESS needs to be modified as follows:

$$\max_{\mathbf{X},\mathbf{N}} \pi = \sum_{j=1}^{J} \left[p_j Y_j \left(N_j, \mathbf{E}\left(X_H\right)\right) - w_j N_j \right] X_j - G_j\left(X_j\right) \tag{2.7}$$

subject to

$$\sum_{j=1}^{J} X_j + X_H \leq \bar{A}, \qquad \mathrm{H} \in \mathrm{J}, j \neq H, \tag{2.8}$$

which implies that increasing habitat area can boost yield, by Eq. (2.6), and hence profit, Eq. (2.7), but this potential must be weighed against the reduction in area available for crops, Eq.

(2.8). The optimal solution or trade-off can be found through suitable modification of the Lagrangean specified in Eq. (2.3). In addition to Eqs. (2.4) and (2.5) the solution to this problem is characterized by the following condition

$$\frac{dL}{dX_H} = 0 \Rightarrow \sum_{j \neq H}^{J} p_j \left(\frac{\partial Y_j}{\partial E_1} \frac{\partial E_1}{\partial X_H} + \frac{\partial Y_j}{\partial E_2} \frac{\partial E_2}{\partial X_H} + \cdots + \frac{\partial Y_j}{\partial E_I} \frac{\partial E_I}{\partial X_H} \right) X_j - \frac{\partial G_H}{\partial X_H} = \lambda, \tag{2.9}$$

where the term in parentheses (via the Chain Rule) is the cumulative change in the yield of crop *j* attributable to the simultaneous changes in flows of the different ecosystem services $E_1, E_{2,\ldots,} E_I$ brought about by the change in habitat area X_H. Accordingly the first term in the parentheses is the change in yield brought about by the change in E_1, to which the change in yield brought about by the change in E_2 is added and so on. In this way we capture the effect on yield of changes in multiple services in an additive process as linked to habitat area.

According to condition (2.9) the farmer should increase the area of habitat until the marginal increase in total revenue from all crops brought about by the concomitant increases in ESS (and less any nonmonetary costs of increasing habitat area), is equal to the implicit cost, λ, of using an additional unit of land for habitat (since λ is the forgone profit of not growing commercial crops on the land). In this sense the optimization of ESS follows identical principals for optimizing other inputs: habitat area and hence ESS should be increased until the marginal benefit of doing so equals the marginal cost. The difference is the indirect management required for augmenting ESS via land use.

In the next section we specify the production functions to be used in our empirical modelling of ESS.

3 Empirical production function and economic model

For the empirical modelling we single out two groups of ESS that influence crop production. Services generated by below-ground organisms (or soil biodiversity) such as earth-worms, mites and bacteria, and those generated by above-ground organisms such as beetles, bees and spiders. As soil biodiversity forms the basis of soil productivity, we begin by specifying a basic production function that only considers the influence of below-ground ESS on yield.

3.1 Below-ground ecosystem services

Soil organic carbon (SOC) concentration has been shown to be a good indicator of flows of below-ground ESS affecting yield (Brady et al., 2015). Consequently we propose to use SOC concentration as an indicator of the multiple below-ground services that co-vary with SOC. Following Brady et al. (2015), the yield of crop *j* in year *t* considering below-ground services given a constant rate of above-ground services is modelled as:

$$Y_j^0 = a_{1,j} + a_{2,j} N_j + a_{3,j} N_j^2 + a_{4,j} C + a_{5,j} C^2 + a_{6,j} N_j C \tag{2.10}$$

where N_j, as previously, is the rate of fertilizer input to crop *j* (kg/ha) and *C* (% SOC) is current SOC concentration at a relevant spatial scale (i.e., depending on data availability, it could be either a farm average or a field-specific measure); and $a_{1,j},\ldots a_{6,j}$ are the parameters of the crop-specific production functions.

Furthermore, because SOC can only be influenced indirectly through farmers' land-use decisions, we model SOC concentration (in accordance with the theoretical model where C is equivalent to some E_i) as a function of land use, i.e., $C=C(\boldsymbol{X})$ where $\boldsymbol{X}=(X_H,X_1,\ldots,X_I)$. For the purposes of this paper, however, we ignore the fact that SOC is also a stock variable that is determined by historical land-use rather than current land-use alone. For short-term decision making this static framework is sufficient to derive marginal valuations of natural capital and supporting ecosystem services to farmers in each landscape, however, for long-term analyses we will not be able to study the optimal adjustment path, but rather base the analysis of the future potential of ecological intensification on land-use assumptions . Hence it is not necessary for our purposes to specify the relevant dynamic model in which we would need to introduce time variables, but leave this to future work.

3.2 Above-ground ecosystem services

We now extend the basic production function, Eq. (2.10), to consider the impact of changes in the rate of *pollination* services provided by mobile-insects to flowering crops (e.g., oilseed rape). To model the effect of pollination on the yield of pollination-dependent crop k $\left(k \subset J\right)$ when considering both above- and below-ground ecosystem services we assume the following relationship

$$Y_k^E\left(N,C,P\right) \;=\; \left[1 \;+\; a_7\left(P-\overline{P}\right)\right]Y_k^0\left(N,C \mid \overline{P}\right) \tag{2.11}$$

where the variable P ($0 \le P \le 1$) describes the effect of insect pollination and $\overline{P}$ is the background or normal rate of pollination services reaching the crop, and the parameter a_7 ($0 \le a_7 \le 1$) determines the change in yield when moving from no insect pollination services ($P = 0$) to the maximum rate of pollination services ($P = 1$).

Similar to C, we introduce the variable P as being equivalent to some E_i that can only be influenced indirectly through farmers' land-use decisions, specifically through managing the area of pollinator habitat in the landscape. Note that in the economic model we focus on how much land is allocated to habitat at a course spatial scale, whereas its exact arrangement in the landscape will be simulated in the multiple PF. Hence we do not need to represent space in the economic model explicitly, but rather assume that the farmer follows the spatial allocation of habitat modelled in the multi-PF. Consequently in the economic model the farmer is assumed to optimize management given a particular allocation of land-use to habitat (i.e., area of total farm arae), implying

$$P = P\left(X_H\right) \tag{2.12}$$

where X_H, as previously, is the area or arable land-use that qualifies as pollinator habitat. Further we assume $\partial P/\partial X_H \ge 0$ and $\partial^2 P/\partial X_H^2 < 0$ implying that increasing the area of habitat increases pollination services but at a decreasing rate.

3.3 Valuing habitat and supporting ecosystem services

As part of this Deliverable we also wish to explore in a comparative analysis the current value of ESS to farmers in the different case-study landscapes. First denote the solution to the farmers' optimization problem when assuming flows of services are held constant at their current levels as ($\boldsymbol{N}^*$, $\boldsymbol{X}^*| C^0,P^0$) and the associated maximized farm profit as $\Pi(\boldsymbol{N}^*, \boldsymbol{X}^*| C^0,P^0)$, then envelope theorems tell us that the marginal value of an extra unit of soil natural capital (MV_C), which is a stock variable, as indicated by a unit change in C is

$$MV_C = \frac{\delta \Pi\left(\mathbf{N}^*, \mathbf{X}^* | C^0, P^0\right)}{\delta C^0} \times \frac{(1+\delta)}{\delta} \tag{2.13}$$

where δ is the discount rate. That is, because C is a stock variable any change in the stock will affect future profits in perpetuity. The correct indicator of the change in value in his case is the present value of the changes in future profits which is calculated by multiplying the marginal change in annual profit by the perpetuity factor (1+δ)/δ (Brady et al., 2015).

In our model we do not currently consider potential stock effects on pollinator communities, rather pollination services are related only to the area of habitat which can be altered annually. Consequently the marginal value of an additional unit of habitat (MV_P) that generates pollination services P is

$$MV_P = \frac{\delta \Pi\left(\mathbf{N}^*, \mathbf{X}^* | C^0, P^0\right)}{\delta P^0} \frac{\delta P^0}{\delta X_H}. \tag{2.14}$$

3.4 Conceptualization of ecological intensification

In this section we illustrate the principles of ecological intensification (Cassman, 1999; Bommarco et al., 2013) as we intend to apply them here and how our model can be used to evaluate its potential to boost agricultural productivity or contribute to more sustainable agriculture. Based on the conceptual graphic developed by Cassman et al. (2003) and a hypothetical crop we show in Figure 1 how our production functions fit into this framework. The curve A represents the standard crop production function specified in Eq. (2.10) when assuming the current SOC concentration is $C=C^0$ and the normal level of pollination services is $P=P^0$, i.e., flows of ESS are constant and can't be influenced by the farmer. According to Eq. (2.4) fertilizer input should be increased until the marginal profit of doing so is zero, which from standard principles of calculus is where the slope of the red price line (i.e., *w/p)* is equal to the slope of the production function, curve A. This tangency (point A*) indicates that the optimal economic yield in this example is currently around 9.5 t/ha and the associated optimal fertilizer input rate is 100 kg/ha.

