30TH INTERNATIONAL CONFERENCE OF AGRICULTURAL ECONOMISTS
JULY 28 – AUGUST 2, 2018 | VANCOUVER

Spatial aggregation of land uses allocation and pesticide efficiency at landscape level A Multi-ware production approach

K.H. Dakpo[1]; M. Vincent[1]; J.-P. Boussemart[2]

1: INRA, Economics, France, 2: IESEG, , France

Corresponding author email: k-herve.dakpo@inra.fr

Abstract:

We extend the single-stage framework of damage-control inputs like pesticides to a multi-ware framework where four technologies are considered. The economic technologies describe the production and the damages due to pests while the ecological technologies represent the dynamics of pests and predators' populations. To account for the possibilities of spatial effects of land uses (crop and non-crop habitats), we consider an analysis at the landscape level and try to find the optimal allocation of the land uses that help minimizing pesticides. To this aim we rely on a prey-predator simulation model. We assess pesticides performance considering nonparametric production frontier techniques. Our results indicate that pesticides can be reduced by 7.7% without reducing the landscape production. In terms of land uses we found that grasslands areas should be increased by more than twice and croplands with medium levels of pesticides unchanged. Croplands with zero and high levels of pesticides should be reduced. In terms of trade-offs between pesticides and the landscape production we found that the spillover effect is very high and result in a negative trade-off because of the destruction of predators by pesticides. Pesticides inefficiency can be reduced when treated areas are spatially aggregated and when grasslands are subsidized.

Acknowledegment:

JEL Codes: D22, C61

#1489

Spatial aggregation of land uses allocation and pesticide efficiency at landscape level

A Multi-ware production approach

Abstract

We extend the single-stage framework of damage-control inputs like pesticides to a multi-ware framework where four technologies are considered. The economic technologies describe the production and the damages due to pests while the ecological technologies represent the dynamics of pests and predators' populations. To account for the possibilities of spatial effects of land uses (crop and non-crop habitats), we consider an analysis at the landscape level and try to find the optimal allocation of the land uses that help minimizing pesticides. To this aim we rely on a prey-predator simulation model. We assess pesticides performance considering nonparametric production frontier techniques. Our results indicate that pesticides can be reduced by 7.7% without reducing the landscape production. In terms of land uses we found that grasslands areas should be increased by more than twice and croplands with medium levels of pesticides unchanged. Croplands with zero and high levels of pesticides should be reduced. In terms of trade-offs between pesticides and the landscape production we found that the spillover effect is very high and result in a negative trade-off because of the destruction of predators by pesticides. Pesticides inefficiency can be reduced when treated areas are spatially aggregated and when grasslands are subsidized.

Key words: efficiency, multi-ware production, pesticides productivity, predator-prey model, spatial aggregation

JEL Codes : C6, D2, Q0, Q1

1-Introduction

In modern agriculture, pesticides use has been driven by pests control and the security of agricultural productivity (Cramer, 1967, Pimentel, 1976, Metcalf, 1996). Cooper and Dobson (2007) have even identified 26 primary benefits and 31 secondary benefits associated to pesticides use (less drudgery in weeding, reduction of fuel consumption for weeding, improvement of the shelf life and longevity of products…). Practically, in the case of a complete ban of pesticides in the US, Knutson et al. (1990) have estimated a decrease of the consumer surplus by $18 billion per year due to higher food costs and lower quality crops and livestock. These figures imply that pesticides allow lower production costs and higher yield which implicitly increase farm profits (Fernandez-Cornejo et al., 1998).

Despite the beneficial impacts of pesticides on agricultural profitability (damage-and risk-reducing inputs) and in most areas of crop production, the risks associated to their use are mostly debated in terms of health and environmental issues. First, over time the appearance of pests genetically resistant to pesticides overuse is now well-documented (Georghiou and Saitō, 1983, Roush and Tabashnik, 1990). This resistance has conducted to the application of large volume of pesticides or the increase of pests' populations or both. Second, the destruction of non-targeted species create resurgence of secondary pests whose natural predators were harmed by pesticides use (Metcalf, 1980). Besides, species like honeybees useful for crop pollination are also affected by insecticides spread (Pimentel et al., 1992). Third since the publication of the book of Carson (1962) 'Silent Spring', there has been a growing public awareness on pesticides toxicity and their danger to human health (Costa et al., 1987). For instance the occurrence of certain cancers (Blair and Zahm, 1993). The presence of pesticides residues in water, air, soil, food and animals have inflected consumers' perception who believe that pesticides have long-term unknown health issues and are responsible for millions of fatalities (Williams and Hammitt, 2001, Saba and Messina, 2003). In the US, the estimated health costs of pesticides are about $1.5 billion in 2005, while the environmental costs reached $8 billion in 1992 (Bourguet and Guillemaud, 2016). According to Wilson and Tisdell (2001), though the aforementioned impacts and their inherent costs, pesticides are still highly present in crop production and this can be explained by the fact that producers are 'locked-in' some kind of pesticides trap due to the adoption of unsustainable production behaviors.

As the world third largest user of pesticides (first in Europe) behind US and Japan (Jacquet et al., 2011), the French government since 2008 with the "Grenelle de l'environnement" round has set the objective of reducing pesticides use by 50% by the horizon 2018 ("plan Ecophyto") (Barzman and Dachbrodt-Saaydeh, 2011). After the failure of this first plan obviously with the increase of pesticides use over the six years that has followed its adoption, a new "plan Ecophyto" has been launched in 2015 with similar objectives of reducing pesticides use by half till 2025. More effectively, France has issued in 2000 an umbrella of taxes under the terminology of tax on polluting activities ("taxe générale sur les activités polluantes" - TGAP). These taxes paid by distributors concerned seven categories of pesticides based on their eco-toxicological and toxicological properties and where valid till 2009. In 2009, TGAP was replaced by a fee paid by customers on non-point source pollution in agriculture ("redevance pour pollutions agricoles diffuses") and which concern three categories (OECD). In Europe, the legislation also encourages low-pesticides farming and promoting integrated pest management (IPM) which has resulted in the banned of many active substances and severe restrictions on the use of others (Hillocks, 2012). Actually, the first policy regulation at the EU level was introduced in 1979 and the first directives in 1991 (91/414/EC) and 1998 (98/8/EC) which were revised several times. The last directive 2009/128/EC stresses on sustainable use of pesticides in the EU and requires from state members to come up with National Action Plans (NAP) to reduce pesticides use in agriculture at rational levels.

As underlined in Skevas et al. (2013a) the design of effective policies towards the reduction of pesticides use and their negative externalities requires some necessary information among which the production structure (production function) for which our article brings additional knowledge by adopting a new approach. While the literature in this area has flourished under the Lichtenberg and Zilberman (1986)'s framework of damage abatement function for assessing pesticides marginal productivity, our article considers a structural representation of the global technology which lies at the intersection of two physical and two ecological processes in light of the multi-ware production discussed in Frisch (1965). The physical processes describe the production of the economic output and the damages inflicted by the presence of pest populations. Physical strong (free) disposability assumption is maintained for the economic output while physical costly disposability is assumed for the output losses. About the ecological technologies, they describe the mechanism underlying the evolution of pest and predator densities. We posit ecological costly disposability for pest densities and ecological free disposability for predator populations. Thus our article can also shed some lights in promoting alternative pest controls (biological controls). In this literature, the closest work to ours is the study of Skevas et al. (2013b) where the authors have included the pesticides spillover (biodiversity loss). However, their framework is based on the Lichtenberg and Zilberman (1986)'s formulation and the interactions between pests and predators is not considered. In fact, the use of the ecosystem to fight pests has been ignored by economists and Feder (1979) has referred to this possibility as species interactions effects. A peculiar interest of our article is to explicitly include entomological knowledge of pest and predator densities while most of the studies lack this type of information. Actually, though the importance of pest population in technology modelling has been stressed in many studies Chambers and Tzouvelekas (2013) have recently underlined the challenge in obtaining the data on biological entities that affect production yield and thus the difficulty of econometric estimations. Therefore, assumptions on the growth of these entities are necessary. To overcome this challenge, we rely on a predator-prey simulation model which was conducted at a landscape level. In this controlled environment, each landscape is a collection of a hundred of producers that decide (maximizing their profit given the land quality and the policy regulations) for different spatially correlated land use allocation (grassland, crop production without pesticides, crop production with medium and high level of pesticides). In this article our decision making unit (DMU) is the landscape level where we can assess the effect of the spatial agglomeration of different land use. In summary our article answers three main questions: i-) first, relying on the non-parametric framework of data envelopment analysis – DEA – (Charnes et al., 1978, Banker, 1984, Färe et al., 1985), we benchmark the landscapes and determine the potential inefficiency (under an optimal land use allocation) in pesticides use along with the inefficiency associated to damages, pests and predators; ii-) second we determine the marginal productivity of pesticides, pest and predator densities. Lot of studies have estimated pesticides productivity but not biological productivity (like natural predators) and also substitutability among the different pests control measures. We found one study that has analyzed host-plant resistance productivity (Widawsky et al., 1998), and Qaim and Zilberman (2003) have focused on genetically modified (GM) crops but we found none on pests' predators density; iii-) third we examine the effects of spatial aggregation of the land uses and other policy determinants on the different inefficiency levels.

The rest of the article is structured as follows: section 2 presents our simulation framework, section 3 presents the structural approach for modelling the landscape production technology, section 4 analyses and discusses the results and, section 5 concludes.

