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Marion Desquilbet, Bruno Dorin, Denis Couvet

Toulouse School of Economics

Land sharing *vs* land sparing for biodiversity: How agricultural markets make the difference

Marion Desquilbet,[a*] Bruno Dorin,[b,c] & Denis Couvet[d]

[a] Toulouse School of Economics (GREMAQ, INRA), 21 allée de Brienne, 31015 Toulouse Cedex 6, France.
[b] CIRAD, UMR CIRED, 73 rue J.F. Breton, 34398 Montpellier, France.
[c] CSH, UMIFRE MAE-CNRS, 2 Aurangzeb Road, New Delhi 110011, India.
[d] UMR CESCO MNHN-CNRS-UPMC, 55 rue Buffon, 75005 Paris, France.
*Corresponding author: marion.desquilbet@toulouse.inra.fr.
Phone (+33) 5 61 12 85 78. Fax (+33) 5 61 22 55 63.

Abstract

We analyze how intensive *versus* extensive farming systems affect land use, biodiversity, and welfare when these production systems are compared at market equilibrium rather than for a target production level. As long as demand reacts to prices and extensive farming has higher production costs, extensive farming tends to be more beneficial to biodiversity than intensive farming, except when there is a very high degree of convexity between biodiversity and yield. This beneficial effect holds in a large set of situations even if, in conformity with short-term estimates in the empirical literature, the price elasticity of demand for agricultural products is very low. Extensive farming's potential benefits for biodiversity must be weighed against higher prices and smaller quantities for consumers, while its effect on agricultural producers is indeterminate. Extensive farming could additionally decrease the agricultural pressure on protected areas by reducing farmers' incentives to infringe on them. A shift from intensive to extensive farming primarily reduces the agricultural outlet for animal feed, for which price elasticity is higher, while leaving the biofuel outlet almost unchanged due to mandatory blending policies. It has no straightforward effect on food security, as it increases food prices but provides better revenues for poor farmers and better ecosystem services for agriculture and for society.

Keywords: conservation, farming, biodiversity, land use, markets, welfare

Land sharing *vs.* land sparing for biodiversity:
How agricultural markets make the difference

1 Introduction

There is now abundant evidence of biodiversity loss (Butchart, 2010; Barnosky et al., 2011). Agriculture is a major cause of such loss, both through its spatial extension (Newbold et al., 2015) and through its intensification (Donald et al., 2001), and this trend is expected to continue, given that demand for agricultural food, feed, fiber, and energy products should increase strongly in the coming decades (Alexandratos and Bruinsma, 2012; Fritz et al., 2013). Given the unequivocal evidence that biodiversity loss can affect ecosystem functioning, productivity, and resilience, as well as biogeochemical cycles (Cardinale et al., 2012, Isbell et al. 2015), alleviating the impact of agriculture on biodiversity is a major concern for human societies.

An important part of the scientific and political debate on biodiversity and agriculture in the last decade has revolved around discussions, analyses, applications, and extensions of the land sparing *vs* land sharing framework proposed by Green et al. (2005). This framework is aimed at understanding the extent to which agriculture should be concentrated on intensively farmed land in order to conserve more biodiversity-rich natural spaces elsewhere (*land sparing*), or, conversely, be more wildlife-friendly but less productive, hence conserving fewer wild natural spaces (*land sharing*). To this end, Green et al. (2005) built a theoretical model that compares the overall biodiversity level obtained from a high-yield *vs* a low-yield farming system when a given production target has to be met. They assume that land quality is homogenous, biodiversity can be captured by a single indicator, and biodiversity per unit of land is a decreasing function of the agricultural yield. If biodiversity is a linear function of yield, they show that the two archetypes of farming systems lead to the same biodiversity level. In the case of a shift from intensive to extensive farming for instance, as much biodiversity is lost on newly cultivated land as is gained on previously cultivated land. When the relationship between biodiversity and yield is convex, however, biodiversity decreases by a high amount on any natural land that is converted to agriculture. Then, shifting from intensive to extensive farming leads in this case to an overall loss of biodiversity. The result is the opposite if the relationship between biodiversity and yield is concave. According to Green et al., the available empirical data from a range of taxa in developing countries support a convex relationship, hence a land sparing strategy. Phalan et al. (2011a) reach a similar conclusion after comparing the densities of trees and birds for different agricultural intensities in Ghana and India.

Green et al.'s (2005) conceptual framework, the implicit assumptions underlying their model, and the generality of their results have been subject to intense discussion and debate among scientists, notably ecologists (see Fischer et al., 2014, for a review). A first dimension of these discussions, and the topic of interest in this article, pertains to the fixed production target used for comparing the two archetypes of farming systems. This setup rests on the authors' premise, exposed in the introduction of their article, that overall food demand is expected to increase two- to threefold by 2050. Their question is then how this demand can be met at the least cost to biodiversity. This setup has been debated on two main grounds. First, the aggregate level of food production is not a direct indicator of food security. Currently food insecurity and food malnutrition (including overnutrition) are rather a problem of regular access to quality and balanced food than a problem of world food production; in addition, current global consumption of plants and plant products raises questions, with one third wasted and one third fed to livestock, while an increasing area of agricultural land is devoted to bioenergy production (Fischer et al., 2011; Paillard et al., 2014; Tscharntke et al., 2012). Second, the intensification of agriculture could give incentives for its expansion, which would then limit effective land sparing for conservation (Matson and Vitousek, 2006; Vandermeer and Perfecto, 2007; Perfecto and Vandermeer, 2010). Such a rebound effect, or Jevons paradox, may indeed occur if intensified agriculture allows productivity gains and is therefore more profitable, thereby leading to a lower price and a higher production and consumption level (Lambin and Meyfroidt, 2011). When faced with such pressure, the effectiveness of land sparing is contingent on the implementation of protected areas, as emphasized by Green et al. (2005), Ewers et al. (2009), Phalan et al. (2011b), and Balmford et al. (2012). However, as pointed out by Fischer et al. (2011), many countries lack the means to protect areas effectively.

A second dimension of the debate on land sparing and sharing (LSS) pertains to the of Green et al.'s (2005) modeling assumptions on the biodiversity-yield relationship. Four types of question or criticism have been raised. First, in their model, the agricultural yield is independent from the biodiversity level, while biodiversity may affect positively agricultural yields by providing better and more resilient local climate conditions, as well as higher services such as pollination, biological control, and soil fertility (see, *e.g.*; Garibaldi et al., 2011). Second, their model assumes a single negative relationship between biodiversity and yield. This assumption is adequate in the case of industrial agriculture specialized in few cultivated plants or domesticated animals boosted with external inputs. But, as documented, for example, by Clough et al. (2011), a positive relationship between biodiversity and yield characterizes the intensification path that bets mainly on biological synergies between many plant and animal species, such as agroecology (Altieri, 1999) and ecological intensification (Bommarco et al.; 2013; Griffon, 2013). To encompass both intensification paths, it would then be necessary to model different biodiversity-yield relationships between conventional intensive agriculture and ecologically intensive agriculture, as represented in Tscharntke et al. (2012: Figure 1 p. 54). Third, their model ignores the fact that the industrial intensification of agricultural production over the past half century has had negative effects not only on biodiversity, but also on numerous health and environmental goods and services useful for society, such as disease and flood control, nutrient recycling, and water purification (Foley et al., 2005). Therefore this model does not integrate the health and environmental costs of industrial agriculture. Fourth, Green et al. (2005) model a unique indicator of biodiversity, and Phalan et al. (2011a) consider two indicators, the abundance of trees and birds, whereas a higher diversity of indicators should be considered (Fischer et al., 2014; Tscharntke et al., 2012). Thus, other plant and animal species –both above and below the ground– also play a key role in the provision of ecosystem services (species biodiversity), as well as the diversity of genes within each species ("genetic" biodiversity).

While the literature provides an extensive discussion of these issues, most of it has taken place without a formal examination of the considered elements. We believe that providing such an analytical framework is useful to show the effects at stake with additional clarity. In this article, we propose an ecological and economical analytical model addressing the first dimension of the discussion mentioned above. With this model, we discuss the limitations of comparing LSS strategies for a given production target. To keep the model as simple and tractable as possible, and to investigate the precise mechanisms at work on this issue, we keep the simple and debatable relationship between biodiversity and yield of the initial LSS framework (second dimension of the discussion) in our model. Additional realism and complexity may be added in a subsequent step.

In order to provide a formal model able to show and discuss the limits of comparing LSS strategies for a given production target, we introduce price as an adjustment mechanism between agricultural supply and demand. With this price adjustment, if extensive farming has a higher cost per unit of production (and *a fortiori* per unit of land), then extensive farming can reach the production level of intensive farming only if farmers receive a higher price, which drives the demand downwards until a new market equilibrium is reached. All in all, we compare the level of biodiversity obtained with each farming system when prices as well as production and consumption levels are the endogenous outcomes of market equilibrium. The effect on global welfare then depends on the relative weights attached to producer and consumer surpluses on the one hand and to biodiversity conservation on the other.