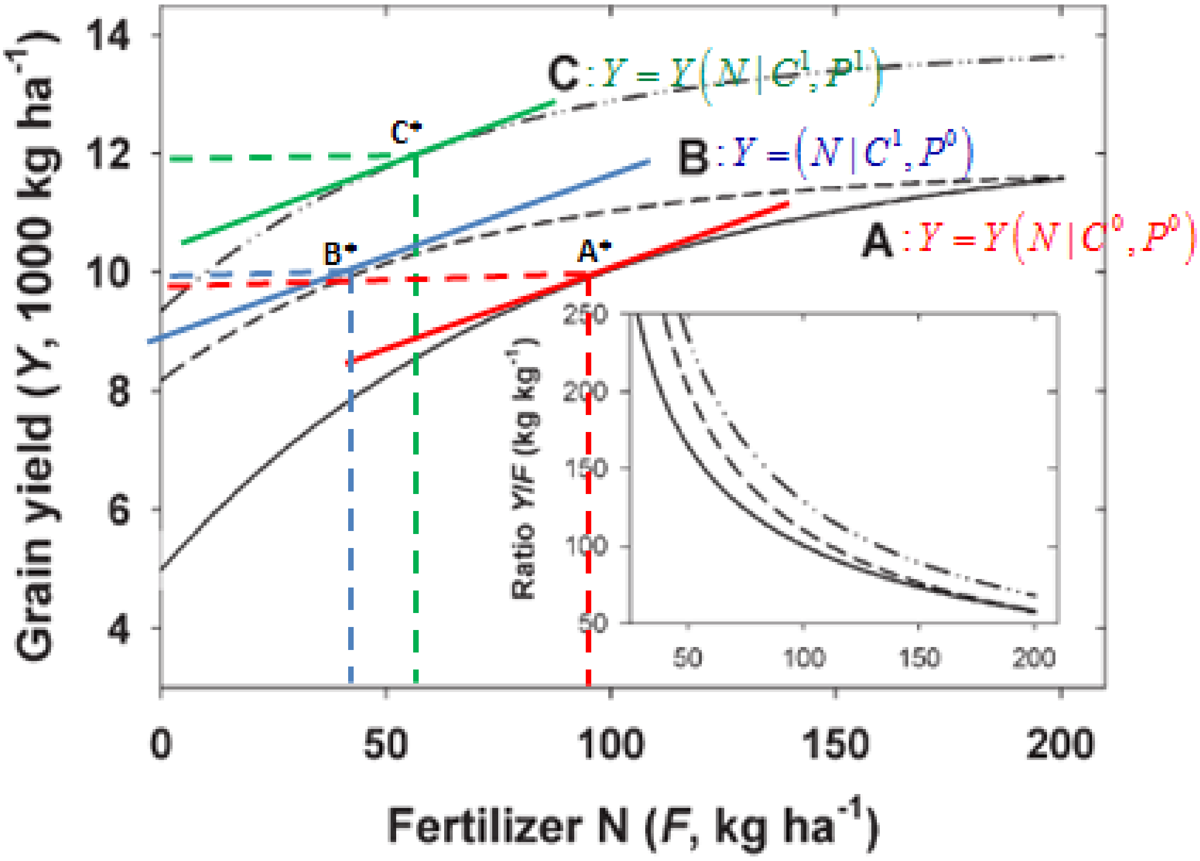

Figure 1. Theoretical potential of ecological intensification to boost productivity and economic optimal yield. Production function showing potential yield and associated fertilization rate with current intensity of ecosystem services (curve A), with higher intensity of below-ground services (curve B) and with higher intensity of both above- and below-ground services (curve C). Source: The diagram is an extension of Cassman et al. (2003, Figure 15)

Now let us assume that the famer invests in better soil management practices that results, over time, in SOC content rising from C^0 to C^1, and hence in higher levels of below-ground services, while pollination services remain constant at P^0. In this case the relevant production function is curve B indicating that the increase in below-ground services boosts soil productivity. Following identical profit-maximization principles, the optimal yield rises to almost 10 t/ha while the associated fertilization rate declines to almost 40 kg/ha (as indicated by the tangency of the blue price line to curve B at point C*).The intensification of below-ground services results under these assumptions in higher optimal yield and lower fertilizer use. Economically speaking the farmer has substituted external inputs with below-ground services, by better utilizing the potential of soil organisms to generate supporting services. This substitution is profitable to the farmer if it is less costly to augment ESS than purchase mineral fertilizer.

Finally, curve C illustrates the effects of simultaneously intensifying flows of above-ground services by taking measures that increase flows of pollination services from P^0 to P^1. Resultant optimal yield is almost 12 t/ha and associated fertilizer rate is around 60 kg/ha (as indicated by the tangency of the green price line to curve C at point C*). The optimal fertilizer rate increases somewhat compared to that implied by curve B because the intensification of pollination services also raises the marginal productivity of applying fertilizer. Accordingly our model has the ability to evaluate the potential of ecological intensification for boosting agricultural productivity and measuring the effects on output, external inputs and farmers' incomes.

4 Procedures for calibrating models to case-study landscapes

To apply the theoretical production functions and resulting economic model to a real region they need to be calibrated. Calibration is a fundamental aspect of developing empirical models of any sort and, generally speaking, involves systematically adjusting the estimates of a model's parameters so that the model's outputs more accurately reflect external benchmarks. Our procedure involves three independent calibration steps:

a) Calibrating generic yield functions to observed yields and input levels
b) Calibrating the pollination function to observed yields and
c) Calibrating farm level production to observed land-use.

4.1 Calibration of basic production functions

To begin with we modify the basic yield function for a particular crop in Eq. (2.10) as follows (and for clarity dropping the crop subscript *j*)

$$Y^{\text{cal}} = a_1^{\text{cal}} + a_2 N + \theta a_3 N^2 + a_4 C + \sigma a_5 C^2 + a_6 NC \tag{2.15}$$

where a_1^{cal}, θ and σ are crop specific calibration parameters. The intercept term a_1^{cal} shifts the production function vertically up or down to calibrate to local productivity; while θ adjusts the curvature of nitrogen response, a_3, to reflect the farmer's observed fertilizer input (which is assumed to be the profit maximizing level) and σ adjusts the curvature of C response, a_4, to calibrate to the SOC concentration that generates maximum potential yield over the range of SOC.

The calibration parameters θ and σ are defined uniquely in terms of the parameters of the model as (see Brady and Hedlund (2015) for derivations):

$$\theta = \frac{w - p\left(\hat{a}_2 + \hat{a}_6 \bar{C}\right)}{2\hat{a}_3 p \bar{N}} \tag{2.16}$$

and

$$\sigma = \left(a_2 a_6 - 2\theta a_3 a_4\right) / (4\theta a_3 a_5 C^{\max} - a_6^2 C^{\max}) \tag{2.17}$$

where $\overline{N}$ is normal nitrogen input, $\overline{C}$ is observed or current SOC concentration and C^{max} is the SOC concentration that generates maximum yield which is

$$C^{\max} = \left(\hat{a}_2 \hat{a}_6 - 2\hat{a}_3 \hat{a}_4\right) / (4\hat{a}_3 \hat{a}_5 - \hat{a}_6^2). \tag{2.18}$$

Finally, to ensure that the modelled economic-optimal yield is identical to observed yield (which we assume is a consequence of farmers optimizing N application rates to maximize profits) we simply redefine a_1 to ensure that $Y^*\left(\overline{C}, N^*\right) = \overline{Y}$ which gives

$$a_1^{\text{cal}} = \overline{Y} - Y^{\text{int}}\left(\overline{C}, N^*\right) - \hat{a}_1. \tag{2.19}$$

To complete the calibration for each landscape model we need the following data:

- Generic yield functions for each crop (i.e., generic values for $a_1,..,a_6$),
- Normal yield $\overline{Y}$ and fertilizer input $\overline{N}$ for each crop and landscape,
- Current SOC concentration $\overline{C}$ at a relevant spatial scale, and
- Output and input prices p and w.

4.2 Calibration of pollination functions

Unfortunately we do not have the data to estimate the current level of pollination services directly; instead these will be inferred through a calibration process that is partly based on assumptions about the current degree of pollination services, and the minimum and maximum yield effects of pollination. For calibration purposes we therefore assume that the normal yield of pollination-dependent crops, $\overline{Y}_k$, results from intermediate pollination services, i.e., $\overline{P} = 0.5$, in which case Eq. (2.11) can be rewritten as

$$Y_k^E\left(N, SOC, P\right) \;=\; \left\{1 \;+\; a_7\left(P - 0.5\right)\right\} Y_k\left(N, SOC \mid \overline{P}\right). \tag{2.20}$$

It follows that yield with no insect pollination, PS=0, is

$$Y_k^{E\min}\left(N, SOC, P = 0\right) \;=\; \left(1 \;-\; \frac{a_7}{2}\right) Y_k\left(N, SOC \mid \overline{P}\right), \tag{2.21}$$

and yield at full insect pollination, PS=1, is

$$Y_k^{E\max}\left(N, SOC, P=1\right) = \left(1 + \frac{a_7}{2}\right) Y_k\left(N, SOC \mid \bar{P}\right). \tag{2.22}$$

With normal pollination Eq. (2.20) reduces back to Eq. (2.11), which is what we want.