2-Simulation framework

As underlined in the Introduction section, the aim of this article is to shed light on the potential reduction in pesticide use given different land use allocations and their spatial aggregation. To this ambition we explicitly account for biological variables (pest and predator densities) by relying on an ecological prey-predator simulation model at the landscape level with economic decisions. Two types of land allocations are considered: non-crop habitats (X_{NCH}) like grasslands and crop habitats. The formers do not generate any private profit but favor the growth of predators while the latter are associated to heterogeneous yields accounting for the damages inflicted by the pests, local land quality and the applied fertilizers. Among the crop habitats three different allocations are allowed depending on the level of pesticides used (treatment frequency index – TFI). Therefore we have crop-habitats with zero level of pesticides (X_0), crop-habitats with medium use of pesticides (X_1) and crop-habitats with high level of pesticides (X_2). Using the TFI corresponding to each land use, pesticides use in volume is obtained by

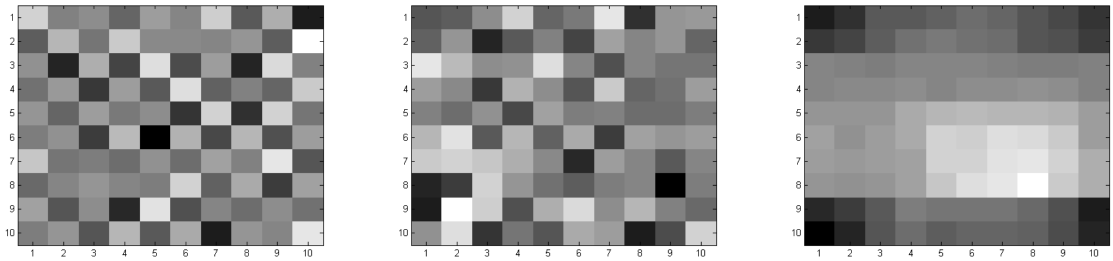
$$\varphi = 0 \times X_{NCH} + 0 \times X_0 + 3 \times X_1 + 6 \times X_2 \tag{1}$$

The landscapes are designed as a lattice of hundred plots of one hectare respectively and, each plot being assigned to individual producer. If we assume that the total of each different land use is expressed in share of the landscape total plots, we have:

$$X_{NCH} + X_0 + X_1 + X_2 = 1 \tag{2}$$

The allocation of the plots to a specific land use depends on agronomic, economic, ecological conditions nd, farmers' preferences. Each plot soil quality is approximated by the potential crop yield (in the absence of pests) and the soil quality of neighboring plots can be correlated or not. Hence each landscape can be described as a distribution of different soil quality with a level of autocorrelation in space. For each simulation, the distribution of the soil quality of the plots and their spatial distribution are randomly decided to capture a wide variety of soil and weather conditions. For instance, Figure 1 illustrates three different spatial distribution of the plots' soil quality.

Figure 1: Landscape description with three different levels of spatial correlation between soil qualities



In the absence of spatial effects namely ecological dynamics, each landscape with the same soil quality distribution will have the same performance. The first step of the simulation model is to randomly draw a distribution of soil quality (one hundred observations) which gives the agronomic potential of the landscape (region). Then in a second step several landscapes can be generated with different spatial correlation between soil qualities.

2.1-The economic model

Each 'rational' producer decides to maximize his utility which is function of the profit corresponding to a specific land use and the aversion to pesticides use (aversion due to health issues of pesticides). Land use is decided based on the return profit which depends on the soil quality (or potential yield), the levels of applied fertilizers, anticipated pest densities, inputs and output prices, fixed and land conversion costs and, policy instruments (taxes and subsidies). The dynamics of pest populations is described by the ecological model presented below. Land conversion costs are asymmetric with additional charges for the change from crop habitat to non-crop habitat (Barraquand and Martinet, 2011). Besides as earlier mentioned non-crop habitats do not generate any private profit but they can be subject to different levels of grassland subsidies. Pesticides costs also depend on the possible taxes and the product price can be affected by a price bonus in case of production without pesticides use. In summary each producer anticipates the profit for each of the four possible land uses and choose the one that maximize his utility at an annual-based. Using these anticipations, the optimal levels of inputs for each land used is obtained and thereby a lattice of land use allocations. In our case of analysis, we have not explored the inefficiency in fertilizer application and assume that producer efficiently use this input.

2.2-The ecological model

The ecological dynamic model describes the evolution of biological populations based on reaction-diffusion equations (Cantrell and Cosner, 2003). These models can account for multi-species in spatially and temporally variable environments. More specifically, in our framework the description of the pest populations and their natural enemies uses a grid dynamical continuous time system where each cell corresponds to a land use (Weinberger, 2002, Guo and Wu, 2012). The differential equations that describe the evolution of each specie consider the diffusion of the individuals (using a discrete Laplace operator), their growth which varies in relation to the land use, the mortality rate induced by pesticides and the interaction effect between pests and their natural enemies. In terms of growths, pest populations are positively affected by all the crop-habitats and have a zero growth on grasslands. On the other hand, natural predators are positively correlated to grasslands and negatively to crop-habitats. In terms of interactions, pest populations decrease with natural predators due to predation while the natural enemies are positively affected by pests. In this latter case pests are source of food for the natural enemies. Given the different biological parameters (pest growth, predation rate, pests and predators diffusion and, the mortality rate associated to pesticides use), about 144 ecological contexts can be simulated. Considering the profit maximization, farmers anticipated pest densities given their knowledge on predation and diffusion and considering that the other producers do not change their land use.

2.3-The data generation and description

For our empirical analysis, we have considered one potential production for the landscape which corresponds to one distribution of soil quality. For this agronomic context all the simulated landscapes will produce the same amount in the absence of pest and limiting factors. Besides, the simulated landscapes are group under 5 different maps which correspond to the spatial aggregation of the soil quality. For simplicity we have considered a unique value for pests and predators' growth and diffusion, pesticides induced mortality rates, predation rate and predators' life expectancy in crop-habitats (in the absence of preys), respectively. We have on the other hand maintained different policy instruments parameters: 6 for pesticides tax, 11 for grassland subsidy, 6 for price bonus in the case of production without pesticides. The combination of the latter parameters are equivalent to $6 \times 11 \times 6 = 396$ policy contexts and in association to the soil quality spatial distributions we generate for each period of time $396 \times 5 = 1980$ different landscapes. Since the ecological-economic model simulated here is dynamic, it runs over a ten-year period $(t = 1, \dots, 10)$ with an initial period $t = 0$. However, to remove the variation due the prey-predator dynamics, we have considered the average of all the variables over the planning horizon. The descriptive statistics can be found in Table 1. For the landscapes under analysis, crop habitats with medium level of pesticides (X_1) are the most important and represent 67% of the total landscape surface. Crop-habitats with zero level of pesticides account for 13% of this surface while grasslands and crop habitats with high level of pesticides use weight 10% respectively. The damages inflicted by pests represent about 10% of the production (before pests). The variables AgG, AgC0, AgC1, AgC2 and IntensityAg represent of the spatial aggregation index of grasslands, X_0, X_1, X_2 and treated plots respectively. The lower these aggregation indices are the lesser the different plots are spatially correlated. The pesticides taxes are applied to each treatment round (TFI) and the bonus increases the product price. The grassland subsidies are equivalent to individual unit of non-crop habitat. For most of the variables, the coefficient of variation or very high implying the existence of a large heterogeneity between the different landscapes.

Table 1: Descriptive statistics of the 1980 landscapes generated

Variables	Mean	Standard deviation	Coefficient of variation	Minimum	Maximum
X_{NCH}	0.10	0.10	0.99	0.01	0.45
X_0	0.13	0.11	0.80	0.00	0.42
X_1	0.67	0.23	0.34	0.06	0.97
X_2	0.10	0.12	1.17	0.00	0.39
Pest Density (P)	0.85	0.25	0.29	0.29	1.59
Predator Density (N)	0.10	0.11	1.07	0.01	0.57
Production (ton/hectare) $[Y]$	5.89	0.45	0.08	4.01	6.70
Damages (ton/hectare) $[D]$	0.65	0.23	0.36	0.12	1.37
Pesticides (total TFI) $[\varphi]$	2.61	0.37	0.14	1.01	3.17
AgG	0.24	0.39	1.64	0.00	1.00
AgC0	0.40	0.30	0.76	0.00	1.00
AgC1	0.75	0.24	0.32	0.00	0.98
AgC2	0.42	0.39	0.94	0.00	1.00
IntensityAg	0.85	0.10	0.11	0.53	0.98
Pesticides Tax (€)	25.00	17.08	0.68	0.00	50.00
Grassland Subsidies (€)	250.00	158.15	0.63	0.00	500.00
Price Bonus (€)	0.25	0.17	0.68	0.00	0.50

3-Structural representation of pest control agents at the landscape level

3.1-Physical and ecological technologies description

This work is grounded on the earlier discussion in Feder (1979) where both pest and predator densities are accounted for. Structurally, we consider four production technologies: two physical processes and two ecological functions at the landscape level. The physical processes describe production yield but also damages associated to the presence of pests. The two ecological functions explain the evolution of pest and predator densities. This sort of representation can be referred to as the multi-ware production system initially discussed in Frisch (1965). The underlying idea of the multi-ware production is that complex system cannot be represented by a single functional form and several relationships must be considered in modelling technically connected products. We therefore define the global landscape technology as follows:

$$\Psi = \Psi_Y \cap \Psi_D \cap \Psi_P \cap \Psi_N \tag{3}$$

where

$$\Psi_Y = \{(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D) \in \mathbb{R}^9 \mid f(X_{NCH}, X_{i=\{0,1,2\}}, D, Y) \leq 0\} \tag{4}$$

$$\Psi_D = \{(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D) \in \mathbb{R}^9 \mid k(X_{NCH}, X_{i=\{0,1,2\}}, P, D) \geq 0\} \tag{5}$$

$$\Psi_P = \{(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D) \in \mathbb{R}^9 \mid g(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi) \geq 0\} \tag{6}$$

$$\Psi_N = \{(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D) \in \mathbb{R}^9 \mid h(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi) \leq 0\} \tag{7}$$

f, k, g and h are all continuously differentiable transformation functions. The technologies presented above in (4) to (7) describe the production of four outputs (two physical or economic and two ecological). Following some concepts put forward in Frisch (1965), the production system in (3) is factorially determined i.e. for each levels of the different inputs, all the outputs are determined. More explicitly, let r be the number of technical relations and m the number of outputs. Frisch (1965) refers to $m - r$ as the degree of assortment of the system which represents the flexibility available to producers from directing inputs to the production of either output. In the case $r = 1$ the flexibility is maximal and we fall into the standard case of a single relation technology. When $m - r = 0$ the flexibility is very low and the system is factorially determined as in our case ($m = 4, r = 4$).