This article is related to other works that introduce an economic dimension into the LSS framework. Hart et al. (2014) investigate the less costly solution to reach a minimum target of wild nature theoretically and with numerical simulations on bird reproduction from mown grasslands in Sweden. Their model examines the first-best allocation of farm practices that minimizes the costs of reaching a minimum wildlife target and does not include prices or market incentives. They show that when wildlife production entails a fixed cost on each unit of land, the optimum is likely split solutions in which some farms pursue high intensity production whereas others make greater compromises in productivity for the sake of nature. If so, policies encouraging the development of specialist environmental providers may perform better than the current environmental schemes of the European Common Agricultural Policy, which are uniformly accessible to all farmers complying with their conditions. With an economic simulation model of market supply and demand, Hertel et al. (2014) examine to what extent the past green revolution in Asia, Latin America, and the Middle East has been and a prospective African green revolution is likely to be land and emission sparing compared with a counterfactual world without these innovations. Our framework, which is simpler and of a smaller empirical ambition, relates to their analysis of market adjustment caused by an agricultural productivity change and intends to relate market effects explicitly to the original focus of the LSS framework, that is, biodiversity change. Martinet (2014) shows, with a three-class land-use model (biological reserve, wildlife friendly agriculture, and intensive agriculture), that LSS strategies are not necessarily mutually exclusive when agricultural productivity is heterogeneous across land. Indeed, it may be both in the interest of farmers and collectively optimal for land with high productivity to be farmed intensively, land with intermediate productivity to be farmed extensively, and land with low productivity to be devoted to natural reserves. The optimal land allocation may be reached by a policy mix of an input tax and a subsidy for natural reserves. This model introduces producers' incentives but not price or welfare effects. The market and welfare framework developed by Meunier (2014), which is closer to ours, explores a different range of questions. The model characterizes the optimal intensification level for a given marginal value of biodiversity and second-best policies that may be implemented when it is not possible to act directly on both the agricultural yield and the farmed area. With this model, policy recommendations that are *a priori* true in a first-best setting are not necessarily true in second-best ones.

Compared with the above economic works, our research investigates in detail how the LSS strategy is affected when intensive and extensive farming are compared at market equilibrium rather than at a given production target. With our model, we find that, even with a convex relationship between biodiversity and yield, extensive farming may increase biodiversity compared with intensive farming. The lower profitability of extensive farming leads to a higher market price and therefore to a lower demand and a lower production output than with intensive farming. Consequently, agricultural land increases less than if the level of production were kept constant, and could even decrease in some situations. Shifting to extensive farming is therefore favorable to biodiversity in more cases than in the initial LSS framework. However, this shift to extensive farming has a detrimental effect on the sum of producer and consumer surplus, with consumer surplus necessarily decreasing, while producer surplus may either increase or decrease. We show these effects in a one-good partial equilibrium model and provide numerical simulations with plausible agricultural supply and demand elasticity values. The model is then extended in two directions. First, we analyze the implementation of protected areas and determine to what extent farmers have incentives to infringe on them, depending on their production system. Second, we analyze how a change in farming system could affect the respective food, feed, and biofuel outlets of agricultural production, and what this means in terms of food security.

2 Theoretical framework

We build our model starting with assumptions to those of Green et al. (2005). In particular, we consider two possible yield levels, a high yield (conventional intensive farming) and a low yield (extensive farming), and we analyze two scenarios where agricultural production is obtained exclusively either by high-yield or by low-yield farming. In order to introduce market mechanisms in a simple way, we define a partial equilibrium model of the agricultural sector with aggregate supply and demand functions on the world level without distinguishing between different countries. We assume that agricultural production costs vary across plots of land, which leads us to derive agricultural supply functions that are price increasing for both production technologies. Finally, we introduce a demand function characterizing how the aggregate consumption of the agricultural good decreases when its price increases, and we assume, for simplicity, that while intensive farming and extensive farming have different impacts on biodiversity conservation, the commodities produced by the two farming systems have the same quality and therefore are considered to be similar by consumers.

2.1 Relationship between biodiversity and yield

We assume that intensive farming has a yield $y_i = 1$, while extensive farming has a lower yield $y_e < 1$. Biodiversity conservation per unit of land is represented by a decreasing function of yield

(1) $f(y) = 1 - y^{\alpha}$,

which may be linear ($\alpha = 1$), convex ($\alpha < 1$), or concave ($\alpha > 1$) (see Figure 1).

This formulation normalizes biodiversity per unit of intensively farmed land to 0 ($f(1) = 0$) and to 1 ($f(0) = 1$) on uncultivated wildlife spaces.[1]

[Insert Figure 1]

[1] Assuming a positive level of biodiversity on intensively farmed land, as in Green et al. (2005), does not change the results of the model.

This assumption has the advantage of simplicity but entails three limitations already discussed in our introduction, as it assumes that *(i)* the biodiversity level cannot affect the agricultural yield, *(ii)* the trade-off between biodiversity and yield is independent of the intensification path, and *(iii)* biodiversity can be characterized by a single indicator. We also assume, as in Green et al. (2005), that any land cultivated with a given farming system has the same yield (y_i for intensive farming, y_e for extensive farming).

As such, this stylized representation can account for two contrasting agricultural systems: *(a)* an agro-industrial system based on large farms that are highly mechanized with powerful motorized machinery and specialized in a few monocultures (or a single animal species) with high use of chemical inputs (fertilizers, pesticides, antibiotics, etc.); and *(b)* a system of extensive farming based on small farms with mixed crop and livestock production that limits the use of chemical inputs by valuing biological interactions between species but requires more time and labor (for crop rotation and care, breeding, harvesting, etc.). This extensive farming offers more favorable conditions for local biodiversity, but attains lower yields than intensive farming, as is generally the case today with organic farming (Seufert et al., 2012), for instance.

2.2 Agricultural production, land use, and profits

We assume that production is carried out by a continuum of perfectly competitive farmers with different agricultural production costs and can be represented by a linear aggregated supply function. We define the inverse supply function as $s_k(q) = a_k\, q - b$ when farmers use farming system k.[2] We assume that the price elasticity of supply is less than 1, which is consistent with elasticities from empirical studies for the majority of agricultural products (Karagiannis and Furtan, 2002), and therefore that parameters a_k ($k = i$ or e) and b are positive.[3] The inverse supply function is defined on an interval where the marginal costs of production are positive and production is consistent with physical limits on land availability. As a classical consequence of the linear approximation, given $b > 0$, our model assumes that any quantity between 0 and b/a_k is produced at no cost, while quantities above b/a_k are produced at a positive and increasing marginal cost (see Figure 2a, where the inverse supply curve S_k intersects the p-axis at b/a_k and therefore represents the marginal cost of production for $q \geq b/a_k$). Assuming a total area of land L with land of type k, total production cannot exceed $L\, y_k$; the quantity supplied thus remains equal to $L\, y_k$ for any price above $a_k\, y_k$ - b. We therefore have:

(1) $\forall\ q \in [b/a_k, L\, y_k],\ s_k(q) = a_k\, q - b.$

[Insert Figure 2]

For each farming system, land use is equal to production divided by yield, as long as some land remains available:

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[2] This function defines that the marginal cost of producing the quantity q of the agricultural good with technology k is equal to $s_k(q)$. In the context of our model, the marginal farmer who enters production – the scenario characterized by the highest cost of production – has a cost equal to $s_k(q)$. The production level q is obtained when the market price p is equal to $s_k(q)$, so that all producers get a positive profit from their production, except the marginal farmer, who produces with a zero profit.

[3] The price elasticity of supply, that is, the percentage change in production resulting from a 1% price increase, is $\varepsilon_{sk} = (p/q)\ \partial q/\ \partial p = (p/q)/(\partial s_k(q)/\partial q) = (a_k\, q\text{-}b)/(a_k\, q)$. It is lower than 1 if and only if $b > 0$.

(2) $\forall\ q \in [b/a_k, L\ y_k]$, $l_k(q) = q/y_k$.

Agricultural producer surplus is given by the area between the price and the marginal cost of production, which is represented by the straight supply line in the (q, p) plane (see Figure 2a). It is given by the sum of the areas of rectangle ABED, equal to $(a_k\ q - b)\ b/a_k$, and of triangle BCE, equal to $(a_k\ q - b)(q - b/a_k)/2$. Its expression is therefore given by:[4]

(3) $\forall\ q \in [b/a_k, L\ y_k]$, $SU^p{}_k(q) = (a_k^2\ q^2 - b^2)/(2\ a_k)$.