The economic model considers how much farmland is taken out of production to create habitat and which crops constitute habitat. Changes in land-use will be translated into spatially explicit land-use information in the multi-PF. The value of *P* for any particular land-use configuration is then calculated by the spatially explicit multi-PF.

To complete the calibration we need the following data from WP 4 and multi-PF:

- An estimate of a_7.
- Assumptions about the minimum and maximum yields Ymin and Ymax.
- An assumption about the area of background habitat to which farmers can increase by creating habitat on their arable land.

Since the multi-PF is not yet complete we will make an assumption about the value of the parameter a_7 for the purposes of this paper which will be based on the literature.

4.3 Calibration of economic model to observed land-uses

The farmers' theoretical objective function Eq. (2.1) includes the nonlinear cost term G_j to capture unobservable opportunity costs. We now introduce the functional form that will be used to model these costs and the steps required to parameterize it based on observed land-uses. Let the cost function have the form (Howitt, 1995a)

$$G_j\left(X_j\right) = \Psi_j X_j + 0.5\Gamma_j X_j^2 \tag{2.23}$$

where Ψ_j and Γ_j are the parameters to be estimated in the calibration procedure. The associated marginal cost function is linear

$$\frac{dG_j}{dX_j} = \Psi_j + \Gamma_j X_j. \tag{2.24}$$

To estimate the parameters we revise the farmers' theoretical decision problem as defined by Eqs. (2.1)-(2.2) as follows:

$$\max_{\mathbf{X}} \pi = \sum_{j=1}^{J} \left[p_j \bar{Y}_j - w_j \bar{N}_j \right] X_j$$

$$s.t.$$

$$\sum_{j=1}^{J} X_j \le \bar{A} \tag{2.25}$$

$$X_j \le \bar{X}_j \left(1+\varepsilon\right) \qquad \forall j$$

where the yield function Y_j and N-fertilizer input rate Nj are replaced by the observed yields and input rates $\bar{Y}_j$ and $\bar{N}_j$ respectively. Further the non-linear cost term in the theoretical objective function G_j has been replaced by a land-use constraint (by the duality of prices and quantity constraints) that constrains the area of each land-use X_j, to the observed area, $\bar{X}_j$, multiplied by a perturbation term (1+ε) where ε is an arbitrarily small number (e.g., 0.0001) that ensures that the land-use constraints don't simultaneously bind with one of the other constraints at observed land-use areas. The problem leaves the following linear program that can be solved using the Lagrangean method

$$L\left(\mathbf{X}\right) = \sum_{j=1}^{J} \left(p_j \bar{Y}_j - w_j \bar{N}_j \right) X_j - \lambda \left(\sum_{j=1}^{J} X_j - \bar{A} \right) - \sum_{j=1}^{J} \mu_j \left[X_j - \left(1+\varepsilon\right) \bar{X}_j \right] \tag{2.26}$$

where the multipliers λ and μ_j are the shadow prices associated with the farm area and land-use constraints respectively, which tell us the rate at which maximum profit changes with respect to changes in the land endowment, $\bar{A}$, and the observed area of each land-use, $\bar{X}_j$.

Clearly the solution to this problem is the observed land-use vector $\bar{\mathbf{X}}$ augmented by the perturbation term; but also, implicitly, the observed yields and fertilizer input rates $\bar{Y}_j$ and $\bar{N}_j$. However the solution also generates nontrivial information that is needed to calibrate the parameters of the nonlinear cost function: the shadow prices of the land-use constraints, μ_j. The parameter values are determined as

$$\Psi_j = -\mu_j \tag{2.27}$$

$$\Gamma_j = \frac{2\mu_j}{\bar{X}_j} \tag{2.28}$$

the proof of which can be found in Howitt (1995b).

Substituting the result of Eq. (2.27) into Eq. (2.23) implies

$$G_j\left(X_j\right) = -\mu_j \bar{X}_j + \mu_j \bar{X}_j = 0, \tag{2.29}$$

which results in the maximized value of profits being unaffected by the cost term, and hence being consistent with opportunity costs being nonmonetary or implicit costs. Further substituting the result of Eq. (2.28) into Eq. (2.24) implies

$$\frac{dG_j\left(\bar{\mathbf{X}}\right)}{dX_j} = \mu_j \tag{2.30}$$

which is simply the shadow price of the land-use constraint, i.e., the marginal cost of increasing land-use *j* by one hectare as implied by the theoretical cost function G_j. Accordingly the calibration procedure reproduces observed or monetary profits as well as complying with the marginal conditions necessary for profit maximization.

5 Representing agriculture in the case-study landscapes

In this section we gather the data necessary to represent the structure of agricultural production in each study landscape and to calibrate the economic models to observed farmer behaviour using the procedures detailed in Section 4. First we provide an overview of agricultural conditions in each landscape followed by landscape specific data.

5.1 Overview of study landscapes

The case-study landscapes are nested within the Eurostat system of regions according to Table 1. In some cases the Liberation field-study sites, eight in each country (Figure 2), span multiple NUTS3 regions hence for these countries (NE, PO and UK) two NUTS3 regions are specified.

Table 1. Location of study landscapes within EUOSTAT system of regions.

Country (NUTS1)	ID	NUTS2 Region	NUTS3 Region
Germany	GE	Bayern	Unterfranken
Hungary	HU	Alföld és Észak	Heves
Italy	IT	Nord-Est	Padova
The Netherlands	NE	Oost-Nederland	Zuidwest-Gelderland and Arnhem/Nijmegen
Poland	PO	Wielkopolskie	Leszczynski and Poznanski[a]
Sweden	SE	Sydsverige	Scania
United Kingdom	UK	South East	Berkshire and Oxfordshire

Notes: a. One of the Polish field sites is located in the NUTS3 region of Gorzowski but since this site has similar conditions to Leszczynski and Poznanski, we consider only these.

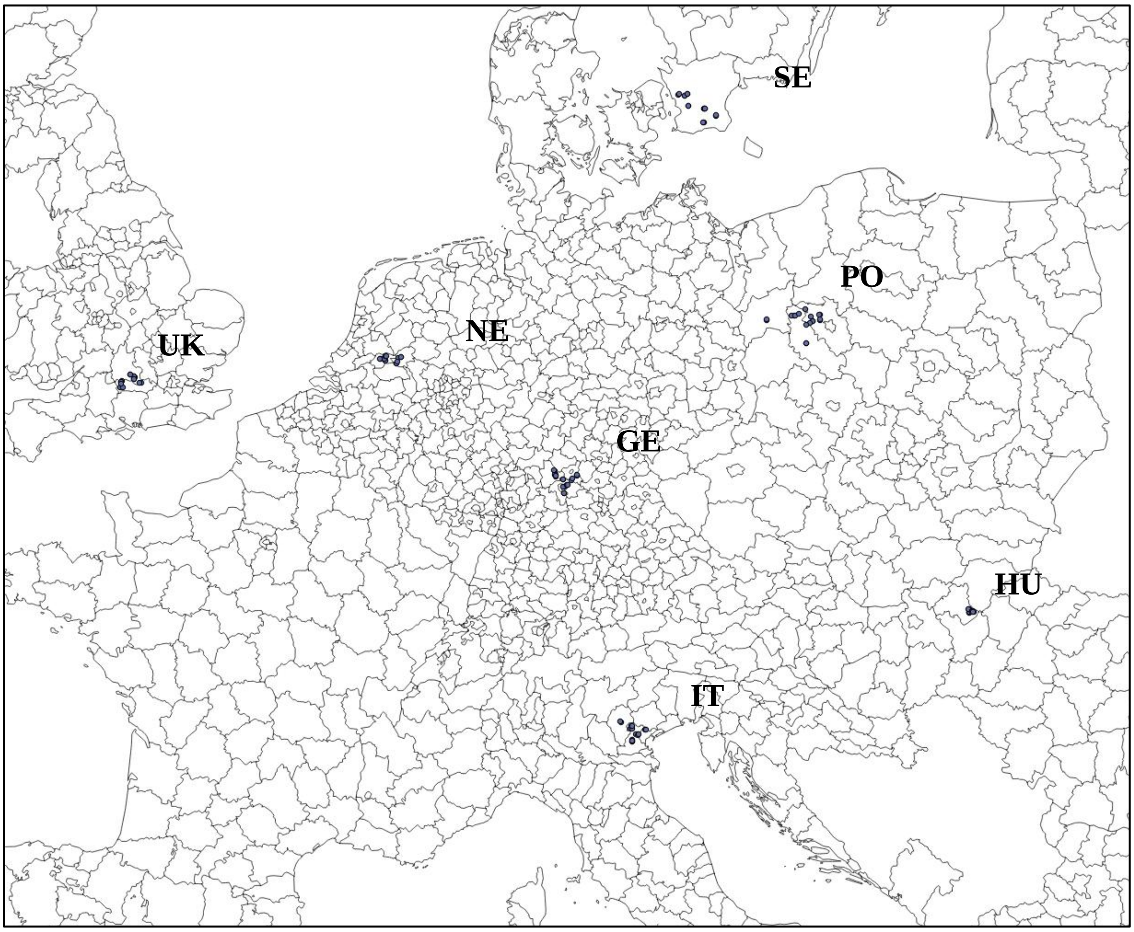

Figure 2. Locations of the seven case-study landscapes in Europe and associated Liberation field sites (dots) at NUTS3 level.