The technology set Ψ_Y describes how the different land uses (X_{NCH}, X_i) and the damages (D) created by pest density generate the good economic output (Y). Following the previous discussions, pesticide levels (φ) do not directly affect the production yield and therefore do not appear in the economic output technology as another production factor. Their effect is indirect through the remaining pest populations that damage the production Y. We impose the following monotonicity conditions on the derivatives of f:

$$f_Y \geq 0 \;\wedge\; f_D \geq 0 \;\wedge\; f_{X_{NCH}} \geq 0 \;\wedge\; f_{X_{i=\{0,1,2\}}} \leq 0 \tag{8}$$

The sign of the derivatives in (8) simply imply that crop-habitats $X_{i=\{0,1,2\}}$ positively affect the production of Y while the more damages we have the less the production of Y is. About non-crop habitats (X_{NCH}) we know from the simulation design that they do not directly produce any economic output. However, we posit that through some substitution possibilities with $X_{i=\{0,1,2\}}$ the level of Y can be either increase of decrease. The sign of the derivative related to X_{NCH} implies that the more non-crop habitats are present in the landscape the lesser is the economic output. The monotonicity conditions in (8) impose the physical free (strong) disposability assumption on the economic output Y. Formally, the free disposability writes as

$$\begin{gathered}\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \Psi_Y \;\wedge\; \bar{X}_{NCH} \leq X_{NCH} \;\wedge \\ \bar{X}_{i=\{0,1,2\}} \geq X_{i=\{0,1,2\}} \;\wedge\; \bar{D} \leq D \;\wedge\; \bar{Y} \leq Y \\ \Rightarrow \left(\bar{X}_{NCH}, \bar{X}_{i=\{0,1,2\}}, P, N, \varphi, \bar{Y}, \bar{D}\right) \in \Psi_Y\end{gathered} \tag{9}$$

The technology Ψ_D shows how the pest densities create damages to the production yield. We posit the following monotonicity conditions which are the polar opposite of the conditions on the technology Ψ_Y:

$$k_D \leq 0 \;\wedge\; k_P \geq 0 \;\wedge\; k_{X_{NCH}} \leq 0 \;\wedge\; k_{X_{i=\{0,1,2\}}} \geq 0 \tag{10}$$

It is worth stressing that in this case P is the remaining level of pest populations. The monotonicity conditions in (10) impose the physical costly disposability of damages and the technology is bounded from below:

$$\begin{gathered}\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \Psi_Y \;\wedge\; \bar{X}_{NCH} \geq X_{NCH} \;\wedge \\ \bar{X}_{i=\{0,1,2\}} \leq X_{i=\{0,1,2\}} \;\wedge\; \bar{D} \geq D \;\wedge\; \bar{P} \leq P \\ \Rightarrow \left(\bar{X}_{NCH}, \bar{X}_{i=\{0,1,2\}}, \bar{P}, N, \varphi, Y, \bar{D}\right) \in \Psi_D\end{gathered} \tag{11}$$

The technology Ψ_P reflects the interaction between land uses, pesticide levels, predator density and pest populations. The monotonicity conditions associated to this technology are summarized below:

$$g_P \leq 0 \;\wedge\; g_{X_{NCH}} \leq 0 \;\wedge\; g_{X_{i=\{0,1,2\}}} \geq 0 \;\wedge\; g_{\varphi} \leq 0 \;\wedge\; g_N \leq 0 \tag{12}$$

Pest population densities are positively associated to crop land uses $\left(X_{i=\{0,1,2\}}\right)$ and negatively to pesticide levels. In the case of this technology, predator densities also help reducing the levels of pests. Non-crop habitats imply zero growth for pests but as for the previous technology (Ψ_Y) are included in the technology described by function $g(\quad)$ to account for substitution possibilities. The classic output free disposability assumption is violated here by pest densities:

$$
\begin{gathered}
\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \Psi_P \ \wedge \bar{X}_{NCH} \geq X_{NCH} \ \wedge \\
\bar{X}_{i=\{0,1,2\}} \leq X_{i=\{0,1,2\}} \ \wedge \ \bar{P} \geq P \wedge \ \bar{\varphi} \geq \varphi \ \wedge \ \bar{N} \geq N \\
\Longrightarrow \left(\bar{X}_{NCH}, \bar{X}_{i=\{0,1,2\}}, \bar{P}, \bar{N}, \bar{\varphi}, Y, D\right) \in \Psi_P
\end{gathered}
\tag{13}
$$

We refer to the property in (13) as the ecological costly disposability of pest densities. This disposability property implies that the technology Ψ_P is bounded from below.

Ψ_N captures the mechanisms of natural predator densities. Explicitly we have:

$$
h_N \geq 0 \ \wedge \ \ h_{X_{NCH}} \leq 0 \ \wedge \ h_{X_{i=\{0,1,2\}}} \geq 0 \ \wedge \ h_{\varphi} \geq 0 \ \wedge \ h_P \leq 0 \tag{14}
$$

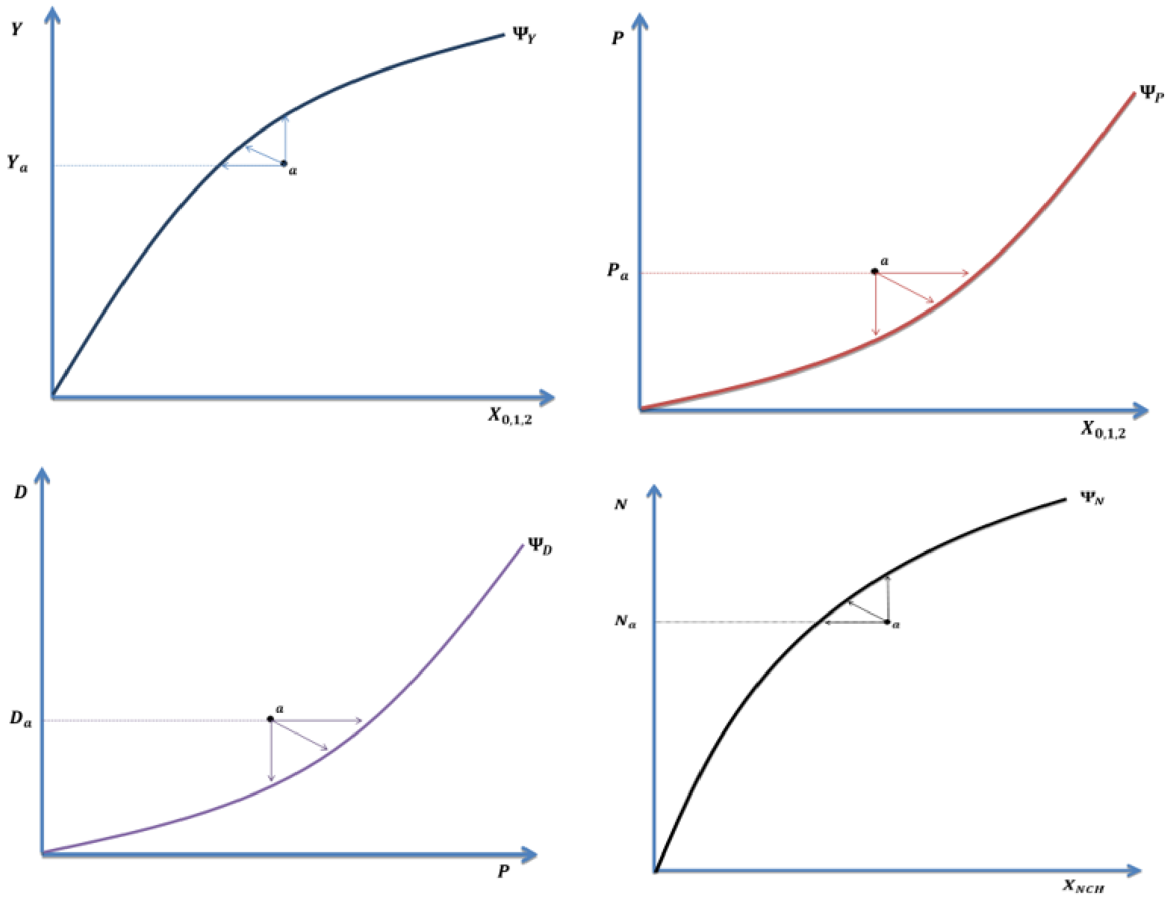
The derivatives in (14) imply that natural predators are favored by non-crop habitats but also by pest populations which constitute here sources of nourishment. On the other side, predator populations are negatively affected by crop-habitats but also by the levels of pesticide use. The disposability assumption for the different variables can be summarized as:

$$
\begin{gathered}
\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \Psi_N \ \wedge \bar{X}_{NCH} \geq X_{NCH} \ \wedge \\
\bar{X}_{i=\{0,1,2\}} \leq X_{i=\{0,1,2\}} \ \wedge \ \ \bar{N} \leq N \ \wedge \ \bar{\varphi} \leq \varphi \ \wedge \ \bar{P} \geq P \\
\Longrightarrow \left(\bar{X}_{NCH}, \bar{X}_{i=\{0,1,2\}}, \bar{P}, \bar{N}, \bar{\varphi}, Y, D\right) \in \Psi_N
\end{gathered}
\tag{15}
$$

We refer to this property as the ecological free disposability of natural predator densities. Given this property the technology Ψ_N is bounded from above.

Graphically the different technologies are represented in Figure 3 respectively to some specific inputs. On this figure we can see that crop-habitats are inputs to the good economic output technology and also favor the apparition of pest populations. Moreover, non-crop habitats are useful for the development of natural predators to pests. About the undesirable economic output they are mainly associated to the presence of pests.

Figure 3: Landscape economic and ecological technologies



3.2-Trade-offs analysis

In this part we derive and analyze different trade-offs between the variables involve in the landscape technology description. For the rest of this analysis we consider the different land uses as the decision variables at the landscape level. Therefore, they will not be used to derive the trade-offs.

- **Indirect effect of pesticides on production yield**

Considering the multi-ware production framework, the trade-off between the good economic output and pesticides use is obtained using implicit function theorem. At a weak efficient point, we have the following conditions

$$\begin{aligned} f\left(X_{NCH}, X_{i=\{0,1,2\}}, D, Y\right) &= 0 \\ k\left(X_{NCH}, X_{i=\{0,1,2\}}, P, D\right) &= 0 \\ g\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi\right) &= 0 \\ h\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi\right) &= 0 \end{aligned} \tag{16}$$

Considering the ecological function $g(\quad)$, one can derive the function describing the level of pest density as follows

$$P = \psi(X_{NCH}, X_{i=\{0,1,2\}}, N, \varphi) \tag{17}$$

Similarly considering the damages transformation function $k(\quad)$ we can also derive

$$D = \mathcal{E}(X_{NCH}, X_{i=\{0,1,2\}}, P) \tag{18}$$

Replacing D in the good output transformation function yields

$$f\left(X_{NCH}, X_{i=\{0,1,2\}}, \mathcal{E}\left(X_{NCH}, X_{i=\{0,1,2\}}, \psi(X_{NCH}, X_{i=\{0,1,2\}}, N, \varphi)\right), Y\right) = 0 \tag{19}$$

By differentiating (17) with respect to Y and φ we have

$$\begin{gathered} f_Y dY + f_D \mathcal{E}_P \psi_\varphi d\varphi = 0 \\ \Leftrightarrow \boldsymbol{\frac{dY}{d\varphi} = -\frac{f_D \mathcal{E}_P \psi_\varphi}{f_Y}} \\ f_Y > 0 \end{gathered} \tag{20}$$

From the developments in the previous section we know that $f_D \geq 0$ and $\mathcal{E}_P = -\frac{k_P}{k_D} \geq 0$ and $\psi_\varphi = -\frac{g_\varphi}{g_P} \leq 0$ and thus $\frac{dY}{d\varphi} \geq 0$ which corresponds to a positive marginal productivity of pesticides use. In (20) it appears that the effect of pesticides on yield passes by their effects in regulating pest populations and the ability of these latter to generate damages to yield.