Lastly but importantly, we assume that intensive farming has a higher profitability than extensive farming ($SU^p{}_i(q) > SU^p{}_e(q)$), which translates into the relationship:

(4) $a_e > a_i$.

This assumption is verified empirically in the case of organic farming when current organic premiums are not applied, mostly due to higher labor costs (Crowder and Reganold, 2015), and is based on the fact that for more than half a century, most agricultural research efforts and public policies were oriented towards intensive large-scale industrial farming due to the relatively low prices of fossil energy, chemical inputs, and machinery and ignorance of the negative environmental externalities of industrial agriculture (see, for example, Vanloqueren and Baret, 2008 and 2009).

With this assumption, shifting from intensive to extensive farming leads to an upward pivotal shift of the agricultural supply curve (as illustrated in Figure 3a), or, in other words, to an increase in the unit production cost of the agricultural good.

[Insert Figure 3]

2.3 Total quantity of biodiversity

If land l_k is allocated to a crop of type k, the total quantity of biodiversity is given by $l_k\ f(y_k) + (L - l_k)\ f(0)$. Given that $f(y) = 1 - y^{\alpha}$, it is written as:

(5) $B_k(l_k) = L - l_k\ y_k^{\alpha}$.

For intensive farming, $y_i = 1$, and therefore $B_i(l_i) = L - l_i$. For extensive farming, biodiversity depends on the shape of the relationship between biodiversity and yield, as shown in Table 1, where all possible cases, including the limit case $\underline{B}_e(l_e)$ where land farmed extensively produces no biodiversity ($\alpha = 0$), the linear case $B_e^l(l_e)$, and the limit case $\overline{B}_e$ where farming land extensively does not decrease its biodiversity ($\alpha \to +\infty$), are described.

[4] The interval on which this surplus is defined follows from the physical limits on land availability defined above.

Table 1. Biodiversity depending on the farming system

Farming system	Biodiversity-Yield relationship: $f(y) = 1 - y^{\alpha}$		Biodiversity $B_k(l_k)$
Intensive ($y_i = 1$)	$f(y) = 0$		$B_i(l_i) = L - l_i$
Extensive ($y_e < 1$)	Linear	$\alpha = 1$	$B_e^l(l_e) = L - l_e\, y_e$
	Convex	$\alpha = 0$	$\underline{B}_e(l_e) = L - l_e$
		$\alpha \in (0, 1)$	between $\underline{B}_e(l_e)$ and $B_e^l(l_e)$
	Concave	$\alpha \to +\infty$	$\overline{B}_e = L$
		$\alpha \in (1, +\infty)$	between $B_e^l(l_e)$ and $\overline{B}_e$

2.4 Consumers, equilibrium, and welfare

We assume that the products of high-yield and low-yield farming are not differentiated for consumers and the purchasing behavior of consumers does not integrate biodiversity, which is a public good. Inverse demand is modeled classicly as a linear decreasing function of quantity, with

(6) $d(q) = c - g\,q$.

Consumer surplus is given in Figure 2b by the triangle FGH, which measures the area between the straight demand line (which represents consumers' willingness to pay), and the equilibrium price. It is given by:

(7) $Su^c(q) = g\,q^2/2$.

We study the equilibrium depending on the farming system, intensive or extensive. Equilibrium is characterized by:

(8) $s_k(q) = d(q)$.

Total welfare is the sum of producer surplus, consumer surplus, and the social utility of the conservation of biodiversity, denoted by an increasing function U:

(9) $W_k(q)= SU^p{}_k(q) + Su^c(q) + U(B_k(l_k(q)))$.

Throughout the rest of this article, we use the term "total surplus" for the sum of producer and consumer surplus (this total surplus is thus different from total welfare, as it does not include biodiversity).

Note that in this welfare function, the utility derived from biodiversity is independent of the producer surplus. As discussed above, this restriction follows from the limitation that enhanced biodiversity cannot improve yield in our model. Also, it should be noted that this welfare function integrates the negative externality of agriculture on biodiversity only. This limitation, which we share with the initial LSS framework, results in an understatement of the global negative externality of intensive farming (as discussed in the LSS debates and presented in our introduction). This understatement may be particularly important in the case where the relationship between biodiversity and yield is convex. Indeed, in this case, biodiversity loss per unit of farmed land is not much higher with intensive farming than with extensive farming in our model, although in actual fact, on each unit of farmed land, intensive farming may have an important detrimental impact on other negative externalities such as farmers' health, or water quality. As we chose to avoid integrating these negative externalities in our framework, this understatement of the global negative externalities of intensive farming, especially in the case of a convex biodiversity-yield relationship, should be kept in mind when gauging the significance of our results.

3 The rebound effect of agricultural intensification

3.1 Graphic analysis of two contrasted cases

Among possible equilibria, Figure 3 illustrates the case of a perfectly inelastic demand (the quantity demanded does not react to prices), with c and $g \to +\infty$ and $c/g = 2/3$; whereas Figure 4 illustrates the case of a perfectly elastic demand (there exists a price level for which the quantity demanded is infinite), with $c = 2/3$ and $g = 0$.[5] Figures 3a and 4a, which are drawn for parameter values $a_i = 1.5$, $a_e = 2$, $y_e = 0.7$ and with total available land L normalized to 1, represent market equilibria for each agricultural system. They depict the quantity q supplied and demanded at any given price p, and the equilibrium prices p_k^* and quantities q_k^* at the intersection of supply and demand curves, for intensive and for extensive farming, respectively. Figures 3b and 4b represent how much land l is used to produce a quantity q. They allow determining the equilibrium land use l_k^* given the equilibrium quantity q_k^*. Figures 3c and 4c represent the amount of biodiversity conservation depending on agricultural land use. If land is farmed intensively, the equilibrium amount of biodiversity conservation B_i^* is determined by the line B_i given the equilibrium land use l_i^*. If land is farmed extensively, the figure represents the three particular cases of the biodiversity-yield relationship detailed in Table 1 where, given the equilibrium land use l_e^*, the equilibrium biodiversity conservation is $\underline{B}_e^*$ (in the limit case $\underline{B}_e(l_e)$ where no biodiversity is conserved on land farmed extensively), B_e^{l*} (in the linear case $B_e^l(l_e)$) or $\overline{B}_e$ (in the limit case $\overline{B}_e$ where all biodiversity is conserved on land farmed extensively).

With perfectly inelastic demand, market equilibrium occurs at price p_i^* if only intensive farming is used, and at a higher price p_e^* if only extensive farming is used (Figure 3a). To attain the production level $q_i^* = q_e^*$, more land has to be farmed extensively (l_e^*) than intensively (l_i^*) (figure 3b). Given these equilibrium land use levels, if the relationship between biodiversity and yield is linear, extensive farming produces the same level of biodiversity as intensive farming ($B_e^{l*} = B_i^*$) (Figure 3c). It produces less biodiversity if this relationship is convex (between $\underline{B}_e^*$ and B_e^{l*}, depending on the degree of convexity), and more biodiversity if this relationship is concave (between B_e^{l*} and $\overline{B}_e$, depending on the degree of concavity). These results are identical to those of Green et al. (2005), as our framework is similar to theirs in the case where equilibrium consumption is the same for both agricultural systems, regardless of their respective profitabilities.

[Insert Figure 3]

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[5] In these graphics, the straight lines S_k and D are the inverse supply (of slope a_k) and the inverse demand (of slope g) that represent prices as functions of quantities; the straight lines L_i and L_e represent land use as a function of quantities produced (production divided by yield); the straight lines B_i and B_e^l, and the straight line $\underline{B}_e$ coinciding with B_i, represent the inverse of functions $B_i(l_i)$, $B_e^l(l_e)$ and $\underline{B}_e(l_e)$.

If demand is perfectly elastic, shifting to extensive farming leaves the price unchanged, decreases the equilibrium production (Figure 4a), and increases land use (Figure 4b). The straight line $\tilde{B}$ represents a convex relationship between biodiversity and yield such that $B_e(l_e^*) = B_i(l_i^*)$, which occurs for $\tilde{\alpha} = 0.19$: in equilibrium, both farming systems yield the same level of biodiversity. Biodiversity decreases with the shift to extensive farming if the relationship between biodiversity and yield presents a "high" degree of convexity (between $\underline{B}_e^*$ and $\tilde{B}$); it increases if it presents a "low" degree of convexity, is linear, or is concave (between $\tilde{B}$ and $\overline{B}_e$).

[Insert Figure 4]

The result of Green et al. (2005) no longer holds if we assume that there is no identical production objective for the two farming systems, but that production results from the market equilibrium. As long as demand is elastic, equilibrium production is lower with extensive farming than with intensive farming; total biodiversity may therefore be higher with extensive farming even when the relationship between biodiversity and yield is convex.