Germany (GE)

The German (GE) landscape is nested in the larger (NUTS2) region of Bayern and the smaller (NUTS3) region of Unterfranken (Lower Franconia). Its climate is temperate with mean precipitation of 500 mm and mean annual temperature of around 9.9°C. The study landscape is characterized by the numerous river valleys of the Maine and its tributaries, as well as fertile plains in the Southern parts of Lower Franconia, which is used intensively for agriculture. The most commonly grown arable crops are cereals, primarly wheat and barley, sugar beets, corn/maize and oilseed rape. Wheat yield can range from 4 t/ha on sandy soils to over 10 t/ha on the most fertile plains, and is generally high with average yields over 7 t/ha. Despite the high level of agricultural intensification and issues with landscape simplification (enlargement of fields, removal of field boundaries etc.), the landscape is still rather heterogeneous, due to the interspersion of agricultural land, the river valleys used intensively for grape production and large forest areas. The intensity and scale of production has increased over time, putting additional pressure on the environment, through increases in fertilizer and chemical use, simplified crop rotations and lack of organic amendments to soils. These developments have led to nitrogen leaching, soil degradation, and declines in biodiversity and associated ecosystem services and mosaic values.

Hungary (HU)

The Hungarian (HU) landscape is nested in the larger region of Alföld és Észak and the smaller region of Heves. The region has a moderately warm climate and is among the driest in the country. The mean annual temperature is 10ºC and annual precipitation is between 450-550 mm, but with high variability in its distribution. Heves has a total area of 49 000 ha and an altitude range of 88-102 m a.s.l. and lies on the north-eastern edge of the Great Hungarian Plain (also known as Alföld or Great Alföld). Land use in the region is characterized by agriculture (50%), forest (30%), nature conservation and research (10%) and tourism (10%). The plain is typical of the extensive nature of agricultural land use in Hungary, with the major activities being livestock grazing (cattle and sheep), hay production and arable cropping dominated by winter wheat, barley, maize, sunflower and oilseed rape. Human settlement, industrial activities and water resource management have low impact on land use in this region. It is a major transitory zone for migratory birds, which is also promoted by state funded agri-environmental schemes. The region has a high variety in soils, the most dominant is the sodic soils "szik" (53%) with some other types of soils (mostly brown soils) with salinization impact due to Kisköre dam (Tisza-lake).

Italy (IT)

The Italian (IT) landscape is nested in the larger (NUTS2) region of Nord-Est and the smaller (NUTS3) region of Padova. The climate is humid sub-Mediterranean with annual rainfall ranging between 1200–1500 mm year^{-1} and a mean annual temperature of 13°C.The investigated area extends for about 10,000 km^2 in the Venetian Plain (north-eastern Italy). About 75% of the study area is dominated by intensive agriculture that is interspersed by urban areas and fragments of semi-natural habitats such as forests, grasslands and hedgerows. The dominant crops are maize, wheat, and soybean, while the cover of permanent grasslands and mass-flowering crops such as oil seed rape or sunflower are very scarce. Farms are generally small. In 2010, the average farm size was c. 7 ha, while the average Standard Output was 47000 euro. The field size is generally around 0.5-1 ha.

Netherlands (NE)

The Dutch (NE) landscape is nested in the larger (NUTS2) region of Oost-Nederland and the smaller (NUTS3) regions of Zuidwest-Gelderland and Arnhem/Nijmegen which are located in the central/east part of the Netherlands. The climate has a maritime influence, with relatively mild summers and winters with an average annual temperature of 10°C and total precipitation of around 800 mm. Soils range from fertile clay deposits along the rivers Maas (Meuse), Waal (Waal), and Nederrijn (Nether Rhine) to nutrient poor sandy soils more northwards. Agricultural land use is also quite diverse ranging from orchards to meadows and arable farming. The Liberation experiment was, however, only performed in the more important, nutrient rich area for arable farming. Similar to the rest of the country yields in this region are generally high, with an average winter wheat yield of around 9 t/ha. Agriculture is intensive, with high inputs of nutrients and agro-chemicals. Mineral fertilizer application, however, is relatively low as animal breeders are abundant and subsequently liquid manure is widely available. Fields are relatively small compared to neighbouring countries with intensive agricultural land use, but semi-natural habitats are scarce. Crop rotations are generally short and potatoes and sugar beets are almost always in the rotation, leading to degraded soils. Due to the high input of manure, there is usually not much concern about declines in soil organic matter and overall soil organic matter levels are stable over time. Biodiversity in arable farmlands has though declined dramatically over recent decades.

Poland (PO)

The Polish landscape is nested in the larger (NUTS2) region of Wielkopolskie and the smaller (NUTS3) region of Poznanski (the experimental sites located in the regions of Leszczynski and Gorzowski have also similar conditions to those found generally in Poznanski). The climate is relatively mild with an average annual temperature of 8.2°C and precipitation of 500-550 mm, which is the lowest in the country. The growing season is though longer compared to the rest of the country, 210-220 days. Agriculture in the region is dominated by family farms with many farms smaller than 5 ha and few larger than 1 000 ha. The average farm size of 13.43 ha is higher than the national average of 10.49 ha. Almost 90% of farms have livestock production which is above the average for Poland, primarily pigs, cattle and poultry. Soils are generally of poor quality and dominated by sandy and loamy types. There are few soils belonging to the highest classes, rather 40% of the arable area is considered poor or very poor from a soil quality perspective. In the past, potato and rye production dominated; however, today the main crops are wheat, barley, oilseed rape, maize and potatoes. There is often a water deficiency during the growing season, since groundwater levels sink, and long periods of dry are frequent.

Sweden (SE)

The Swedish landscape is located in the southern province of Scania. The climate is cold temperate with a mean annual temperature of 7.64°C and precipitation of 655 mm. Its plains which we focus on, have the most fertile agricultural land in Sweden and agriculture is characterized by specialized arable cropping, principally wheat, malt barley, oilseed rape and sugar beets. Yields are high on any standards with an average wheat yield of 7.9 t/ha but yields can exceed 10 t/ha. Arable fields are relatively large and interconnected. Historical removal of field boarders and other impediments have resulted in a simplified landscape. The intensity and scale of production has also increased over time, putting additional pressure on the environment, through increases in fertilizer and chemical use, simplified crop rotations and lack of organic amendments to soils. These developments have led to nitrogen leaching, soil degradation, and declines in biodiversity and mosaic values.

United Kingdom (UK)

The UK landscape is nested in the larger (NUTS1) region of the South East and the smaller (NUTS3) regions of Berkshire and Oxfordshire. The South East is the third largest region in England and the most populous. It also has the largest economy in the country outside London. The climate is temperate with a mean annual temperature of 9.5°C and precipitation of 650 mm of rain per year. Its agriculture is characterized by its diverse lowland landscape comprising open rolling chalk upland (Chilterns), river valleys (Thames Valley and Thames Basin Heath), farmed vale landscapes (Upper Thames Clay Vales), and small farm woodlands. This gives rise to intensively farmed arable land, areas of pasture associated with the valleys, and dairying within the vale landscape. On the chalk uplands in the Chilterns, the agriculture is predominantly arable, with some areas of pasture, grazing on commons, and woodland. Cultivated farmland and pasture across the South East are typically enclosed by hedgerows or their remnants. Arable production occupies around 47% of the agricultural area, with pasture occupying slightly less at 43% primarily in permanent grass, with some temporary leys and rough grazing. The remainder is made up of farm woodland and common land. Within the arable sector, wheat production dominates at 36% of the total arable area, followed by oilseed rape at 18% and then spring malting barley at 15%. Over time, agricultural intensification has led to an increase in the arable (cereals) area with a corresponding reduction in the grass area with a loss of both permanent pasture and meadows and thus a loss of the mosaic of mixed farming systems. The number of small farms has also declined with increasing farm size and loss of field boundaries driven, in part, by the larger modern farm machinery. There has been a corresponding reduction in biodiversity, reflected in the loss of farmland birds and rare arable plants, and some issues with soil erosion and nutrient runoff.