The trade-off in (20) is computed by making abstraction of the natural predators' technology i.e. only the economic (good and undesirable) and the pest densities technologies have been considered.

If we use the economic and the predator density technologies, we have:

$$\begin{gathered} h(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi) = 0 \\ \Rightarrow P = \ell(X_{NCH}, X_{i=\{0,1,2\}}, N, \varphi) \\ \Rightarrow f\left(X_{NCH}, X_{i=\{0,1,2\}}, \mathcal{E}\left(X_{NCH}, X_{i=\{0,1,2\}}, \ell(X_{NCH}, X_{i=\{0,1,2\}}, N, \varphi)\right), Y\right) = 0 \\ \Rightarrow \boldsymbol{\frac{dY}{d\varphi} = -\frac{f_D \mathcal{E}_P \ell_\varphi}{f_Y}} \end{gathered} \tag{21}$$

$$f_D \geq 0 \wedge \mathcal{E}_P = -\frac{k_P}{k_D} \geq 0 \wedge \ell_\varphi = -\frac{h_\varphi}{h_P} \geq 0 \wedge f_Y > 0$$
$$\Rightarrow \frac{dY}{d\varphi} \leq 0$$

The trade-off in (21) can be considered as the spillover effect due to the destruction of the natural predators by the use of pesticides.

All the trade-offs computed till now have only considered the technologies in a partial framework to derive the trade-off between pesticides use and production yield. If all the four technologies are accounted for we have:

$$\begin{gathered} h(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi) = 0 \\ \Rightarrow N = \mathcal{B}(X_{NCH}, X_{i=\{0,1,2\}}, P, \varphi) \\ f(X_{NCH}, X_{i=\{0,1,2\}}, D, Y) = 0 \\ \Rightarrow D = \mathcal{L}(X_{NCH}, X_{i=\{0,1,2\}}, Y) \\ k(X_{NCH}, X_{i=\{0,1,2\}}, P, D) = 0 \\ \Rightarrow P = \omega(X_{NCH}, X_{i=\{0,1,2\}}, D) \\ \Leftrightarrow P = \omega\left(X_{NCH}, X_{i=\{0,1,2\}}, \mathcal{L}(X_{NCH}, X_{i=\{0,1,2\}}, Y)\right) \\ g(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi) = 0 \end{gathered} \tag{22}$$

If we replace the implicit values of P and N in the expression of $g(\quad)$ in the last equation in (22) and differentiate that expression with respect to Y and φ, we obtain:

$$\begin{gathered} g_P\, \omega_D\, \mathcal{L}_Y dY + g_N\, \mathcal{B}_P \omega_D\, \mathcal{L}_Y dY + g_N \mathcal{B}_\varphi d\varphi + g_\varphi d\varphi = 0 \\ \Leftrightarrow \boldsymbol{\frac{dY}{d\varphi} = -\frac{g_N \mathcal{B}_\varphi + g_\varphi}{g_P\, \omega_D\, \mathcal{L}_Y + g_N\, \mathcal{B}_P \omega_D\, \mathcal{L}_Y}} \\ g_P\, \omega_D\, \mathcal{L}_Y + g_N\, \mathcal{B}_P \omega_D\, \mathcal{L}_Y > 0 \end{gathered} \tag{23}$$

where

$$\mathcal{B}_\varphi = -\frac{h_\varphi}{h_N} \leq 0 \wedge \omega_D = -\frac{k_D}{k_P} \geq 0 \wedge \mathcal{L}_Y = -\frac{f_Y}{f_D} \leq 0 \wedge \mathcal{B}_P = -\frac{h_P}{h_N} \geq 0 \tag{24}$$

The trade-off in (23) is of unrestricted sign (because of the numerator) hence it can be either positive or negative. The spillover effect corresponds to the expression $\left(-\, g_N \mathcal{B}_\varphi / (g_P\, \omega_D\, \mathcal{L}_Y + g_N\, \mathcal{B}_P \omega_D\, \mathcal{L}_Y)\right) \leq 0$ which implies that pesticides may negatively affect yield by destroying natural predators to pest populations.

- **Trade-off between *Y* and *N***

Using the same strategy as previously the trade-off between the good economic output and the natural predator populations can be derived as follows (considering the four technologies):

$$
\begin{gathered}
f\left(X_{NCH}, X_{i=\{0,1,2\}}, D, Y\right) = 0 \\
\Rightarrow D = \mathcal{L}\left(X_{NCH}, X_{i=\{0,1,2\}}, Y\right) \\
k\left(X_{NCH}, X_{i=\{0,1,2\}}, P, D\right) = 0 \\
\Rightarrow P = \omega\left(X_{NCH}, X_{i=\{0,1,2\}}, D\right) \\
\Leftrightarrow\ P = \omega\left(X_{NCH}, X_{i=\{0,1,2\}}, \mathcal{L}\left(X_{NCH}, X_{i=\{0,1,2\}}, Y\right)\right) \\
g\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi\right) = 0 \\
\Rightarrow \varphi = \mathcal{M}\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N\right) \\
h\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi\right) = 0
\end{gathered}
\tag{25}
$$

Let's replace P and φ by their implicit values in the last expression of (25). Then the trade-off can be computed by:

$$
\begin{gathered}
\boldsymbol{\frac{dY}{dN} = -\frac{h_N + h_\varphi \mathcal{M}_N}{h_P \omega_D \, \mathcal{L}_Y + h_\varphi \mathcal{M}_P \omega_D \, \mathcal{L}_Y}} \\
h_P \omega_D \, \mathcal{L}_Y + h_\varphi \mathcal{M}_P \omega_D \, \mathcal{L}_Y > 0
\end{gathered}
\tag{26}
$$

Where

$$
\mathcal{M}_N = -\frac{g_N}{g_\varphi} \leq 0 \ \wedge \ \mathcal{M}_P = -\frac{g_P}{g_\varphi} \leq 0
\tag{27}
$$

The trade-off in (26) is also undefined in sign (because of the numerator) reflecting a possible beneficial or detrimental effect of natural predators on production yield. The spillover effect is $-h_\varphi \mathcal{M}_N / \left(h_P \omega_D \, \mathcal{L}_Y + h_\varphi \mathcal{M}_P \omega_D \, \mathcal{L}_Y\right) \geq 0$ which traduces the beneficial effect of natural predators by limiting the destructive capacity of pests. Moreover, the direct effect of natural predators is negative on production yield.

- **Trade-off between *N* and φ**

One may wonder what is the relation that exists between the two ways for controlling pest populations (biological and chemical controls). To this aim we also derive the trade-off between N and φ. Since those two variables only appear in the functions $g(\ \ )$ and $h(\ \ )$, the other two-transformation functions can be ignored. Using as previously implicit function theorem, we have:

$$
\begin{gathered}
g\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi\right) = 0 \\
\Longrightarrow P = \mathcal{J}\left(X_{NCH}, X_{i=\{0,1,2\}}, N, \varphi\right) \\
h\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi\right) = 0 \\
\Leftrightarrow h\left(X_{NCH}, X_{i=\{0,1,2\}}, \mathcal{J}\left(X_{NCH}, X_{i=\{0,1,2\}}, N, \varphi\right), N, \varphi\right) = 0
\end{gathered} \tag{28}
$$

By differentiating $h(\quad)$ with respect to N and φ, we obtain:

$$
\begin{gathered}
\boldsymbol{\frac{dN}{d\varphi} = -\frac{h_P \mathcal{J}_\varphi + h_\varphi}{h_P \mathcal{J}_N + h_N}} \\
\mathcal{J}_\varphi = -\frac{g_\varphi}{g_P} \leq 0 \ \wedge \ \mathcal{J}_N = -\frac{g_N}{g_P} \leq 0 \\
\Longrightarrow \boldsymbol{\frac{dN}{d\varphi} \leq 0}
\end{gathered} \tag{29}
$$

From the trade-off presented in (29), both damage-control processes are substitutes.

3.3-Activity analysis representation

In this part we measure pesticides use efficiency using data envelopment analysis (DEA). Let's assume j to be the identifier of each landscape and J the total number of simulated landscapes. The different technologies described in (4) to (7) can be non-parametrically described by the following models under the convexity assumption and variable returns to scale (VRS) as:

$$
\Psi_Y = \left\{
\begin{gathered}
\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \mathbb{R}^9 \mid \\
\sum_{j=1}^{J} \lambda_j X_{NCH,j} \geq X_{NCH} \ \wedge \sum_{j=1}^{J} \lambda_j X_{i=\{0,1,2\},j} \leq X_{i=\{0,1,2\}} \ \wedge \\
\sum_{j=1}^{J} \lambda_j D_j \geq D \ \wedge \ \sum_{j=1}^{J} \lambda_j Y_j \geq Y \ \wedge \ \sum_{j=1}^{J} \lambda_j = 1
\end{gathered}
\right\} \tag{30}
$$

$$
\Psi_D = \left\{
\begin{gathered}
\left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \mathbb{R}^9 \mid \\
\sum_{j=1}^{J} \vartheta_j X_{NCH,j} \leq X_{NCH} \ \wedge \sum_{j=1}^{J} \vartheta_j X_{i=\{0,1,2\},j} \geq X_{i=\{0,1,2\}} \ \wedge \\
\sum_{j=1}^{J} \vartheta_j P_j \geq P \ \wedge \ \sum_{j=1}^{J} \vartheta_j D_j \leq D \ \wedge \ \sum_{j=1}^{J} \vartheta_j = 1
\end{gathered}
\right\} \tag{31}
$$

$$\Psi_P = \left\{ \begin{array}{c} \left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \mathbb{R}^9 \mid \\ \sum_{j=1}^{J} \mu_j X_{NCH,j} \leq X_{NCH} \ \wedge \sum_{j=1}^{J} \mu_j X_{i=\{0,1,2\},j} \geq X_{i=\{0,1,2\}} \ \wedge \\ \sum_{j=1}^{J} \mu_j P_j \leq P \ \wedge \ \sum_{j=1}^{J} \mu_j N_J \leq N \ \wedge \ \sum_{j=1}^{J} \mu_j \varphi_j \leq \varphi \ \wedge \ \sum_{j=1}^{J} \mu_j = 1 \end{array} \right\} \tag{32}$$

$$\Psi_N = \left\{ \begin{array}{c} \left(X_{NCH}, X_{i=\{0,1,2\}}, P, N, \varphi, Y, D\right) \in \mathbb{R}^9 \mid \\ \sum_{j=1}^{J} \eta_j X_{NCH,j} \leq X_{NCH} \ \wedge \sum_{j=1}^{J} \eta_j X_{i=\{0,1,2\},j} \geq X_{i=\{0,1,2\}} \ \wedge \\ \sum_{j=1}^{J} \eta_j P_j \leq P \ \wedge \ \sum_{j=1}^{J} \eta_j N_j \geq N \ \wedge \ \sum_{j=1}^{J} \eta_j \varphi_j \geq \varphi \ \wedge \ \sum_{j=1}^{J} \eta_j = 1 \end{array} \right\} \tag{33}$$