We complete the analysis by considering welfare changes caused by a shift from intensive to extensive farming.

If demand is perfectly inelastic (Figure 3), shifting to extensive farming benefits producers (whose global surplus decreases by *EFAB* but increases by $p_e^* p_i^* EC$, with a positive balance), but is detrimental to consumers (whose surplus decreases by $p_e^* p_i^* BC$) and to total surplus (which decreases by *CFAB*).[6] If the relationship between biodiversity and yield is concave, welfare decreases less than total surplus, or even increases, thanks to the increase in biodiversity; if, on the contrary, this relationship is convex, welfare decreases more than total surplus because of the decrease in biodiversity.

In the case where demand is perfectly inelastic (Figure 4), shifting to extensive farming hurts producers (whose surplus decreases by *E'FAB'*), but does not affect consumers. The welfare loss is higher than the loss of producer surplus if the relationship between biodiversity and yield is characterized by a high degree of convexity (the biodiversity line is between $\underline{B}_e^*$ and $\tilde{B}$). In the opposite case (the biodiversity line is between $\tilde{B}$ and $\overline{B}_e$), the social utility of the higher biodiversity level associated with extensive farming alleviates or even cancels out the loss of producer surplus.

3.2 Comparative statics analysis

The previous graphic results are obtained for perfectly elastic or perfectly inelastic demand. We now extend them analytically to the case where demand is imperfectly elastic (that is, the slope of the inverse of the linear demand curve *c* is positive and finite). Given the definition of supply and demand in equations (1) and (5), the equilibrium equation (7) yields the equilibrium quantity q_k^*. The equilibrium price p_k^* is then defined equivalently by $s_k(q_k^*)$ or by $d(q_k^*)$. The equilibrium farmed land, producer surplus, consumer surplus, and biodiversity level are obtained from equations (2), (3), (7), and (5), respectively. Equilibrium values are given in Table 2. We infer Proposition 1 from these values.

[6] These changes in surplus correspond to the established result in the literature, whereby a productivity loss is detrimental to consumer surplus and total surplus, but may increase producer surplus if it is accompanied by a price increase because of an inelastic demand (Karagiannis and Furtan, 2002).

Table 2. Equilibrium values of the model's variables

Price	$p_k^* = (a_k c - b g)/(a_k + g)$
Agricultural production	$q_k^* = (b + c)/(a_k + g)$
Farmed land	$l_k^* = (b + c)/((a_k + g)y_k)$
Producer surplus	$SU^p{}_k^* = a_k(b + c)^2/(2(a_k + g)^2) - b^2/(2a_k)$
Consumer surplus	$SU^c{}_k^* = g\,(b + c)^2/(2(a_k + g)^2)$
Biodiversity	$B_k^* = 1 - (b + c)y_k^{\alpha - 1}/(a_k + g)$

Note: a_i and a_e are the slopes of the intensive and extensive inverse supply curves, with $a_e > a_i$; b is the opposite of the intercept of the linear supply curve; c and g are the intercept and the slope of the inverse demand curve; $y_i = 1$ is the yield of intensive farming; $y_e < 1$ is the yield of extensive farming; and α is the parameter characterizing the degree of concavity or convexity of the relationship between biodiversity and yield. All these parameters are positive. A necessary and sufficient condition for equilibrium is $a_k c > b g$: the equilibrium price is positive.

Proposition 1. *Effects of a shift from intensive to extensive farming.*

As long as land availability is not exhausted, under extensive farming:

- price increases, production decreases, consumer surplus decreases, the sum of consumer and producer surplus decreases;

- land use, biodiversity, and producer surplus may increase or decrease:

- *Land use increases if and only if* $g + a_i > (g + a_e)\, y_e$;
- *Biodiversity increases if and only if* $g + a_e > (g + a_i)\, y_e^{\alpha - 1}$ *(or equivalently,* $\alpha > \tilde{\alpha}$, *with* $\tilde{\alpha} = 1 - ln((a_e + g)/(a_i + g)) / ln(1/y_e)$*);*
- *Producer surplus increases if and only if* $(b+c)^2\, [a_i/(a_i+g)^2 - a_e/(a_e+g)^2] > b^2(a_e - a_i)/(a_e\, a_i)$.

From this proposition, shifting from intensive to extensive farming may result in a decrease in land use under certain parameter values, thereby resulting in a biodiversity increase whatever the shape of the relationship between biodiversity and yield.[7] The most expected scenario, however, is that land use increases when shifting to extensive farming, which, according to the above proposition, is the case under the following conditions: demand does not respond excessively to price (g is high enough), the yield of extensive farming (y_e) is small enough compared with the yield of intensive farming ($y_i = 1$), and/or the unit costs of production are not excessively higher with extensive farming than with intensive farming (a_e not much higher than a_i). When land use increases, biodiversity increases with the shift to extensive farming when the relationship between biodiversity and yield is linear or concave ($\alpha \geq 1$).[8] When this relationship is convex ($\alpha < 1$), biodiversity may either increase or decrease, depending on the relative values of parameter α, the yield of extensive farming (y_e),

[7] Given that $y_e \in (0, 1)$ and $\alpha > 0$, we have $y_e^\alpha < 1$. Land use decreases when $(g + a_e)\, y_e > g + a_i$, which implies $(g + a_e)\, y_e > (g + a_i)\, y_e^\alpha$, the condition under which biodiversity increases.

[8] Given that $a_e > a_i$ and $y_e < 1$, we have $ln((a_e + g)/(a_i + g)) / ln(1/y_e)) > 0$, therefore $\tilde{\alpha} < 1$.

the inverse demand slope (g), and the extensive and intensive inverse supply slopes (a_i and a_e). Biodiversity is more likely to increase as the quantities demanded respond to prices (low g), as extensive supply responds less to price than intensive supply (a_e sufficiently higher than a_i), and when the relationship between biodiversity and yield has a low degree of convexity (α close to 1).[9] Finally, it should be noted that, as is usually the case in this type of model, there is no intuitive interpretation of the cases where producer surplus increases or decreases.[10]

This proposition extends the graphic evidence provided above on the conditions under which the basic result of the initial LSS framework holds. In this initial model, given an exogenous production target, land sparing performs better than land sharing in terms of biodiversity conservation as long as the relationship between biodiversity and yield is convex, that is, as long as putting a plot of land into agricultural production causes a sharp decrease in its biodiversity. Proposition 1 shows that this result no longer holds when the two types of farming are compared in market equilibrium situations instead of for a given production target. As long as extensive farming is more costly than intensive farming and demand reacts to prices, a shift from intensive to extensive farming results in a price increase and drops in agricultural production and consumption. This market reaction reduces the negative impact of extensive farming on land use and therefore on biodiversity loss and extends the range of situations in which extensive farming performs better than intensive farming in terms of conserving biodiversity. It follows that when both farming systems are compared at market equilibria rather than for a given production target, a convex relationship between biodiversity and yield is not a sufficient condition for the superiority of intensive farming in terms of biodiversity conservation; this superiority holds only for a sufficiently high degree of convexity of this relationship and a sufficiently low price elasticity of demand (that is, a sufficiently low reaction of demand to prices). This shift to extensive farming, however, occurs to the detriment of consumer surplus, as consumers reduce their purchases due to higher prices, and to the detriment of the aggregate producer and consumer surplus, owing to the higher costs of production for the product of extensive farming.

The rebound effect of market intensification, that is, the increase in the equilibrium market size caused by the shift from extensive to intensive farming, hinges on the condition that demand for the agricultural good increases when its price decreases. However, available empirical evidence suggests that price elasticities of demand for agricultural goods are low, at least in the short run (see, *e.g.*, USDA ERS, 2015, and FAPRI, 2015). To assess to what extent the integration of market equilibrium empirically affects the result of the initial LSS framework in a context where the reaction of demand to prices is low, in the next section we run numerical simulations with plausible values of supply and demand elasticities. These simulations also allow us to provide better insights into the welfare effects of our model.

[9] In the case where the relation between biodiversity and yield is convex, given that $y_e \in (0, 1)$ et $\alpha \in [0, 1)$, we have $y_e^{\alpha-1} > 1$, with $y_e^{\alpha-1} \to 1$ when $\alpha \to 1$ and $y_e^{\alpha-1} = 1/ y_e$ when $\alpha = 0$.

[10] Analogously to Karagiannis and Furtan (2002), who consider an infinitesimal variation of the slope of the supply curve, it is only possible to interpret a necessary condition for an increase in producer surplus. This necessary condition is that the section between square brackets of the left-hand term in the inequality presented in Proposition 1 be positive, which is the case if and only if $a_i\, a_e > g^2$ (the product of the two slopes of inverse supply is higher than the square of the inverse demand slope).