5.2 Structure of agricultural production in study regions

Table 2 overviews the size structure of farming in the case-study landscapes based on EUROSTAT data for the NUTS3 regions detailed in Table 1.

For The Netherlands and United Kingdom we have therefore aggregated the data for both NUTS3 regions, whereas for Poland we only use the data for the region of Poznanski since it is most relevant for our purposes. To gain an indication of the relative importance of small as opposed to large farms we have arbitrarily defined farms less than 50 ha as small and those larger as large. The average size of small and large farms as well as their proportion of arable land varies considerably among regions. Most land in Germany, Hungary Sweden and the UK is managed by large farms whereas in Italy, The Netherlands and Poland the area is more evenly divided across size classes. Last we overview the data for specialist field-crop farms which we intend to focus on in this study. This type of farming is quite prevalent in all regions (>= 30% of the arable area) but only minor in the Netherlands which needs to be kept in mind when considering the implications of the modelling results for this landscape.

Table 2. Farm structure in study regions according to EUROSTAT (2007) at NUTS3 level

		GE	HU	IT	NE	PO[a]	SE	UK
All Farms								
Number	nr	11 450	18 730	34 940	2 145	19 850	2 690	2 120
Agricultural Area (AA)	ha	354 240	118 040	149 330	40 940	289 120	201 577	120 115
Ave size	ha	31	6	4	19	15	75	57
Small Farms (< 50 ha)								
Proportion of All Farms	%	82%	98%	97%	90%	97%	61%	74%
Proportion of AA	%	36%	27%	60%	57%	54%	14%	12%
Ave size	ha	14	2	3	12	8.1	17	9.0
Large Farms (≥ 50 ha)								
Proportion of All Farms	%	18%	2%	3%	10%	3%	39%	26%
Proportion of AA	%	64%	73%	40%	43%	46%	86%	88%
Ave size	ha	108	221	66	80	196	166	197
Specialist field crop farms								
% AA	%	47%	61%	65%	9%	29%	71%	64%
Number	nr	4 220	1 710	24 500	145	5 850	1 722	475
Area	ha	165 750	71 980	96 420	3 885	84 730	143 335	77 365
Ave size All	ha	39	42	4	26	14	83	166
Ave < 50	ha	17	12	2	16	8	19	27
Ave ≥ 50	ha	137	1 478	61	106	195	184	606

Notes: a. Data for the NUTS3 region Poznanski.

5.3 Structure of crop production in study regions

5.3.1 Crop areas

To ensure that modelled crop production in the calibration year is representative of arable farming in each region, we base the proportion of the modelled farm area sown to the major crops in each landscape on Eurostat data for the relevant NUTS3 regions (Table 3), rather than the distribution of crops on our sample of farms used for the field experiments (Table 4). This is because the experimental sites have been chosen based on soil rather than farm properties, and hence are not necessarily representative of cropping in the larger region (Table 4).

Table 3. Distribution of crops at NUTS3 according to EUROSTAT in 2007

Crop	**GE**	**HU**	**IT**	**NL**	**PL**	**SE**	**UK**
Wheat	33%	46%		20%	15%	38%	48%
Rye	4%			0%	15%	3%	
Barley	25%	9%		3%	15%	26%	13%
Oats	1%				12%	4%	3%
Maize	1%	10%	76%	3%	3%		
Other Cereals	3%	3%	24%	1%	18%	1%	0%
Potatoes				4%	3%	2%	0%
Sugar beet	8%			6%	4%	15%	0%
Oilseed rape	15%	31%		1%	10%	8%	20%
Forage	11%			62%	5%	3%	16%

Table 4. Distribution of crops on surveyed farms by EUROSTAT classifications

Crop	**GE**	**HU**	**IT**	**NL**	**PL**	**SE**	**UK**
Wheat	20%	23%	7%	21%	20%	42%	42%
Rye	9%				4%		
Barley	24%	8%	23%	8%	8%	32%	15%
Oats		3%					
Maize	17%	12%	15%	8%	21%		
Other cereals	4%				8%		
Potatoes				5%	2%		
Sugar beet	7%		9%	3%	19%	10%	
Oilseed rape	10%	22%	8%	26%	17%	16%	22%
Forage		17%	24%		2%		

For modelling purposes we intend only to consider the major arable crops grown in each region which according to Table 3 and Table 4 are:

- Winter wheat
- Barley
- Maize
- Sugar beet
- Oilseed rape (OSR).

5.3.2 Normal yields and fertilizer application rates for modelled crops

To estimate normal yields of crops in each landscape we use the average yields reported from our farmer surveys conducted in the region (Table 5). These have also been validated by our regional farm experts and where necessary the yields have been adjusted to reflect regional averages.

Table 5. Normal yields (t/ha average across surveyed farms)

Crop	**GE**[a]	**HU**	**IT**	**NL**	**PL**	**SE**	**UK**
Winter wheat	7.7	4.5	6.0	8.9	6.3	8.3	7.1
Winter barley	6.9		4	6.5	7.1	6.8	7.5
Spring barley	5.8	3.3			4.5	6.6	
Oilseed rape (OSR)	4.3	1.6	4.0	2.8	4.2	3.8	2.8
Maize/Corn	56.9/5.3[b]	5.7	11.5	70.0	38.7		
Sugar beet	86.8		55	88.4	60.0	61.8	

Notes: a. For Germany validated with http://www.effizientduengen.de, http://www.regierung.unterfranken.bayern.de/aufgaben/uiz/7/01455/index.html; b.yield for maize silage and grain respectively.

Normal fertilizer input rates have been obtained from our farmer surveys (primarily winter wheat) and regional experts: nitrogen (Table 6), phosphorous (Table 7) and potassium (Table 8).

Table 6. Normal nitrogen (N kg/ha) input to crops

Crop	**GE**	**HU**[a]	**IT**	**NL**	**PL**	**SE**	**UK**
Winter wheat	190	90	180	170	130	170	185
Winter barley	140		120	na	160		140
Spring barley	60			110	100	91	95
Oilseed rape	190	90	170	212	230	168	190
Maize/Corn	160	90	260	Max 390	180	170	
Sugar beet	140		150	200	170	120	

Note: a. Application rates are identical in Hungary due to limitations on fertilizer application associated with agri-environmental schemes.

Table 7. Normal phosphorous (P kg/ha) input to crops

Crop	**GE**	**HU**	**IT**	**NL**	**PL**	**SE**	**UK**
Winter wheat	40	35		na	70	17	50
Winter barley					80		40
Spring barley		35		60	50	17	95
Oilseed rape	60	35		45	100	28	40
Maize/Corn		35		Max 34	60		
Sugar beet	100			Max 70	100	27	

Table 8. Normal potassium (K kg/ha) input to crops

Crop	**GE**	**HU**	**IT**	**NL**	**PL**	**SE**	**UK**
Winter wheat	40	20		na	120	18	45
Winter barley					160		45
Spring barley		20		130	100	13	45
Oilseed rape	50	20		60	260	31	45
Maize/Corn		20		na	170		
Sugar beet	350			Max 175	300	39	

5.3.3 SOC content across experimental fields

To model changes in below-ground ecosystem services we need measurements of SOC content typical for each landscape. As part of the Liberation field experiments we have measured SOC content which is shown to vary quite considerably among and within landscapes (Table 9).

Table 9. Soil organic carbon concentration across experimental fields

	Mean	**StD**	**Median**	**Max**	**Min**
GE	1.42	0.80	1.16	4.36	0.87
HU	2.12	0.56	1.92	3.63	1.58
IT	2.03	1.04	1.81	4.65	0.40
NE	1.70	0.39	1.72	2.28	0.90
PO	1.05	0.43	0.93	2.26	0.52
SE	1.92	0.43	2.00	2.50	1.15
UK	1.27	0.48	1.16	2.83	0.73

Source: Liberation field experiments.

6 Exploratory results: the potential for ecological intensification to boost future agricultural productivity

Guided by the theoretical results derived in Sections 3.3 and 3.4 we now use the calibrated economic models (Section 6) to *explore* the potential of ecological intensification to boost future agricultural productivity and support farm incomes across the different study landscapes. For this purpose we assume the future to be 25 years from now. In particular soil natural capital changes only slowly in response to changes in management practices; thus motivating the relatively long time horizon. As should be clear from the theoretical model, we do not model the adjustment process (i.e., dynamics) but rather contrast a typical farm found today in each landscape with the same farm 25 years hence; given various assumptions about the future state of natural capital and supporting ecosystem services.

The results are deemed exploratory because the ecological parameters used in the modelling are preliminary and have not yet been subjected to rigorous validation using the multi-PF (WP 4). Nevertheless the simulations are done within plausible ranges of the parameters and the results should be within the realms of what is possible to achieve in the future.