For each of the technologies described above, the following conditions must be satisfied in reference to the equation in (2):

$$\begin{gathered} \sum_{j=1}^{J} \lambda_j X_{NCH,j} + \sum_{j=1}^{J} \lambda_j X_{i=\{0,1,2\},j} = 1 \\ \sum_{j=1}^{J} \vartheta_j X_{NCH,j} + \sum_{j=1}^{J} \vartheta_j X_{i=\{0,1,2\},j} = 1 \\ \sum_{j=1}^{J} \mu_j X_{NCH,j} + \sum_{j=1}^{J} \mu_j X_{i=\{0,1,2\},j} = 1 \\ \sum_{j=1}^{J} \eta_j X_{NCH,j} + \sum_{j=1}^{J} \eta_j X_{i=\{0,1,2\},j} = 1 \end{gathered} \tag{34}$$

Those conditions ensure that the sum of the optimal shares of all land uses always equal to one. However, it is not necessary to explicitly include these conditions in the technology representations in (30) to (33) because from the simulation we know that for each land scape the sum-up condition is satisfied and thus the conditions in (34) are equivalent to the VRS convexity constraint. For instance

$$\begin{gathered} \sum_{j=1}^{J} \lambda_j X_{NCH,j} + \sum_{j=1}^{J} \lambda_j X_{i=\{0,1,2\},j} = 1 \\ X_{NCH,j} + X_{i=\{0,1,2\},j} = 1 \ \forall j \\ \Rightarrow \sum_{j=1}^{J} \lambda_j = 1 \end{gathered} \tag{35}$$

Since pesticides can be algebraically computed using the coefficients mentioned in the simulation section, it is appropriate for assessing inefficiency to endogeneize the levels of (the share of) land uses knowing that the sum equals 1. Land uses are decision variables in our estimation.

We propose to use a directional distance function – DDF – (Chambers et al., 1996, Chambers et al., 1998) to assess the efficiency at the landscape level. The efficiency model is summarized in (36)

$$
\begin{gathered}
INE = \max_{\lambda,\vartheta,\mu,\eta,X_0,X_{NCH},X_{i=\{0,1,2\}},\beta}\left(\beta_{\varphi} + \beta_D + \beta_P + \beta_N\right) \\
s.t. \sum_{j=1}^{J}\lambda_j X_{NCH,j} \geq X_{NCH} \wedge \sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} \leq X_{i=\{0,1,2\}} \wedge \\
\sum_{j=1}^{J}\lambda_j D_j \geq D - \beta_D \vec{g}_D \wedge \sum_{j=1}^{J}\lambda_j Y_j \geq Y \wedge \sum_{j=1}^{J}\lambda_j = 1 \wedge \\
\sum_{j=1}^{J}\vartheta_j X_{NCH,j} \leq X_{NCH} \wedge \sum_{j=1}^{J}\vartheta_j X_{i=\{0,1,2\},j} \geq X_{i=\{0,1,2\}} \wedge \\
\sum_{j=1}^{J}\vartheta_j P_j \geq P - \beta_P \vec{g}_P \wedge \sum_{j=1}^{J}\vartheta_j D_j \leq D - \beta_D \vec{g}_D \wedge \sum_{j=1}^{J}\vartheta_j = 1 \wedge \\
\sum_{j=1}^{J}\mu_j X_{NCH,j} \leq X_{NCH} \wedge \sum_{j=1}^{J}\mu_j X_{i=\{0,1,2\},j} \geq X_{i=\{0,1,2\}} \wedge \\
\sum_{j=1}^{J}\mu_j P_j \leq P - \beta_P \vec{g}_P \wedge \sum_{j=1}^{J}\mu_j N_J \leq N + \beta_N \vec{g}_N \wedge \qquad (36) \\
\sum_{j=1}^{J}\mu_j \varphi_j \leq \varphi - \beta_{\varphi} \vec{g}_{\varphi} \wedge \sum_{j=1}^{J}\mu_j = 1 \wedge \\
\sum_{j=1}^{J}\eta_j X_{NCH,j} \leq X_{NCH} \wedge \sum_{j=1}^{J}\eta_j X_{i=\{0,1,2\},j} \geq X_{i=\{0,1,2\}} \wedge \\
\sum_{j=1}^{J}\eta_j P_j \leq P - \beta_P \vec{g}_P \wedge \sum_{j=1}^{J}\eta_j N_j \geq N + \beta_N \vec{g}_N \wedge \\
\sum_{j=1}^{J}\eta_j \varphi_j \geq \varphi - \beta_{\varphi} \vec{g}_{\varphi} \wedge \sum_{j=1}^{J}\eta_j = 1 \wedge \\
\sum_{j=1}^{J}\lambda_j X_{NCH,j} = \sum_{j=1}^{J}\vartheta_j X_{NCH,j} \wedge \sum_{j=1}^{J}\lambda_j X_{NCH,j} = \sum_{j=1}^{J}\mu_j X_{NCH,j} \wedge \\
\sum_{j=1}^{J}\lambda_j X_{NCH,j} = \sum_{j=1}^{J}\eta_j X_{NCH,j} \wedge \sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} = \sum_{j=1}^{J}\vartheta_j X_{i=\{0,1,2\},j} \wedge
\end{gathered}
$$

$$\sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} = \sum_{j=1}^{J}\mu_j X_{i=\{0,1,2\},j} \wedge \sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} = \sum_{j=1}^{J}\eta_j X_{i=\{0,1,2\},j} \wedge$$
$$(\beta_\varphi, \beta_D, \beta_P, \beta_N) \geq 0$$

$(\beta_\varphi, \beta_D, \beta_P, \beta_N)$ are the inefficiency scores and $(\vec{g}_\varphi, \vec{g}_D, \vec{g}_P, \vec{g}_N)$ are the directional vectors which we retain to be equal to the observed levels. To ensure consistency between the different technologies, the last three lines represent some dependence constraints that link up the four technologies at the optimal levels of land uses in each technology. It is worth noting that since the land use variables are endogenous and do not affect the objective function, their respective constraints can be removed from the optimization (except for the dependence constraints). Model (36) therefore simplifies as follows:

$$INE = \max_{\lambda,\vartheta,\mu,\eta,X_0,X_{NCH},X_{i=\{0,1,2\}},\beta} (\beta_\varphi + \beta_D + \beta_P + \beta_N)$$
$$s.t. \sum_{j=1}^{J}\lambda_j D_j \geq D - \beta_D \vec{g}_D \wedge \sum_{j=1}^{J}\lambda_j Y_j \geq Y \wedge \sum_{j=1}^{J}\lambda_j = 1 \wedge$$
$$\sum_{j=1}^{J}\vartheta_j P_j \geq P - \beta_P \vec{g}_P \wedge \sum_{j=1}^{J}\vartheta_j D_j \leq D - \beta_D \vec{g}_D \wedge \sum_{j=1}^{J}\vartheta_j = 1 \wedge$$
$$\sum_{j=1}^{J}\mu_j P_j \leq P - \beta_P \vec{g}_P \wedge \sum_{j=1}^{J}\mu_j N_J \leq N + \beta_N \vec{g}_N \wedge$$
$$\sum_{j=1}^{J}\mu_j \varphi_j \leq \varphi - \beta_\varphi \vec{g}_\varphi \wedge \sum_{j=1}^{J}\mu_j = 1 \wedge$$
$$\sum_{j=1}^{J}\eta_j P_j \leq P - \beta_P \vec{g}_P \wedge \sum_{j=1}^{J}\eta_j N_j \geq N + \beta_N \vec{g}_N \wedge \tag{37}$$
$$\sum_{j=1}^{J}\eta_j \varphi_j \geq \varphi - \beta_\varphi \vec{g}_\varphi \wedge \sum_{j=1}^{J}\eta_j = 1 \wedge$$
$$\sum_{j=1}^{J}\lambda_j X_{NCH,j} = \sum_{j=1}^{J}\vartheta_j X_{NCH,j} \wedge \sum_{j=1}^{J}\lambda_j X_{NCH,j} = \sum_{j=1}^{J}\mu_j X_{NCH,j} \wedge$$
$$\sum_{j=1}^{J}\lambda_j X_{NCH,j} = \sum_{j=1}^{J}\eta_j X_{NCH,j} \wedge \sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} = \sum_{j=1}^{J}\vartheta_j X_{i=\{0,1,2\},j} \wedge$$
$$\sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} = \sum_{j=1}^{J}\mu_j X_{i=\{0,1,2\},j} \wedge \sum_{j=1}^{J}\lambda_j X_{i=\{0,1,2\},j} = \sum_{j=1}^{J}\eta_j X_{i=\{0,1,2\},j} \wedge$$
$$(\beta_\varphi, \beta_D, \beta_P, \beta_N) \geq 0$$