3.3 Numerical simulations

In order to give some orders of magnitude in our highly stylized and aggregated world model, we rely on the estimates of agricultural supply and demand elasticities provided by Roberts and Schlenker (2013), who avoid the complexity of multiple food products by considering an aggregate caloric equivalent on the world level of corn, wheat, rice and soybeans, four commodities to which they attribute three quarters of caloric content of food production worldwide. With an original framework that identifies supply elasticities of storable commodities using past shocks as exogenous price shifters, they estimate short-run elasticities varying between 0.087 and 0.116 for supply and between −0.066 and −0.028 for demand, depending on econometric specifications (see their Table 1, p. 2279), while they estimate a slightly higher longer-run supply response, between 0.118 and 0.137 (see their Table 6, p. 2287). We ran our simulations with the lower and higher values mentioned above for demand and supply elasticities, assuming that the equilibrium with intensive farming is characterized by a supply elasticity $\varepsilon_{si} \in \{0.09, 0.14\}$ and a demand elasticity $\varepsilon_d \in \{-0.07, -0.03\}$. As in former graphical illustrations, we normalized the equilibrium with intensive farming to $p_i^* = 1/2$ and $q_i^* = 2/3$.[11]

In these simulations, we rule out situations where, from Proposition 1, the shift to extensive farming unequivocally leads to increase biodiversity, and we concentrate on situations in which biodiversity may *a priori* increase or decrease, that is, cases where the shift to extensive farming increases land use ($g + a_i > (g + a_e)\, y_e$) and where the relationship between biodiversity and yield is convex ($\alpha < 1$). We assume that the shift from intensive to extensive farming decreases yields by 10% ($y_e = 0.9$). Then, the assumption of a convex relationship between biodiversity and yield on extensively farmed land is equivalent to $0 \leq f(y_e) < 0.1$ (that is, biodiversity conservation on extensively farmed land is less than 10% of the biodiversity of unfarmed land).[12] Simulations were performed with ten equidistant values for $f(y_e)$, ranging from 0.01 (high degree of convexity) to 0.09 (low degree of convexity). The extensive inverse supply slope, a_e is by assumption (4) higher than a_i. In addition, from Proposition 1, the assumption that extensive farming increases land use is equivalent to $a_i < a_e^L$, where $a_e^L = (g + a_i)/y_e - g$. In the simulations, a_e is varied with ten equidistant values between $1.1a_i$ and $0.9\, a_e^L$.

Figure 5 shows the distribution of biodiversity gains and losses resulting from the shift to extensive farming. Biodiversity decreases on average by 1% in all simulations, but with a standard deviation of 6% (Figure 5a). Thus, these simulations show that even in the unfavorable case where the elasticity of demand at the initial intensive equilibrium is low, the shift to extensive farming increases land use, and the link between biodiversity and yield is convex, biodiversity increases with the shift to extensive farming for an important set of parameter values. This is all the more so when the degree of convexity of the biodiversity-yield relationship is low. Thus, in our simulations, if land, when farmed extensively (that is, with a yield equivalent to 90% of the intensive yield), conserves only 2% of the level of biodiversity that would prevail on uncultivated land ($f(y_e) = 0.02$), the shift from intensive to extensive farming leads to a 7% decrease in biodiversity on average (with a standard

[11] For each simulation, the slopes and intercepts of the inverse intensive supply and demand, b, c, a_i and g, are computed in order to obtain the equilibrium $p_i^* = 1/2$ and $q_i^* = 2/3$, given the supply elasticity $\varepsilon_{si} = p_i^*/(a_i\, q_i^*)$ and the demand elasticity, $\varepsilon_d = -\, p_i^*/(g\, q_i^*)$, and given the equilibrium relation $p_i^* = a_i\, q_i^* - b = c - g\, q_i^*$.

[12] We have $f(0.9) = 1 - 0.9^{\alpha}$. $\alpha \in [0, 1)$ is equivalent to $0 \leq 1 - 0.9^{\alpha} < 0.1$.

deviation of 3%). With four times more biodiversity per land unit, that is, 8% of the biodiversity level of uncultivated land ($f(y_e)$ = 0. 08), such a shift in farming practices increases biodiversity by 5% on average (with a standard deviation of 3%).

[Insert Figure 5]

We now turn to the analysis of the surplus effects obtained in these simulations (Figure 6). While the theoretical effect of a shift to extensive farming on producer surplus is indeterminate, this surplus increases in all our simulations, given that we calibrate our model with higher absolute values of supply elasticities than demand elasticities (see footnote 12); while the price increase caused by the shift to extensive farming necessarily deteriorates consumer surplus (see Proposition 1). Our simulations bring out a negative correlation between producer and consumer surplus (Figure 6d). The outcome on biodiversity is more scattered (Figures 6a-6c) because the level of biodiversity per unit of extensively farmed land, $f(y_e)$, which varies across our simulations, affects the global biodiversity level; whereas, since it has no effect on market equilibrium, it does not affect consumer and producer surplus levels. The simulations show a positive correlation between producer surplus and biodiversity and a negative correlation between consumer or total surplus, on the one hand, and biodiversity, on the other. These simulations therefore illustrate an additional dimension brought about by the introduction of market equilibrium into the framework of land sharing and land sparing, namely, a trade-off between biodiversity, on the one hand, and consumer surplus, as well as the aggregate producer and consumer surplus, on the other hand.

[Insert Figure 6]

Finally, it should be noted that the change in producer surplus is sensitive to the specification chosen for the supply curve shift caused by the change in the agricultural production method; a specification about which economic theory is not conclusive (as discussed by Alston et al., 1995, pp. 63-64). Instead of a pivotal supply shift (increase in the slope from a_i to a_e, for a given intercept $-b$), Appendix 1 presents simulation results under the alternative assumption of a parallel supply shift (increase in the intercept from $-b_i$ to $-b_e$, for a given slope a). Given that the elasticities of supply and demand are calibrated with very low values in our simulations, the effects of a parallel or a pivotal supply shift are qualitatively the same. The results, however, could be less robust to this specification change with higher calibrated elasticities.

4 The rebound effect with protected areas and food-feed-biofuel outlets

We now consider successively two extensions of our model in order to integrate two dimensions of the debates surrounding the assumption of an exogenous production target in the initial LSS framework. One pertains to the difficulty of implementing protected areas to restrict farmed land on the world level, and the other to the existence of several outlets of agriculture that do not all contribute equally to food security. These extensions enable us to clarify how the rebound effect of agricultural intensification affects the equilibrium in both cases.

4.1 Pressure of agriculture on protected areas

Our previous framework considers only the case where agricultural land use is determined by the equilibrium of the agricultural market and does not allow land sparing beyond this equilibrium use. This sparing option is less restrictive than in the initial LSS framework, where production is limited to a target level, possibly one lower than the market equilibrium level. In this extension, we introduce protected areas in our model in order to allow for such land sparing in the strict sense of the term.

The introduction of an aggregate protected area is analyzed graphically in Figure 7. To keep this graphic clear, we concentrate on the case of a linear relationship between biodiversity and yield and plot the equilibria with intensive and extensive farming separately. In the absence of a protected area, the intensive equilibrium, at A in Figure 7a, is characterized by price p_i^*, quantity q_i^* (Figure 7a), land use l_i^* (Figure 7b), and a biodiversity level B_i^* (figure 7c); while the extensive equilibrium, at E in Figure 7d, is characterized by p_e^*, q_e^* (Figure 7d), l_e^* (Figure 7e), and B_e^* (Figure 7f).

[Insert Figure 7]

We consider the implementation of a protected area aimed at conserving a minimum level of biodiversity B_c. We concentrate on the case where biodiversity protection imposes a binding constraint, that is, where a protected area has to be implemented, whatever the farming system, in order to conserve the target biodiversity level. The protection of biodiversity imposes a cap on land use L_{ic} when farming is intensive and a higher cap (that is, a higher possible land use in agriculture) L_{ec} when farming is extensive, as represented in Figures 7c and 7f by the thick vertical line (the dotted parts of the straight lines representing the trade-off between biodiversity and land use then no longer apply). As yield levels are exogenous, this cap on land use is equivalent to a maximum production quota q_c, which is identical for both production systems, given the assumption of a linear relationship between biodiversity and yield (see Figures 7b and 7e). Given this protected area, the equilibrium is at the intersection of the demand curve and the vertical thick line representing the production restriction, *i.e.*, at point C with intensive farming (Figure 7a) and at point F with extensive farming (Figure 7d). In both equilibria, the agricultural price (p_{ic} for intensive farming, p_{ec} for extensive farming) is higher than the marginal cost of production (mc_i for intensive farming, mc_e for extensive farming). Therefore, with both farming systems, some farmers would find it profitable to enter some of the land devoted to the protected area into production (those with a marginal cost of production ranging from mc_i to p_{ic} in the case of intensive farming, and those with a marginal cost of production ranging from mc_e to p_{ec} in the case of extensive farming). In this graphic illustration, farmers' incentive to encroach on protected areas is higher for intensive farming than for extensive farming ($p_{ic} - mc_i > p_{ec} - mc_e$ in Figures 7a and 7f).