To begin with we estimate the current (marginal) value of ecosystem services to farmers in each landscape. After this we evaluate the impacts of optimizing ecosystem services to year 25 by assuming that farmers are free to maximize pollination services to their theoretical maximum but can only achieve a maximal growth rate in soil natural capital (as indicated by SOC content) of 1% p.a (Haddaway et al., 2015). To consider the likely costs of augmenting flows of ecosystem services we make a conservative assumption about the proportion of arable land that needs to be rested from commodity production for rejuvenating SOC and creating pollinator habitat. We set this area at 25% of the total farm area. The opportunity cost of increasing ES in this case is the potential output from using all land in commodity production.

As stated in Section 4.2 we need to make an assumption about the value of the parameter a_7 for modelling pollination services. According to studies on the impacts of varying levels of pollination services on yields of oilseed rape the effect can vary from a situation with zero insect pollination by 10-50% , but with a range of 20-30% being more likely (Kołtowski, 2005), hence we set a_7=0.25. This implies that current yields of oilseed rape in the case-study landscapes can be boosted by at most 12.5% by optimizing habitat area (or decline by 12.5% in the absence of pollination) according to our calibrated models.

6.1 Marginal valuation of natural capital and ecosystem services

As indicated by the overview of the case study landscapes (Section 5) agricultural productivity varies across the landscapes in terms of both productivity and profitability. This variability is also likely to affect the economic value to farmers of preserving ecosystem services in their respective landscapes.

The marginal value of conserving soil natural capital in each landscape is shown in Figure 3. Recall from Eq. (2.13) that a change in soil natural capital will affect profits in all future periods hence the values in Figure 3 are the present values of all future impacts on profits discounted at 3%. Consequently a small change in soil natural capital, via its impacts on yields and fertilizer input-use efficiency, would have a relatively large impact on the farmers' wealth. This implies that small increments in soil natural capital and associated below-ground ecosystem services have the potential to boost future farm incomes.

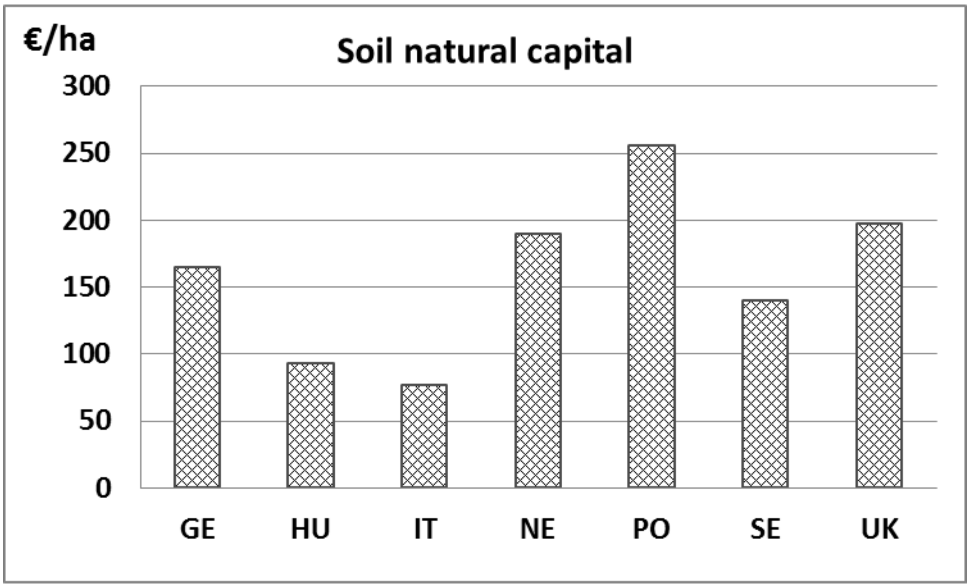

Figure 3. The current marginal economic value of soil natural capital across the study landscapes.

The marginal values of pollination services shown in Figure 4 have been calculated according to Eq. (2.14). In principle these values represent the additional profit that would be earned per ha of oilseed rape if current pollination levels rose by 1%, or vice versa. Hence intensification of pollination services has the potential to boost productivity and thereby incomes in all regions.

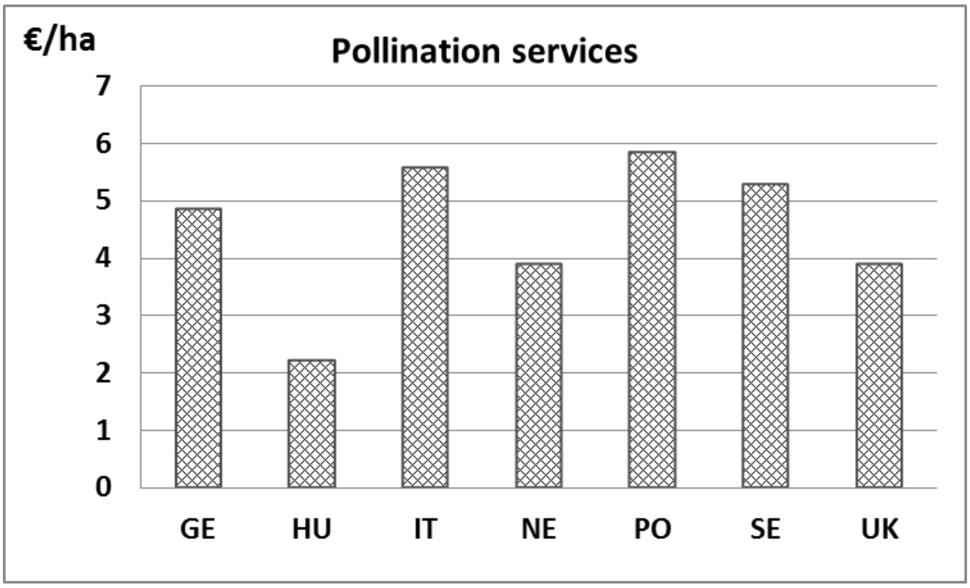

Figure 4. The current marginal economic value of pollination services across the study landscapes.

6.2 Potential impact of ecological intensification on productivity

To model the potential for intensifying below-ground services to boost productivity we assume that farmers can raise soil natural capital by at most 28% on its current level (i.e., corresponding to an annual growth rate of 1% p.a. over 25 years). The resultant impact on wheat yields and associated fertilizer input in each landscape are shown in Figure 5, where intensification of below ground services in the future is represented by the shift from curve A to B. Symmetrically, one can even contemplate the impact of eroding soil natural capital on productivity, in which case the production function A would shift downwards to a similar degree that curve B has shifted upwards.

Similarly, the effects of intensifying ecosystem services on the productivity of oilseed rape are shown in Figure 6, where the shift to curve A represents the effect of intensifying below-ground services and curve C that of intensifying both below-ground and pollination services. The upward shift to curve C as a result of boosting pollination services is supported by a large number of empirical studies (Garibaldi et al., 2013). However, recall that the size of the shift according to our results needs to be taken with caution and requires more rigorous validation, which is being done as part of the development of the multi-PF in WP 4, hence the results should be interpreted as plausible but primarily exploratory.

In accordance with our conceptualization of ecological intensification (recall Figure 1), intensifying ecosystem services—in particular simultaneously intensifying both above- and below-ground services as in the case with oilseed rape—is shown to have a substantial potential to improve productivity in all landscapes. Then again, losses of services as a result of overly intensive production would have the potential to substantially reduce future productivity.