To determine the different trade-offs discussed in the previous section, we need to estimate the shadow prices of the constraints in (37). To this aim, we provide below the dual of model (37)

$$
\begin{aligned}
INE = \max_{S} \, & \left(S_D^{\Psi_Y} D + S_Y^{\Psi_Y} Y - S_{vrs}^{\Psi_Y} + S_P^{\Psi_D} P - S_D^{\Psi_D} D - S_{vrs}^{\Psi_D} - S_P^{\Psi_P} P - S_N^{\Psi_P} N \right. \\
& \left. - S_\varphi^{\Psi_P} \varphi - S_{vrs}^{\Psi_P} - S_P^{\Psi_N} P + S_N^{\Psi_N} N + S_\varphi^{\Psi_N} \varphi - S_{vrs}^{\Psi_N}\right) \\
s.t. \; & S_D^{\Psi_Y} D_j + S_Y^{\Psi_Y} Y_j - S_{vrs}^{\Psi_Y} - \left(S_{X_{NCH},d1} + S_{X_{NCH},d2} + S_{X_{NCH},d3}\right) X_{NCH,j} \\
& - \left(S_{X_{i=\{0,1,2\},d1}} + S_{X_{i=\{0,1,2\},d2}} + S_{X_{i=\{0,1,2\},d3}}\right) X_{i=\{0,1,2\},j} \leq 0 \\
& S_P^{\Psi_D} P_j - S_D^{\Psi_D} D_j - S_{vrs}^{\Psi_D} + S_{X_{NCH},d1} X_{NCH,j} + S_{X_{i=\{0,1,2\},d1}} X_{i=\{0,1,2\},j} \leq 0 \\
& -S_P^{\Psi_P} P_j - S_N^{\Psi_P} N_j - S_\varphi^{\Psi_P} \varphi_j - S_{vrs}^{\Psi_P} + S_{X_{NCH},d2} X_{NCH,j} + S_{X_{i=\{0,1,2\},d2}} X_{i=\{0,1,2\},j} \leq 0 \\
& -S_P^{\Psi_N} P_j + S_N^{\Psi_N} N_j + S_\varphi^{\Psi_N} \varphi_j - S_{vrs}^{\Psi_N} + S_{X_{NCH},d3} X_{NCH,j} + S_{X_{i=\{0,1,2\},d3}} X_{i=\{0,1,2\},j} \\
& \leq 0 \\
& \left(S_D^{\Psi_Y} - S_D^{\Psi_D}\right) \vec{g}_D \leq 1 \\
& \left(S_P^{\Psi_D} - S_P^{\Psi_P} - S_P^{\Psi_N}\right) \vec{g}_P \leq 1 \\
& \left(S_N^{\Psi_P} - S_N^{\Psi_N}\right) \vec{g}_N \leq 1 \\
& \left(-S_\varphi^{\Psi_P} + S_\varphi^{\Psi_N}\right) \vec{g}_\varphi \leq 1 \\
& 1 = 1, \ldots, J \\
& S_D^{\Psi_Y}, S_P^{\Psi_D}, S_D^{\Psi_D}, S_P^{\Psi_P}, S_N^{\Psi_P}, S_\varphi^{\Psi_P}, S_P^{\Psi_N}, S_N^{\Psi_N}, S_\varphi^{\Psi_N} \geq 0 \\
& S_{vrs}^{\Psi_Y}, S_{vrs}^{\Psi_D}, S_{vrs}^{\Psi_P}, S_{vrs}^{\Psi_N}, S_{X_{NCH},d1}, S_{X_{NCH},d2}, S_{X_{NCH},d3}, S_{X_{i=\{0,1,2\},d1}}, S_{X_{i=\{0,1,2\},d2}}, \\
& S_{X_{i=\{0,1,2\},d3}} \text{ free}
\end{aligned}
\tag{38}
$$

where $S_P^T, S_N^T, S_Y^T, S_D^T, S_\varphi^T, S_{vrs}^T$ are respectively the shadow prices of pests, predators, good economic production, bad economic production (damages), pesticides use and the convexity constraint under the technology T; $\left(S_{X_{NCH},d1}, S_{X_{NCH},d2}, S_{X_{NCH},d3}, S_{X_{i=\{0,1,2\},d1}}, S_{X_{i=\{0,1,2\},d2}}, S_{X_{i=\{0,1,2\},d3}}\right)$ are the shadow prices associated to the different dependence constraints on land uses.

The estimation of model (38) may result in many zero shadow prices for many of the variables and therefore undefined trade-offs. To prevent this situation, we have relied on the estimation of production facets where all our required prices are well defined [in allusion to full dimensional efficient facets – FDEFs where in these case all the shadow prices are properly defined (Olesen and Petersen, 2015)]. For this case, the facets' equations are associated to the hyperplanes that define each of our technology. For simplicity, independently considered, those hyperplanes write as

$$
\begin{aligned}
f &:= S_D^{\Psi_Y} D_j + S_Y^{\Psi_Y} Y_j - S_{vrs}^{\Psi_Y} + S_{X_{NCH}}^{\Psi_Y} X_{NCH,j} - S_{X_{i=\{0,1,2\},j}}^{\Psi_Y} X_{i=\{0,1,2\},j} + c_1 = 0 \\
k &:= S_P^{\Psi_D} P_j - S_D^{\Psi_D} D_j - S_{vrs}^{\Psi_D} - S_{X_{NCH}}^{\Psi_D} X_{NCH,j} + S_{X_{i=\{0,1,2\}}}^{\Psi_D} X_{i=\{0,1,2\},j} + c_2 = 0
\end{aligned}
\tag{39}
$$

$$g \coloneqq -S_P^{\Psi_P} P_j - S_N^{\Psi_P} N_j - S_\varphi^{\Psi_P} \varphi_j - S_{vrs}^{\Psi_P} - S_{X_{NCH}}^{\Psi_P} X_{NCH,j} + S_{X_{i=\{0,1,2\}}}^{\Psi_P} X_{i=\{0,1,2\},j} + c_3 = 0$$

$$h \coloneqq -S_P^{\Psi_N} P_j + S_N^{\Psi_N} N_j + S_\varphi^{\Psi_N} \varphi_j - S_{vrs}^{\Psi_N} - S_{X_{NCH}}^{\Psi_N} X_{NCH,j} + S_{X_{i=\{0,1,2\}}}^{\Psi_N} X_{i=\{0,1,2\},j} + c_4 = 0$$

where c_1, c_2, c_3, c_4 are positive constants so that the inequalities can be transformed into equalities. All the facets can be estimated using a convex hull algorithm and to choose, the appropriate one for each observation we retain the closest target approach (Portela et al., 2003). The different trade-offs can be computed using the formulas in (23), (26) and (29) and the hyperplanes' equations defined in (39).

- Trade-off between good economic output and pesticides

From (23) and the hyperplanes equations in (39) we can write the following

$$\frac{\boldsymbol{dY}}{\boldsymbol{d\varphi}} = -\frac{S_N^{\Psi_P{}^*}\left(\frac{S_\varphi^{\Psi_N{}^*}}{S_N^{\Psi_N{}^*}}\right) - S_\varphi^{\Psi_P{}^*}}{\left(\frac{S_D^{\Psi_D{}^*}}{S_P^{\Psi_D{}^*}}\right)\left(\frac{S_Y^{\Psi_Y{}^*}}{S_D^{\Psi_Y{}^*}}\right)\left[S_P^{\Psi_P{}^*} + S_N^{\Psi_P{}^*}\left(\frac{S_P^{\Psi_N{}^*}}{S_N^{\Psi_N{}^*}}\right)\right]} \tag{40}$$

- Trade-off between good economic output and natural predators

As previously the trade-off between Y and N can be obtained using the formula in (26) and the hyperplanes equation in (39). We have:

$$\frac{\boldsymbol{dY}}{\boldsymbol{dN}} = -\frac{S_N^{\Psi_N{}^*} - S_\varphi^{\Psi_N{}^*}\left(\frac{S_N^{\Psi_P{}^*}}{S_\varphi^{\Psi_P{}^*}}\right)}{\left(\frac{S_D^{\Psi_D{}^*}}{S_P^{\Psi_D{}^*}}\right)\left(\frac{S_Y^{\Psi_Y{}^*}}{S_D^{\Psi_Y{}^*}}\right)\left[S_P^{\Psi_N{}^*} + S_\varphi^{\Psi_N{}^*}\left(\frac{S_P^{\Psi_N{}^*}}{S_\varphi^{\Psi_N{}^*}}\right)\right]} \tag{41}$$

- Trade-off between predator populations and pesticides

The trade-off between N and φ is presented in (29) and is similarly computed as the previous ones using the formula described below:

$$\frac{\boldsymbol{dN}}{\boldsymbol{d\varphi}} = -\frac{S_P^{\Psi_N{}^*}\left(\frac{S_\varphi^{\Psi_P{}^*}}{S_P^{\Psi_P{}^*}}\right) + S_\varphi^{\Psi_N{}^*}}{S_P^{\Psi_N{}^*}\left(\frac{S_N^{\Psi_P{}^*}}{S_P^{\Psi_P{}^*}}\right) + S_N^{\Psi_N{}^*}} \tag{42}$$

4-Results

In this part we present and discuss the results related to the different inefficiency scores, optimal land use proportions and trade-offs estimates mentioned in the previous section. The spatial effects of land use are assessed through a second stage where inefficiency scores are regressed on the spatial aggregation indices along with the policy instruments variables.

4.1-Inefficiencies and optimal land uses

By its deterministic nature, DEA lacks of statistical inference and several attempts in the literature have tried to overcome this issue (Simar and Wilson, 1998, Simar and Wilson, 1999a, Simar and Wilson, 1999b). In this article, we rely on subsampling techniques to correct the bias associated to the DDF estimates (Kneip et al., 2008, Simar and Wilson, 2011, Simar et al., 2012). The idea of the subsampling is to draw with replacement (in our case) a sample of size $m < n$ which serves as benchmark for the observations under scrutiny. The operation is run several times ($B = 1000$ replications) to derive the unknown distribution parameters. The advantage of the subsampling is to account for heterogeneity in the variables distribution. As underlined in Dakpo et al. (2017), the main challenge is to adapt the subsampling to multiple technologies framework especially in the choice of the convergence rate. Following these authors, we retain for this work the slowest convergence rate among the four technologies if independently considered. Moreover, we have considered several possibilities for the subsample size (m) and applied the Politis et al. (2001), Bickel and Sakov (2008)'s volatility criteria minimization (standard deviation for our case) for the choice of the proper size for each observation and parameter (mean and confidence intervals). Table 2 presents the bias-corrected inefficiency scores mean and confidence intervals. The results reveal an average inefficiency score of 7.7% in pesticides use. The highest inefficiencies are recorded for the natural predators (about 600%). This result may be a reflection of a high heterogeneity between the landscapes in terms of predator populations and may imply that these populations are very sensitive to the allocation of land uses and also to the spatial aggregation of these latter. Damages inefficiencies are also high and represent an average about 63.2%. Finally, the inefficiency in pest levels is around 45.7% on average. All these inefficiency results shed light on the high leeway in biological populations management. Besides all the inefficiencies are significantly different from zero given their confidence interval.