This graphic analysis can be generalized by determining analytically the wedge between the price and the marginal cost of production resulting from the implementation of the protected area under each production system. From our equilibrium model, it is easily calculated that this wedge is given by:

(10) $p_{kc} - mc_{kc} = b + c - (a_k + g)\,(1 - B_c)\,y_k^{1-\alpha},\ k \in \{i, e\}$,[13]

[13] A binding target level of biodiversity B_c introduces a cap on land use l_{kc} with farming system $k \in \{i, e\}$. From equation (5), this cap is defined by $l_{kc} = (1 - B_c)\,y_k^{-\alpha}$; from equation (4), it results in a production cap

where p_{kc} and mc_{kc} are respectively the price and the marginal cost of production when the equilibrium is constrained by the implementation of a binding protected area B_c.

From this equation, the condition under which the price-cost wedge is higher with intensive than with extensive farming is $p_{ic} - mc_{ic} > p_{ec} - mc_{ec} \Leftrightarrow (a_e + g)\, y_e^{1-\alpha} > a_i + g$, which yields Proposition 2.

Proposition 2. *Farmers' incentive to infringe on protected areas.*

The implementation of binding protected areas aimed at conserving a given level of biodiversity introduces a wedge between the price and the marginal cost of production on the agricultural market in equilibrium, which creates an incentive for potential producers whose marginal cost of production is smaller than the equilibrium price to infringe on these protected areas. The price-cost wedge, and therefore the incentive for infringement, is higher with intensive than with extensive farming if and only if $(a_e + g)\, y_e^{1-\alpha} > a_i + g$.

The difference between equilibrium prices and marginal costs of production illustrates formally the argument raised in the LSS debate that it may not be possible to implement land sparing in practice. When the production cap introduced by protected areas for biodiversity conservation is binding, the encroachment of agriculture on these protected areas is profitable; therefore, public policies are needed to prevent farmers from impinging on these areas. Such policies could be *(i)* dissuasive coercive measures, with a high social and financial cost of monitoring and enforcement, or *(ii)* financial support to farmers in order to compensate them for revenue losses caused by protected areas. Not only are these policies costly to implement, but their ability to limit land use effectively on a large scale is an open empirical question (Phelps et al., 2013). This extension of our model also highlights that protected areas aimed at preserving a minimum biodiversity level may be even more difficult to implement if agricultural production systems are intensive rather than extensive, as farmers may then have a higher incentive of infringement. From Proposition 2, and given that $a_e > a_i$ (equation 4), this necessarily holds as long as the relationship between biodiversity and yield is linear and concave ($\alpha \geq 1$) and holds with a convex relationship ($\alpha < 1$) for a sufficiently low degree of convexity.

4.2 Food, feed and biofuel outlets

The debates and discussions around the assumption of an exogenous production target in the LSS initial framework have also pointed out the argument that currently food security is not a problem of world food production but of access to food for some people, and therefore, as expressed by Tscharntke et al. (2012), "*food security is largely independent of the land sharing vs sparing debate.*" Although our model is not really fit for addressing food security issues beyond food production, it may be helpful to get some insights on such issues by incorporating an extension with different possible outlets of the agricultural product. This

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$q_{kc} = (1 - B_c)\, y_k^{1-\alpha}$. The price equilibrium is at the intersection of the production cap and the inverse demand curve (6), $p_{kc} = c - g\, q_{kc}$, while the marginal cost of production is at the intersection of the production cap and the inverse supply curve (1), $mc_{kc} = a_k\, q_{kc} - b$. The price-cost wedge is therefore $p_{kc} - mc_{kc} = b + c - (a_k + g)\, q_{kc}$, which, given the expression of q_{kc}, yields equation (10).

multi-outlet model lets one analyze to what extent the choice of an intensive or extensive production system, via its effect on market equilibria, may actually favor specific uses, with possible consequences for food security.

We still consider a unique agricultural product, assumed to be a plant product. We distinguish three possible outlets for this product: food excluding animal products (simply named "food" thereafter), denoted by F; animal feed for the production of meat, milk products, and eggs (or simply "feed"), denoted by f; and biofuels, denoted by b. For simplification, we assume that these three demands are independent. They are modeled as:

(11) $d^k(q) = c_k - g_k\, q,\ k = F, f$ or b.

The total inverse demand function is then given by:

(12) $c = (\sum_k c_k / g_k) / (\sum_k 1 / g_k)$; $g = 1 / (\sum_k 1 / g_k),\ k = F, f$ or b. [14]

The former framework applies, with demand parameters c and g now defined by (12) as functions of the parameters of the three inverse demand functions.

The literature usually does not distinguish between price elasticities of food, feed, or biofuel uses of plants and plant products. The reason is that their estimation is very difficult, given that most cereals can be used to feed humans, animals, and ethanol plants, while most oilseeds can be used to produce edible oil or biodiesel conjointly with meals for animal feed. We assume that feed demand (that is, the demand for plant products used for animal feed) reacts more to prices than food demand (that is, the demand for plant products used for human food), since demand elasticities for animal food products such as milk or meat are higher than demand elasticities for cereal foodstuffs such as rice or bread (USDA ERS, 2015). On the contrary, biofuel demand reacts very little to prices, given current policies mandating that biofuels must be blended into fossil fuel (as in the United States, Europe, and Brazil) (HLPE, 2013). More precisely, with a mandatory rate of biofuel blending in fossil fuel, demanded quantities decrease only slightly with an increase in the agricultural price, due to the indirect effect that this price increase has in increasing fuel prices and therefore decreasing demand for fuel (De Gorter and Just, 2009). Therefore, it appears legitimate to consider that the inverse demand for biofuels has a higher slope than the inverse demand for food, which itself has a higher slope than the demand for feed:

(13) $g_b > g_F > g_f$.

As analyzed previously, a shift from intensive to extensive farming leads to an increase in the equilibrium price. Given Assumption (13), this price increase decreases the outlet mainly for feed, for which demand is more elastic, and, to a lesser extent, for food; while biofuel demand is quasi identical with both farming systems, as illustrated in Figure 8.

Insert Figure 8

This analysis allows us to discuss the argument developed by Angelsen (2010) that "*higher yield can reduce the food share, as food demand is typically more price inelastic than demand for nonfood commodities*." Our analysis shows that as long as our assumptions on price elasticities for the different agricultural outlets are plausible, his result holds in our context in terms of feed *versus* food consumption, but not in terms of biofuel *versus* food consumption. In our model, extensive farming may alleviate pressures on biodiversity by increasing the agricultural price mainly to the detriment of outlets for feed and, to a lesser

[14] For each product, the demand function is $D^k(p) = c_k / g_k - p/g_k$. Total demand is therefore $D(p) = (\sum_k c_k / g_k) - (\sum_k 1 / g_k)\, p$; from which we deduce the expression of total inverse demand in (11).

extent, for food; while it does not limit significantly biofuel outlets, which are ensured by public policies mandating their incorporation into fossil fuel.

It is of interest to emphasize that as a consequence of mandatory blending policies, the change in farming systems has a small effect on the biofuel outlet. The scientific debate on the environmental effects of biofuels remains largely centered on greenhouse gas emissions, which may decrease or increase depending notably on indirect changes in land use. However their effect on biodiversity, which is much less studied, is indubitably negative (see Krausmann et al., 2013), and, given current policies enhancing their use, a change in farming system cannot be expected to mitigate this negative impact significantly.

On the contrary, a change from intensive to extensive farming systems causes a significant decrease in the feed outlet. This could have a positive impact on biodiversity by reducing the higher pressure on land that the demand for animal food products (and thus for feed to produce them) exerts compared with the demand for plant foodstuffs for direct human consumption. Indeed, about three calories (or proteins) of plant commodities fit for human consumption (*e.g.*, cereals or oilseeds) are currently used to feed animals and produce one calorie (or protein) of edible animal products (meat, milk, and eggs) (Paillard et al., 2014)[15]. Moreover, this 3:1 ratio tends to increase over time as the higher the demand for animal food products, the more profitable it becomes to convert grazing pastures (or forests) into feed crops, often monocultures of cereals (*e.g.*, corn) and oilseeds (*e.g.*, soybeans), to produce more animal food products per unit of land than with pastures.