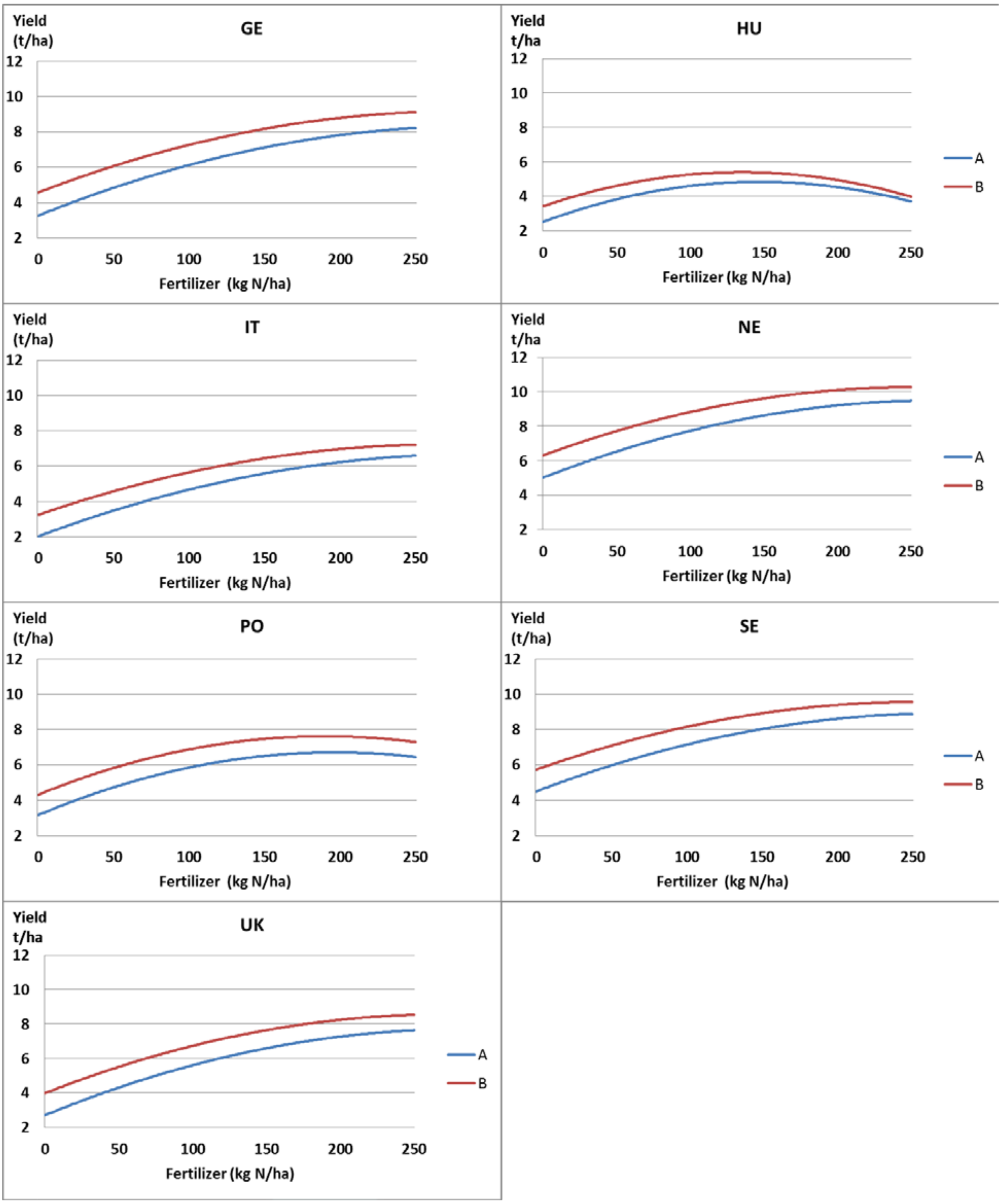

Figure 5. Potential for ecological intensification to boost productivity of winter wheat in study landscapes. Production function given current SOC content (A) and future SOC content with a 1% annual growth rate (B).

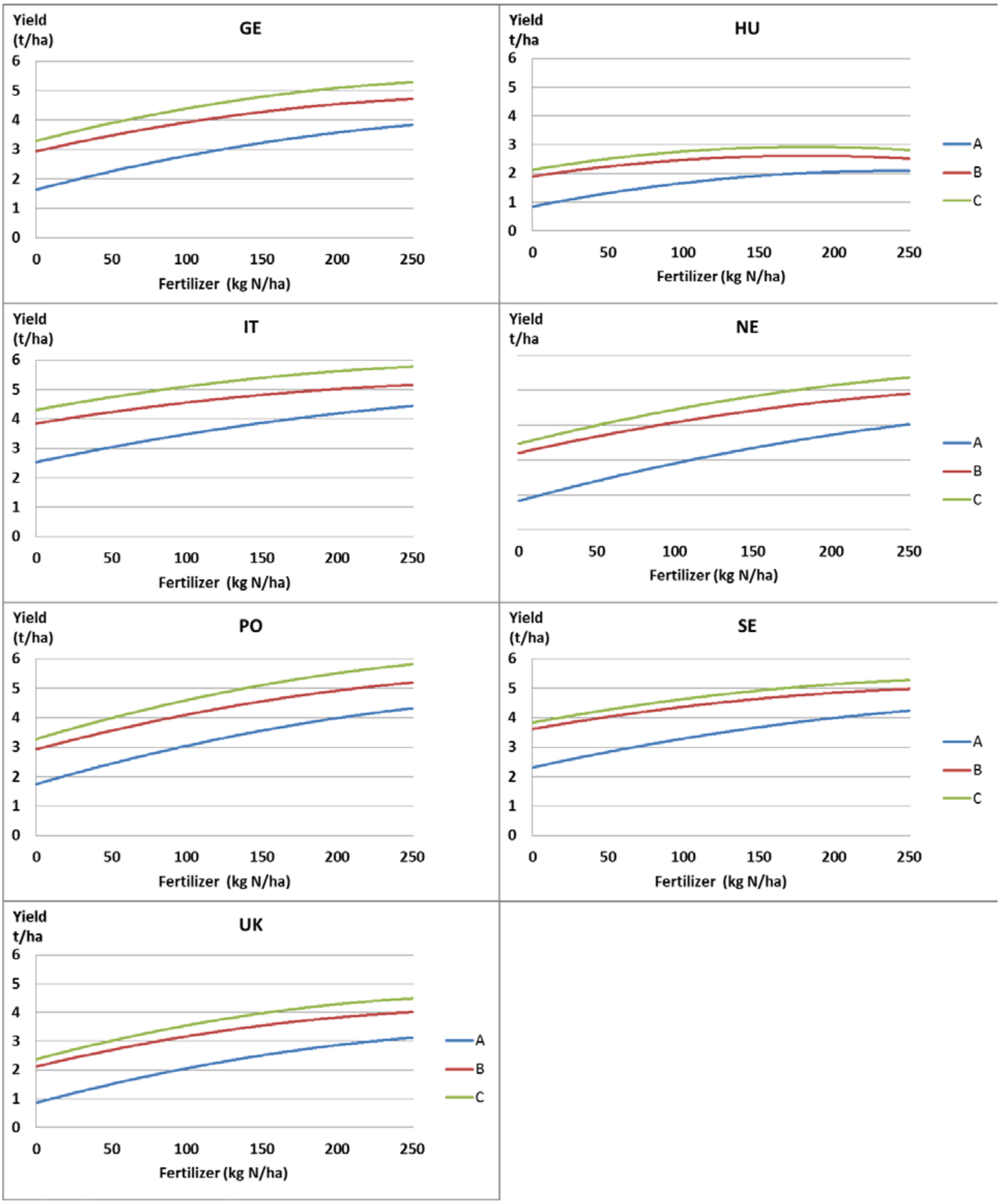

Figure 6. Potential for ecological intensification to boost productivity of oilseed rape in study landscapes. Production function given current SOC content (A), future SOC content with 1% growth rate (B) and curve B plus maximized pollination services (C) .

6.3 *Impact of ecological intensification on optimal farm production and profits*

We now explore the impacts of ecological intensification on the economic optimal yields (Figure 7) and associated fertilizer input rates (Figure 8) for winter wheat and oilseed rape. Two future scenarios are compared to currently optimal levels (scenario **TODAY**). The scenario **FUTURE_max** is the maximum potential of ecological intensification, according to our models, to boost productivity and **FUTURE_min** is a conservative scenario that assumes that 25% of a farm's land (or equivalent reduction in input intensity) needs to be rested (spared, shared, fallowed, etc.) from crop production for the purposes of regenerating soil natural capital and increasing the area of pollinator habitat.

FUTURE_max indicates that optimal yields could be increased in all regions and require less fertilizer input than today. However if land needs to be rested from production then the average optimal yield of winter wheat would decline to below current levels, but with it average fertilizer input could be reduced dramatically. From a farmers' perspective the lower wheat yields could therefore be balanced by the associated reductions in fertilizer costs.

Indeed our analysis of farm profits (Figure 9) shows that the reduction in costs is potentially so substantial that farm profits would even rise under the conservative FUTURE_min scenario.

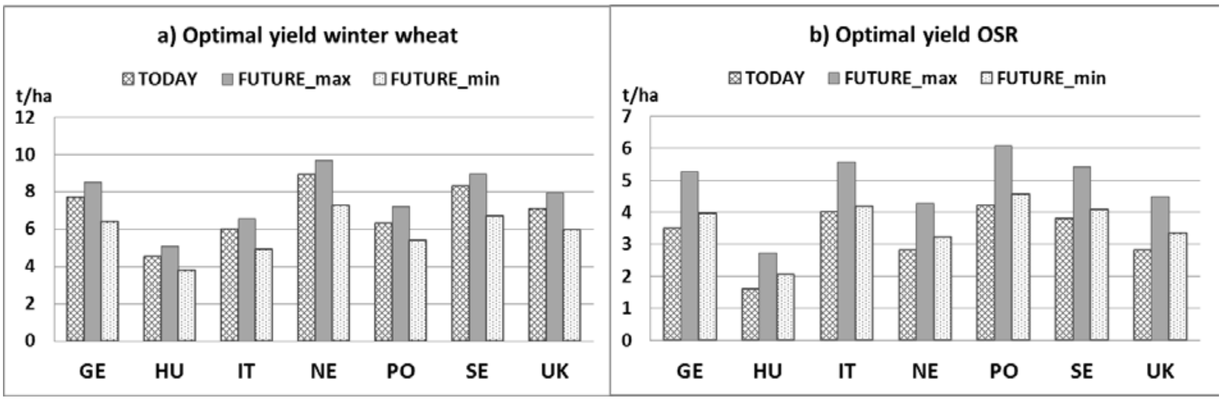

Figure 7. Impacts of ecological intensification on future economic optimal yields of **a)** winter wheat and **b)** oilseed rape

Yields of oilseed rape increase in both future scenarios thanks to the additional benefits of higher levels of pollination services. This adds credence to our hypothesis that while the contribution of any single ecosystem service to productivity might be relatively small, the cumulative effect of multiple services, say through managing the entire landscape, is potentially large.