Table 2: Inefficiency scores associated to damages, pests, natural predators and pesticides use

Measures	Statistics	β_D	β_P	β_N	β_φ
Original inefficiency estimates	Mean	0.650	0.474	5.951	0.066
	Standard deviation	0.193	0.160	6.472	0.049
Bias-corrected inefficiency scores (mean)	**Mean**	**0.632**	**0.457**	**5.999**	**0.077**
	Standard deviation	**0.249**	**0.205**	**6.489**	**0.058**
95% confidence interval of Inefficiency scores	Lower bounds	0.614	0.433	5.813	0.062
	Upper bounds	0.685	0.514	6.203	0.092

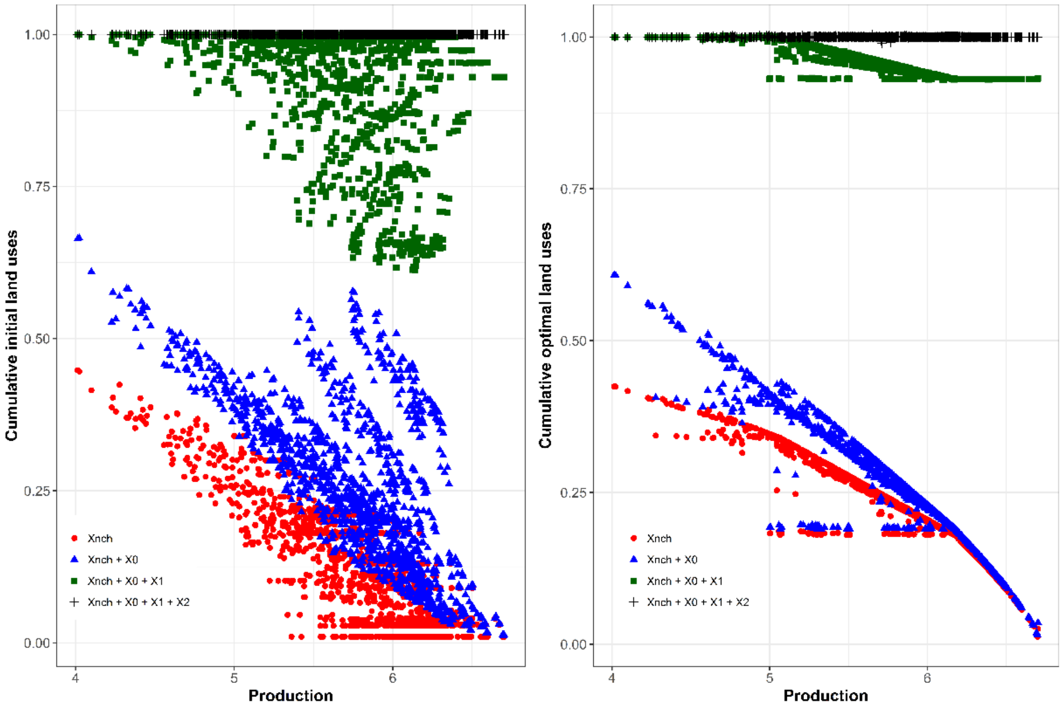
The optimal land uses allocation are presented in Table 3. Compare to the initial land uses allocation in the sample (and presented in Table 1), the average share of grasslands should be increased by more than twice the original observation (21% vs 10%) while the share of crops with zero levels of pesticides must be seriously decreased from 13% to 3%. The same latter observation is also valid for crops with high level of pesticides which must decrease from 10% to 5%. About crops with medium use of pesticides, their proportion should be slightly increase from 67% to 71% on average. These results imply that focus should be given to grasslands and medium usage of pesticides for optimality.

Table 3: Optimal land uses allocation

Statistics	X_{NCH}	X_0	X_1	X_2
Minimum	0.01	0.00	0.39	0.00
1st quartile	0.18	0.01	0.67	0.05
Median	0.20	0.02	0.71	0.06
Mean	**0.21**	**0.03**	**0.71**	**0.05**
3rd quartile	0.24	0.04	0.74	0.07
Maximum	0.42	0.18	0.91	0.07

Figure 4 shows the evolution of the cumulative land use proportions in relation to the landscape production levels. While the distribution with the initial values show a wide dispersion, the observations are more concentrated when considering the optimal values (right plot on Figure 4). Besides on the plot with optimal values we can see a clear gap between grasslands and crops free pesticides $(X_{NCH} + X_0)$ on one side and crop with medium and high use of pesticides $(X_1 + X_2)$ on the other side. This gap can be explained by the high level of land use with medium levels of pesticides (X_1). For low production levels, we can see on both plots that X_{NCH} and X_0 weigh more than half of the total land uses with even zero values for very intensive crops X_2. Most producing landscapes are characterized with lower proportions of X_{NCH} and X_0 (less than 10% at very high production levels), lesser X_1 so they have more intensive crops X_2 (about 5%). Clearly depending on the levels of production a proper distribution of land uses is associated.

Figure 4: Cumulative land use allocation vs landscape production



4.2-Trade-offs analysis

As previously discussed, the trade-offs are computed using the estimation of production facets where the required shadow prices are properly defined. To this aim we use the convex hull algorithm of the geometry package (Habel et al., 2015). For easy interpretability we present the elasticities in Table 4. The results in Table 4 reveals that the spillover effects of pesticides use are on average of higher importance than the direct effect and hence the negative average elasticity of pesticides (-1.782). Let's recall that the direct effect of pesticides is the reduction of pests' populations which is beneficial to production and the spillover effect (indirect) is related to the destruction of natural predators' populations and therefore may have a negative impact on production. This result is partly observed in the trade-off between production and natural predators which is very high and positive on average (0.229) therefore the indirect effect of pesticides by eliminating predators will be negative and also high. All these observations can be understandable given that the results discussed in the previous subsection reveal that at the optimality grasslands areas should be double and we know from construction that these areas are beneficial to the natural predators' populations. It seems that the landscapes simulated in our case give a very weight to pests' natural enemies. The substitution rate between both damages control possibilities (natural predators and pesticides) is very high and monotonic as demonstrated in subsection 3.2. For instance, on average, when pesticides treatment is increased by 1%, natural predators' numbers can fall by about 200%. However, the lower figures for the median (-64.57) and the third quartile (-7.68) suggests an important heterogeneity between the landscapes.

Table 4: Elasticities between different variables

Statistics	$\frac{dY}{d\varphi}$			$\frac{dY}{dN}$			$\frac{dN}{d\varphi}$
	Direct effect	Spillover effect	Total effect	Direct effect	Spillover effect	Total effect	Total effect
1st quartile	0.062	-2.641	-2.438	-0.005	0.002	-0.000	-199.400
Median	0.122	-1.952	-1.219	-0.001	0.017	0.006	-64.570
Mean	**0.774**	**-2.556**	**-1.782**	**-0.019**	**0.248**	**0.229**	**-200.700**
3rd quartile	-0.375	0.357	0.031	-0.000	0.326	0.324	-7.680

4.3-Determinants of inefficiency

To assess the impact of the spatial aggregation indices and the policy instruments on the different inefficiency scores, we run in a second stage regression estimations where the dependent variables are the different inefficiency scores. However, to account for the deterministic nature of DEA we have considered the bootstrap estimates of the inefficiency scores. Hence, for each inefficiency measures we run $B = 1000$ different regressions using the corresponding bootstrap estimates. Besides since the inefficiency scores are obtained using subsampling, those scores are not anymore bounded by zero and we could thereby run ordinary least squares for each regression. The summary of these estimations are presented in Table 5. We have considered the five spatial aggregation indices and the three policy instruments. About the policy instruments, we have computed the total optimal pesticides tax per unit of product $\left[tax \times \frac{(1-\beta_\varphi)\varphi}{Y}\right]$. We follow the same procedure for grassland subsidies $\left[\frac{subsidy \times X_{NCH}^{opt}}{Y}\right]$. Therefore, both the policy instruments mentioned above can be directly compared to the price bonus. For damages and pests, the spatial aggregation of X_{NCH} and X_0 have positive impacts on their inefficiency while the spatial aggregation of X_1, X_2 and treated plots decrease the inefficiency. In other words, to decrease pest levels and the inherent damages, land uses that require the applications of pesticides need to be spatially aggregated while grassland and crop-free pesticides need to be spatially dispersed for performance improvement. For natural predators, the inefficiency is decreased only when X_{NCH} are spatially aggregated. However, the sources of inefficiency for natural predators are the spatial aggregation of X_0, X_2 and treated plots. It appears that for both biological populations the requirement in terms of spatial aggregation of the land uses goes in opposite direction. For pesticides, it seems that the major source of efficiency improvement is the spatial aggregation of the treated plots while when X_1 and X_2 are spatially aggregated, this increase the pesticides use inefficiency. This latter observation goes in the same sense as the former one in terms of the aggregation of the treated plots as beneficial for efficiency. In terms of policy instruments, against all odds, pesticide taxes and production price bonus (for crop-free pesticides) increase the inefficiency of all the variables considered while grassland subsidies decrease their respective inefficiency.