This decrease in the feed outlet would be detrimental in terms of consumer surplus, but not necessarily so much in terms of food security if we consider the two following points: *(i)* human beings can live on a vegetarian diet only and *(ii)* per capita consumption of animal food products is by far the highest in rich countries, as is the feed use of plant commodities (that is, plants and plant products that could be directly used for food) for producing animal food products.[16] A shift to extensive farming would therefore have a stronger impact on consumers in rich countries, by increasing the price of non-vegetarian foods, which they tend to overconsume to the detriment of their health (cardiovascular and other diseases). Public policies encouraging a shift to extensive farming could actually complement other policies aimed at influencing consumption patterns in order to decrease the overconsumption of non-vegetarian food (Paillard et al., 2014).

The price increase caused by a shift to extensive farming would be more directly detrimental to food security by reducing the vegetarian food outlet, since it could impact more specifically consumers in poor countries, especially poor urban consumers who rely on imports, as happened during the 2007-08 international food price hike. However, three factors may balance this effect. First, this increase in agricultural prices could benefit a population of consumers amongst the poorest in the world, that is, the hundreds of millions of small agricultural producers concentrated in Asia, Africa, and Latin America who now account for the main share of those active in agriculture around the world (Dorin et al., 2013). Second, the additional biodiversity resulting from a shift to extensive farming could have beneficial effects on the provision of ecosystem services associated with the health and welfare of consumers, notably the poorest ones (ten Brink, 2011), such as biological plant, animal, and

[15] This ratio is a world average excluding biomass not edible for humans but edible for animals, such as pastures, fodder crops, and crop residues.

[16] In poor countries, there is a significantly higher use of non-food biomass for feed (such as bush or crop/food residues), as arable land is mainly cultivated for food. Milk and meat yields are lower per animal, but these animals provide other key services (traction; soil fertilization, fuel or building material with animal faeces).

human disease control (instead of pesticides or antibiotics), water purification, and nutrient recycling. Third, although this effect lies outside the scope of our model, additional biodiversity resulting from a shift to extensive farming may have positive medium- and long-run effects on yields and their resilience, by improving soil fertility, local climate conditions, and/or pollination, which would then diminish the sensitivity of domestic productions to the shocks arising from environmental fluctuations, trade policies, and international market volatility that endanger global food security (Suweis et al., 2015).

5 Conclusions

The effect of farming intensification on biodiversity has been highly disputed in the academic literature, especially in ecology, since Green et al.'s (1995) LSS article promoting farm intensification as a possible means to increase biodiversity by sparing land. Here we propose an analytical framework that compares intensive and extensive agriculture not for a given production target, as in the initial LSS model, but at market equilibrium. We show that the integration of market effects extends the set of situations in which extensive farming is more favorable to biodiversity than intensive farming. As long as demand reacts to prices and extensive farming is more costly than intensive farming, the rebound effect of farming intensification results in an increase in equilibrium production, which limits the extent to which intensive farming is able to spare land from agricultural use. As a result, intensive farming may be more detrimental to biodiversity than extensive farming even when biodiversity is more affected by the conversion of land to agriculture than by the degree of agricultural intensification. In other words, unlike the case in the initial LSS framework, intensive farming does not necessarily perform better than extensive farming in terms of biodiversity conservation as long as the relationship between biodiversity and yield is convex; the outcome of farming on biodiversity is actually better with an intensive rather than extensive production system only if the degree of this convexity is sufficiently low. We also point out that shifting to extensive farming decreases consumer surplus as well as the sum of consumer and producer surplus, while its effect on producer surplus is indeterminate. Therefore, when extensive farming is best for biodiversity, a trade-off exists between biodiversity conservation and consumer and producer surplus.

We also discuss to what extent the implementation of protected areas may effectively avoid the rebound effect of intensive farming. In our model, protected areas act in the same way as a production quota, and therefore introduce a positive wedge between the agricultural consumer price and the marginal cost of production. As a result, farmers have an incentive to infringe on these protected areas. Because of the rebound effect of market intensification, this incentive for infringement is higher when farming is intensive rather than extensive for a large set of situations, in which case farming intensification makes the enforcement of protected areas even more difficult. Finally, we argue that the decrease in market production caused by a shift from intensive to extensive farming would affect feed outlets in the first place, and the food security loss created by the increase in food prices would be mitigated notably by improved living conditions for poor farmers, the provision of enhanced ecosystem services, and the positive long-run effect of biodiversity on yields (an effect that is not integrated in our modeling framework) and their resilience to shocks. We also point out that the size of biofuel outlets is not expected to be significantly affected by a change in production systems as long as public policies mandate biofuel blending in fossil fuels.

This research allows formal comparison of intensive and extensive production systems' outcomes on biodiversity at market equilibrium rather than for a target production level. However, our model does not address the other dimension of the debates and discussions around the initial LSS framework related to its oversimplifying assumptions about the relationship between biodiversity and yield. Our model overstates the set of situations in which intensive farming produces a better outcome than extensive farming by ignoring the negative externalities besides biodiversity loss that are brought about by intensive farming. This is especially the case when farming intensification has a lower negative impact on biodiversity than on these other externalities, which we expect to be especially the case in our model with a convex relationship between biodiversity and yield. In addition, our model ignores the positive and dynamic effects of yield gains allowed by enhanced biodiversity, especially with an agroecological intensification path. The analysis of such effects in a dynamic bio-economic framework will be the subject of future research.

Our analysis could also be extended to distinguish between different countries, depending on their level of development and place in the international trade of agricultural commodities. This would enable us to analyze in more detail the effects of a farming system change on different agricultural outlets and the three components of welfare (producer surplus, consumer surplus, and biodiversity) for each type of country. It would also be interesting to model agrofood chains, for instance by distinguishing between farmers and industrial input suppliers (chemical fertilizers, pesticides and fossil energy). While a shift to extensive farming has an indeterminate effect on the agricultural producer's surplus in our model, it would affect negatively suppliers of the industrial inputs used mainly in intensive farming. In this way, the market and welfare effects of our model could be studied in greater detail.

References

Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: the 2012 revision*. ESA Working Paper 12-03, FAO, Rome, 157 p.

Alston, J.M., Norton, G.W., & Pardey, P.G. (1995). *Science under scarcity: Principles and practice for agricultural research evaluation and priority setting*. Ithaca, NY: Cornell University Press.

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment*, 74, 19-31.

Angelsen, A. (2010). Policies for reduced deforestation and their impact on agricultural production. *Proceedings of the National Academy of Sciences*, 107(46), 19639-19644.

Balmford, A., Green, R., & Phalan, B. (2012). What conservationists need to know about farming. *Proceedings of the Royal Society B: Biological Sciences*, 279, 2714-2724.

Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O., Swartz, B., Quental, T. B., et al. (2011). Has the Earth's sixth mass extinction already arrived? *Nature*, 471(7336), 51-57.

Bommarco, R., Kleijn, D., & Potts, S.G. (2013). Ecological intensification: harnessing ecosystem services for food security. *Trends in Ecology and Evolution*, 28(4), 230-238.

Butchart, S.H.M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J.P.W., Almond, R.E., et al. (2010). Global biodiversity: indicators of recent declines. *Science*, 328(5982), 1164-1168.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., et al. (2012). Biodiversity loss and its impact on humanity. *Nature*, 486, 59-67.

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., et al. (2011). Combining high biodiversity with high yields in tropical agroforests. *Proceedings of the National Academy of Sciences*, 108, 8311–8316.

Crowder, D.W., & Reganold, J.P., 2015. Financial competitiveness of organic agriculture on a global scale. *Proceedings of the National Academy of Sciences*, 112, 7611-7616.

De Gorter, H., & Just, D.R. (2009). The economics of a blend mandate for biofuels. *American Journal of Agricultural Economics*, 91(3), 731-750.

Donald, P. F., Green, R. E., & Heath, M. F. (2001). Agricultural intensification and the collapse of Europe's farmland bird populations. *Proceedings of the Royal Society of London B: Biological Sciences*, 268(1462), 25-29.

Dorin, B., Hourcade, J.C., & Benoit-Cattin, M. (2013). *A world without farmers? The Lewis path revisited*. WP 47-2013, CIRED, France.

Ewers, R.M., Scharlemann, J.P.W., Balmford, A., & Green, R.E. (2009). Do increases in agricultural yields spare land for nature? *Global Change Biology*, 15, 1716-1726.

FAO (2009). *The state of food and agriculture: livestock in the balance*. Rome. 180 p.

Fischer, J., Batary, P., Bawa, K.S., Brussaard, L., Chappell, M.J., Clough, Y., et al. (2011). Conservation: limits of land sparing. *Science*, 334, 593.