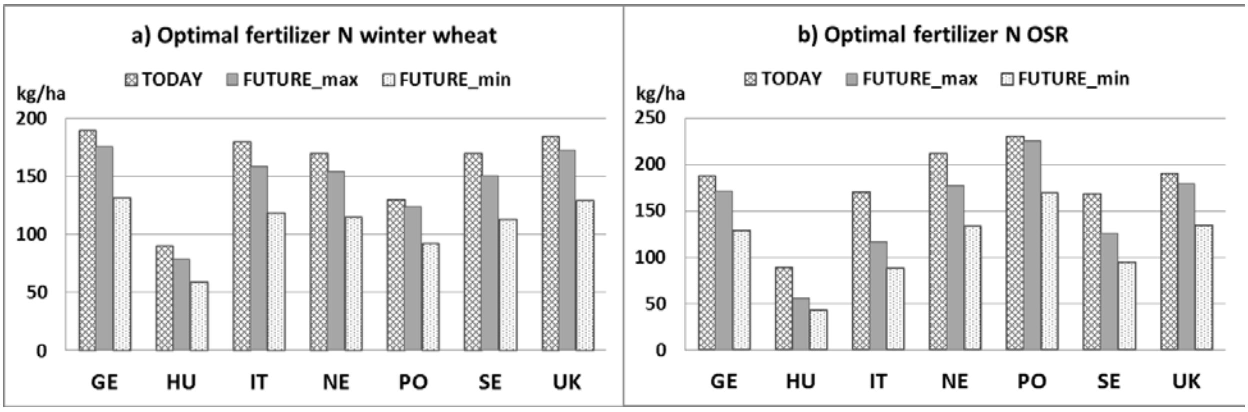

Figure 8. Impacts of ecological intensification on future economic optimal fertilizer input rates for a) winter wheat and b) oilseed rape compared to currently optimal rates.

Ecological intensification has the potential to substantially boost farm profits (Figure 9 scenario FUTURE_max) but this potential will be mitigated by the extent to which land needs to be rested from production (FUTURE_min). Nevertheless even with our conservative future scenario where we assume that a very large farm area is kept from production, i.e., 25%, it will be possible for farmers to maintain their incomes due to the productivity gains generated by intensifying ecosystem services. The smaller the net area that needs to be kept out of production the greater the potential benefits of ecological intensification (Figure 10).

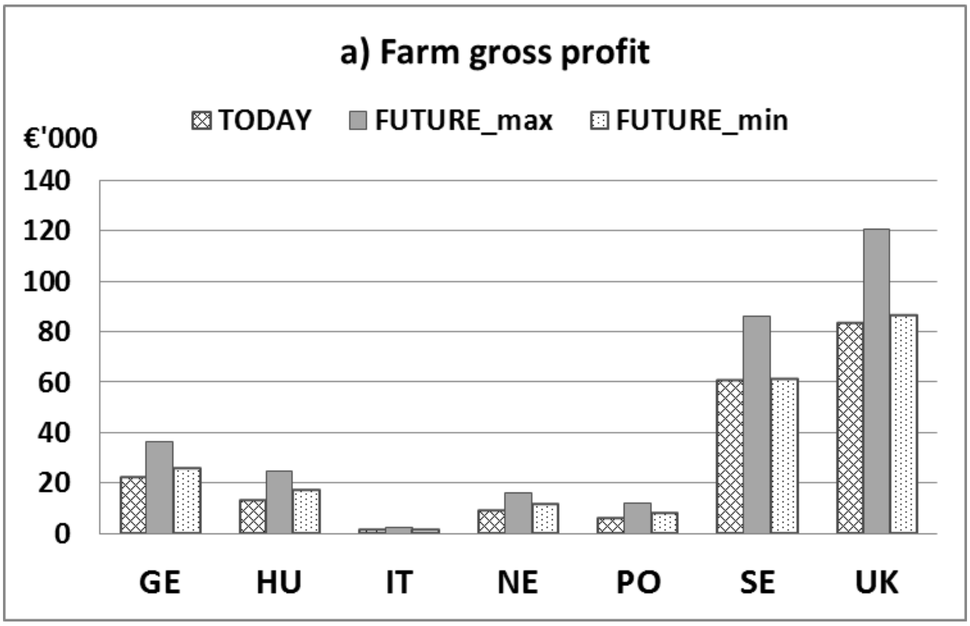

Figure 9. Impact of ecological intensification on future gross farm profits compared to today.

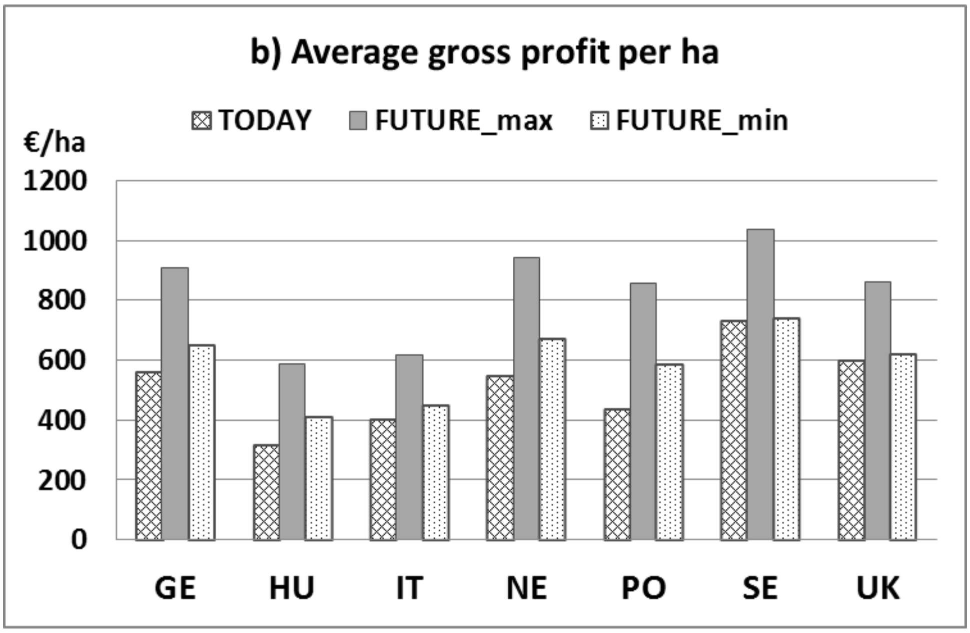

Figure 10. Impact of ecological intensification on future average gross profits per ha compared to today.

7 Summary and next steps

The focus of this deliverable has been on developing and calibrating an ecological-economic optimization model for the seven Liberation study landscapes to economic and agronomic data, while using preliminary parameter values for the ecosystem-service production functions to generate some exploratory results. Hence the presented results are preliminary and should be interpreted with caution.

The calibrated ecological-economic models for the seven landscapes are a key achievement towards quantifying and communicating the expected impacts of ecological intensification on agricultural production and farmers' livelihoods, and for evaluating policy options.

During the development of these models we have achieved the following sub-goals:

- Included below-and above ground ecosystem services as inputs in the agricultural production function.
- Integrated the extended production functions within a farm-economic optimization model.
- Derived a theoretical framework for optimizing the ecological intensification of agriculture.
- Extended an existing economic model to build an ecological-economic optimization model for optimizing ecosystem services.

- Compiled economic, agronomic and ecological data for each of Liberation's seven case-study landscapes (with support from all project partners) into a consistent database.
- Calibrated the ecological-economic optimization model to the database for each landscape using state-of-the- art calibration procedures (i.e., Positive Mathematical Programming).
- Generated exploratory results of the potential for ecological intensification to boost agricultural productivity and support farm incomes.

Our highly exploratory and hence preliminary results indicate that ecological intensification has the potential to boost future agricultural productivity and farm incomes while reducing environmental degradation, but it will involve potentially substantial short-term costs to achieve higher levels of services in the future. Consequently, the time lag between implementing measures to benefit biodiversity and realizing higher flows of ecosystem services is likely to hinder ecological intensification under the current policy framework.

In the next step we will link our models with the multiple production function developed in WP 4 to validate the production functions and test their sensitivity to changing conditions.

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