Table 5: bootstrap regression estimates of the determinants of inefficiency scores

	β_D			β_P			β_N			β_φ		
	Coef.	lo	up	Coef.	lo	up	Coef.	lo	up	Coef.	lo	up
(Intercept)	1.010	0.909	1.064	0.799	0.689	0.857	4.018	3.254	4.230	0.155	0.111	0.271
AgG	0.055	0.040	0.092	0.027	0.008	0.057	-4.679	-5.591	-4.590	0.001	-0.009	0.019
AgC0	0.227	0.162	0.242	0.173	0.117	0.190	1.401	1.317	3.164	0.006	-0.008	0.028
AgC1	-0.025	-0.065	-0.007	-0.029	-0.067	-0.007	-0.499	-0.641	0.544	**0.085**	**0.068**	**0.130**
AgC2	-0.097	-0.107	-0.084	-0.067	-0.077	-0.054	0.859	0.539	0.891	**0.038**	**0.025**	**0.048**
IntensityAg	-0.456	-0.518	-0.333	-0.406	-0.475	-0.276	3.169	2.780	3.477	**-0.252**	**-0.408**	**-0.194**
PesticidesTax/Prod	0.015	0.013	0.017	0.017	0.015	0.019	0.479	0.406	0.490	**0.001**	**0.000**	**0.002**
GrassSub/Prod	-0.013	-0.014	-0.011	-0.011	-0.012	-0.009	-0.492	-0.496	-0.480	**-0.004**	**-0.006**	**-0.003**
PriceBonus	0.297	0.266	0.367	0.247	0.210	0.309	11.745	10.531	11.947	**0.295**	**0.268**	**0.323**

5-Conclusion

In this article, we have introduced a novel approach in treating damage-control inputs in the presence of information on biological populations (pests and natural predators). Our framework extends the classic model of a single technology to a multi-ware approach where several technologies are considered: two economic and two ecological. The economic technologies are associated to the production and the damages generated by the presence of pests. The ecological technologies describe the evolution of pests and natural predators' populations. The global technology lies at the intersection of the four technologies mentioned. We have described theoretically and also using activity analysis the whole production system. Moreover, to account for spatial effects of different land uses (crop and non-crop habitats) our analysis has been conducted at the landscape level and we tried to find the optimal allocation of the land uses in order to reduce the levels of pesticides use. We have also extended our analysis to the estimation of the trade-off between pesticides and landscape production. Finally, in a second stage we examine the effect of the spatial aggregation of the different land uses on the inefficiencies estimated.

To answer all the questions pointed above, we have use a prey-predator simulation model. Our main results reveal that grassland areas can be increased by twice their initial proportion, while croplands with medium levels of pesticides should be maintained. About croplands with zero and high levels of pesticides they should be reduced. This should induce a reduction of pesticides by about 7.7% while producing the same amount. As the results give a high importance to grasslands which favor the development of pests' natural enemies, the trade-off between pesticides and production is negative on average due the fact that their spillover effects are highly negative. The spillover effect of pesticides is the destruction of natural predators and thereby induce a negative effect of pesticides on production. In terms of the determinants of pesticides performance, it appears that it is beneficial to performance when the treated plots are spatially aggregated and the grasslands subsidized.

The results presented and discussed in this article imply that at a territorial level biological control can be used in association to chemical control (pesticides) to fight pests and minimize the damages to crop. Besides high importance can be given to natural predators to a point where pesticides use can have a detrimental impact of production. Though these results are obtained from a simulated model they shed some lights on very important societal questions on pesticides use. Future path of research can also undertake a sensitivity analysis as robustness of the results discussed earlier.

References

Banker, R. D. (1984). Estimating Most Productive Scale Size Using Data Envelopment Analysis. *European Journal of Operational Research* 17: 35-44.
Barraquand, F. and Martinet, V. (2011). Biological conservation in dynamic agricultural landscapes: Effectiveness of public policies and trade-offs with agricultural production. *Ecological Economics* 70: 910-920.
Barzman, M. and Dachbrodt-Saaydeh, S. (2011). Comparative analysis of pesticide action plans in five European countries. *Pest Management Science* 67: 1481-1485.
Bickel, P. J. and Sakov, A. (2008). On the choice of m in the m out of n bootstrap and confidence bounds for extrema. *Statistica Sinica* 18: 967-985.
Blair, A. and Zahm, S. H. (1993). Patterns of Pesticide Use among Farmers: Implications for Epidemiologic Research. *Epidemiology* 4: 55-62.
Bourguet, D. and Guillemaud, T. (2016). The Hidden and External Costs of Pesticide Use. In E. Lichtfouse (ed), *Sustainable Agriculture Reviews: Volume 19*. Cham: Springer International Publishing, 35-120.
Cantrell, R. S. and Cosner, C. (2003). *Spatial Ecology via Reaction-Diffusion Equations*. Wiley.
Carson, R. (1962). *Silent Spring*. Fawcett.
Chambers, R. G., Chung, Y.and Fare, R. (1998). Profit, directional distance functions, and Nerlovian efficiency. *Journal of Optimization Theory and Applications* 98: 351-364.
Chambers, R. G., Chung, Y. H.and Fare, R. (1996). Benefit and distance functions. *Journal of Economic Theory* 70: 407-419.
Chambers, R. G. and Tzouvelekas, V. (2013). Estimating population dynamics without population data. *Journal of Environmental Economics and Management* 66: 510-522.
Charnes, A., Cooper, W. W.and Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research* 2: 429-444.
Cooper, J. and Dobson, H. (2007). The benefits of pesticides to mankind and the environment. *Crop Protection* 26: 1337-1348.
Costa, L. G., Galli, C. L.and Murphy, S. D. (1987). *Toxicology of pesticides: experimental, clinical and regulatory perspectives*. Springer-Verlag.
Cramer, H.-H. (1967). Plant protection and world crop production. *Plant protection and world crop production.*
Dakpo, K. H., Jeanneaux, P.and Latruffe, L. (2017). Greenhouse gas emissions and efficiency in French sheep meat farming: A non-parametric framework of pollution-adjusted technologies. *European Review of Agricultural Economics* 44: 33-65.
Färe, R., Grosskopf, S.and Lovell, C. A. K. (1985). *The Measurement of Efficiency of Production*. Springer.
Feder, G. (1979). Pesticides, Information, and Pest Management under Uncertainty. *American Journal of Agricultural Economics* 61: 97-103.
Fernandez-Cornejo, J., Jans, S.and Smith, M. (1998). Issues in the Economics of Pesticide Use in Agriculture: A Review of the Empirical Evidence. *Review of Agricultural Economics* 20: 462-488.
Frisch, R. (1965). *Theory of Production*. Dordrecht Reidel Publishing Company.
Georghiou, G. P. and Saitō, T. (1983). *Pest resistance to pesticides*. Plenum Press.
Guo, J. S. and Wu, C. H. (2012). RECENT DEVELOPMENTS ON WAVE PROPAGATION IN 2-SPECIES COMPETITION SYSTEMS. *Discrete and Continuous Dynamical Systems-Series B* 17: 2713-2724.
Habel, K., Grasman, R., Gramacy, R. B., Stahel, A.and Sterratt, D. C. (2015). geometry: Mesh Generation and Surface Tesselation.
Hillocks, R. J. (2012). Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Protection* 31: 85-93.
Jacquet, F., Butault, J.-P.and Guichard, L. (2011). An economic analysis of the possibility of reducing pesticides in French field crops. *Ecological Economics* 70: 1638-1648.
Kneip, A., Simar, L.and Wilson, P. W. (2008). Asymptotics and Consistent Bootstraps for Dea Estimators in Nonparametric Frontier Models. *Econometric Theory* 24: 1663-1697.

Knutson, R. D., Taylor, C. R., Penson, J. B.and Smith, E. G. (1990). Economic Impacts of Reduced Chemical Use. *Choices* 5: 25-31.
Lichtenberg, E. and Zilberman, D. (1986). The Econometrics of Damage Control: Why Specification Matters. *American Journal of Agricultural Economics* 68: 261-273.
Metcalf, R. L. (1980). Changing role of insecticides in crop protection. *Annual review of entomology* 25: 219-256.
Metcalf, R. L. (1996). Applied Entomology in the Twenty-First Century. *American Entomologist* 42: 216-227.
OECD *OECD Economic Surveys: France 2011*. OECD Publishing.
Olesen, O. B. and Petersen, N. C. (2015). Facet Analysis in Data Envelopment Analysis. In J. Zhu (ed), *Data Envelopment Analysis*. Springer US, 145-190.
Pimentel, D. (1976). World Food Crisis: Energy and Pests. *Bulletin of the Entomological Society of America* 22: 20-26.
Pimentel, D., Acquay, H., Biltonen, M., Rice, P., Silva, M., Nelson, J., Lipner, V., Giordano, S., Horowitz, A.and D'Amore, M. (1992). Environmental and Economic Costs of Pesticide Use. *BioScience* 42: 750-760.
Politis, D. N., Romano, J. P.and Wolf, M. (2001). On the asymptotic theory of subsampling. *Statistica Sinica* 11: 1105-1124.
Portela, M. C. A. S., Borges, P. C.and Thanassoulis, E. (2003). Finding Closest Targets in Non-Oriented DEA Models: The Case of Convex and Non-Convex Technologies. *Journal of Productivity Analysis* 19: 251-269.
Qaim, M. and Zilberman, D. (2003). Yield effects of genetically modified crops in developing countries. *Science* 299: 900-902.
Roush, R. T. and Tabashnik, B. E. (1990). *Pesticide Resistance in Arthropods*. Chapman and Hall.
Saba, A. and Messina, F. (2003). Attitudes towards organic foods and risk/benefit perception associated with pesticides. *Food Quality and Preference* 14: 637-645.
Simar, L., Vanhems, A.and Wilson, P. W. (2012). Statistical inference for DEA estimators of directional distances. *European Journal of Operational Research* 220: 853-864.
Simar, L. and Wilson, P. W. (1998). Sensitivity analysis of efficiency scores: How to bootstrap in nonparametric frontier models. *Management Science* 44: 49-61.
Simar, L. and Wilson, P. W. (1999a). Performance of the bootstrap for DEA estimators and iterating the principle. *Handbook on data envelopment analysis*. Springer, 241-271.
Simar, L. and Wilson, P. W. (1999b). Some problems with the Ferrier/Hirschberg bootstrap idea. *Journal of Productivity Analysis* 11: 67-80.
Simar, L. and Wilson, P. W. (2011). Inference by the m out of n bootstrap in nonparametric frontier models. *Journal of Productivity Analysis* 36: 33-53.
Skevas, T., Lansink, A.and Stefanou, S. E. (2013a). Designing the emerging EU pesticide policy: A literature review. *Njas-Wageningen Journal of Life Sciences* 64-65: 95-103.
Skevas, T., Stefanou, S. E.and Lansink, A. O. (2013b). Do Farmers Internalise Environmental Spillovers of Pesticides in Production? *Journal of Agricultural Economics* 64: 624-640.
Weinberger, H. F. (2002). On spreading speeds and traveling waves for growth and migration models in a periodic habitat. *Journal of Mathematical Biology* 45: 511-548.
Widawsky, D., Rozelle, S., Jin, S.and Huang, J. (1998). Pesticide productivity, host-plant resistance and productivity in China. *Agricultural Economics* 19: 203-217.
Williams, P. R. D. and Hammitt, J. K. (2001). Perceived Risks of Conventional and Organic Produce: Pesticides, Pathogens, and Natural Toxins. *Risk Analysis* 21: 319-330.
Wilson, C. and Tisdell, C. (2001). Why farmers continue to use pesticides despite environmental, health and sustainability costs. *Ecological Economics* 39: 449-462.