Fischer, J., Abson, D.J., Van Butsic, Chappell, M.J., Ekroos, J., Hanspach, J., Kuemmerle, T., Smith, H.G., & von Wehrden, H. (2014). Land Sparing Versus Land Sharing: Moving Forward. *Conservation Letters*, 7, 149-157.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science*, 309, 570-574.

Food and Agricultural Policy Research Institute (FAPRI) (2015). FAPRI elasticity database, http://www.fapri.iastate.edu/tools/elasticity.aspx. Accessed online August 3, 2015.

Fritz, S., See, L., van der Velde, M., Nalepa, R. A., Perger, C., Schill, C., et al. (2013). Downgrading recent estimates of land available for biofuel production. *Environmental Science & Technology*, 47, 1688-1694.

Garibaldi, L.A., Aizen, M.A., Klein, A.M, Cunningham, S.A., & Harder, L.D. (2011). Global growth and stability of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy of Sciences*, 108, 5909-5914.

Green, R.E., Cornell, S.J., Scharlemann, J.P.W., & Balmford, A. (2005). Farming and the fate of wild nature. *Science*, 307, 550-555.

Griffon, M., 2013. *Qu'est-ce que l'agriculture écologiquement intensive ? Matière à débattre et décider*, Quae, Versailles, 221 p.

Hart, R., Brady, M., & Olsson, O. (2014). Joint production of food and wildlife: uniform measures or nature oases? *Environmental and Resource Economics*, 59, 187-205.

Hertel, T.W., Ramankutty, N., & Baldos, U.L. (2014). Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO_2 emissions. *Proceedings of the National Academy of Sciences*, 111, 13799-13804.

HLPE (2013). *Biofuels and food security.* A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Isbell, F., Tilman, D., Polasky, S., & Loreau, M. (2015). The biodiversity‐dependent ecosystem service debt. *Ecology Letters*, 18(2), 119-134.

Karagiannis, G., & Furtan, W.H. (2002). The effects of supply shifts on producers' surplus: the case of inelastic linear supply curves. *Agricultural Economics Review*, 2002, 3, 5-11.

Krausmann, F., Erb, K.H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., et al. (2013). Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences*, 110, 10324–10329.

Lambin, E.F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, 108, 3465–3472.

Martinet, V. (2014). The economics of the food versus biodiversity debate. Paper prepared for presentation at the EAAE 2014 Congress "Agri-Food and Rural Innovations for healthier societies", Ljubljana, Slovenia, August 26-29.

Matson, P.A., & Vitousek, P.M. (2006). Agricultural intensification: will land spared from farming be land spared for nature? *Conservation Biology*, 20, 709-710.

Meunier, G. (2014). Land-sparing vs land-sharing with incomplete policies. INRA ALISS Working Paper 2014-05.

Newbold, T., Hudson, L. N., Hill, S. L., Contu, S., Lysenko, I., Senior, R. A., et al. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, 520(7545), 45-50.

Paillard, S., Tréyer, S., & Dorin, B. (Eds.) (2014). *Agrimonde - Scenarios and Challenges for Feeding the World in 2050*, The Netherlands: Springer, 250 p. (first print: 2011).

Perfecto, I., & Vandermeer, J. (2010). The agroecological matrix as an alternative to the land-sparing/agriculture intensification model. *Proceedings of the National Academy of Science*, 107, 5786-5791.

Phalan, B., Onial, M., Balmford, A., & Green, R.E. (2011a). Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science*, 333, 1289-1291.

Phalan, B., Balmford, A., Green, R.E., & Scharlemann, J.P.W. (2011b). Minimizing the harm to biodiversity of producing more food globally. *Food Policy*, 36, S62-S71.

Phelps, J., Carrasco, L.R., Webb, E.L., Koh, L.P., & Pascual, U. (2013). Agricultural intensification escalates future conservation costs. *Proceedings of the National Academy of Science*, 110, 7601-7606.

Seufert, V., Ramankutty, N., & Foley, J.A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, 485, 229-232.

Suweis, S., Carr, J.A., Maritan, A., Rinaldo, A., & D'Odorico, P., 2015. Resilience and reactivity of global food security. *Proceedings of the National Academy of Sciences*, 112, 6902-6907.

ten Brink, P. (ed.) (2011). *TEEB: The economics of ecosystems and biodiversity in national and international policy making*. Earthscan, London.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., et al. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation*, 151, 53-59.

USDA ERS (United States Department of Agriculture, Economic Research Service), 2015. Commodity and food elasticities. http://www.ers.usda.gov/data-products/commodity-and-food-elasticities/about.aspx. Accessed online August 3, 2015.

Vandermeer, J., & Perfecto, I. (2007). The agricultural matrix and a future paradigm for conservation. *Conservation Biology*, 21, 224-227.

Vanloqueren, G., & Baret, P.V. (2008). Why are ecological, low-input, multi-resistant wheat cultivars slow to develop commercially? A Belgian agricultural 'lock-in' case study. *Ecological Economics*, 66, 436 – 446.

Vanloqueren, G., & Baret, P.V. (2009). How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. *Research Policy*, 38, 971–983.

Appendix 1. Comparative statics with a parallel supply shift

With a parallel supply shift, the inverse supply function is $s_k(q) = a\,q - b_k$ if farmers use production type k, with a and b_k positive ($k = i$ ou e) and $b_e < b_i$.[17] Producer surplus is $SU^p{}_k(q) = (a^2\,q^2 - b_k^2)/(2\,a)$.

Solving the model with these supply functions, we obtain the following equilibrium values: $p_k^* = (a\,c - b_k\,g)/(a + g)$, $q_k^*=(b_k + c)/(a + g)$, $l_k^*=(b_k + c)/((a + g)y_k)$, $SU^p{}_k^* = a(b_k + c)^2/(2(a + g)^2) - b_k^2/(2a)$, $SU^c{}_k^* = g\,(b_k + c)^2/(2(a + g)^2)$ and $B_k^* = 1 - (b_k + c)(1 - f(y_k))/((a + g)y_k)$. The results of Proposition 1 still hold, except for the conditions under which land use, biodiversity, and producer surplus increase or decrease. Here, land use increases if and only if $c + b_e > (c + b_i)\,y_e$; biodiversity increases if and only if $(c + b_i)\,y_e > (c + b_e)\,(1- f(y_e))$; and producers surplus increases if and only if $(2a+g)\,(b_e + b_i)\,g > 2a^2c$.

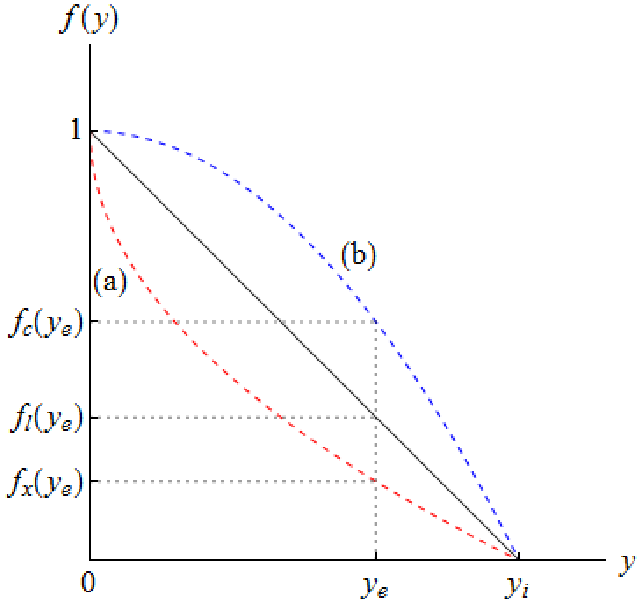
Simulations are performed with the same assumptions as those adopted with a pivotal supply shift for supply and demand elasticities and equilibrium price and quantity in the intensive equilibrium, yield with extensive farming, and degree of convexity of the relationship between biodiversity and yield. Land use increases with extensive farming as long as the intercept of the extensive inverse supply, b_e, is higher than the value $b_e^L = (c + b_i)\,y_e - c$. In the simulations, b_e is varied with ten equidistant values between $1.1\,b_e^L$ and $0.9\,b_i$.

[Insert Figure A1]

[Insert Figure A2]

[17] The intercept of the extensive inverse supply curve is $- b_e$. With the assumption that $b_e < b_i$, a shift from intensive to extensive farming shifts the supply curve upwards.

Figure 1. Relationship between biodiversity and yield



Note: Biodiversity is a decreasing function of yield, which may be linear (plain line, $f(y_e)$ = 1 – y), convex (dashed curve a, here in the case of $f(y)=1-y^{1/2}$), or concave (dashed curve b, here in the case of $f(y)=1-y^2$).

Figure 2. Producer and consumer surpluses

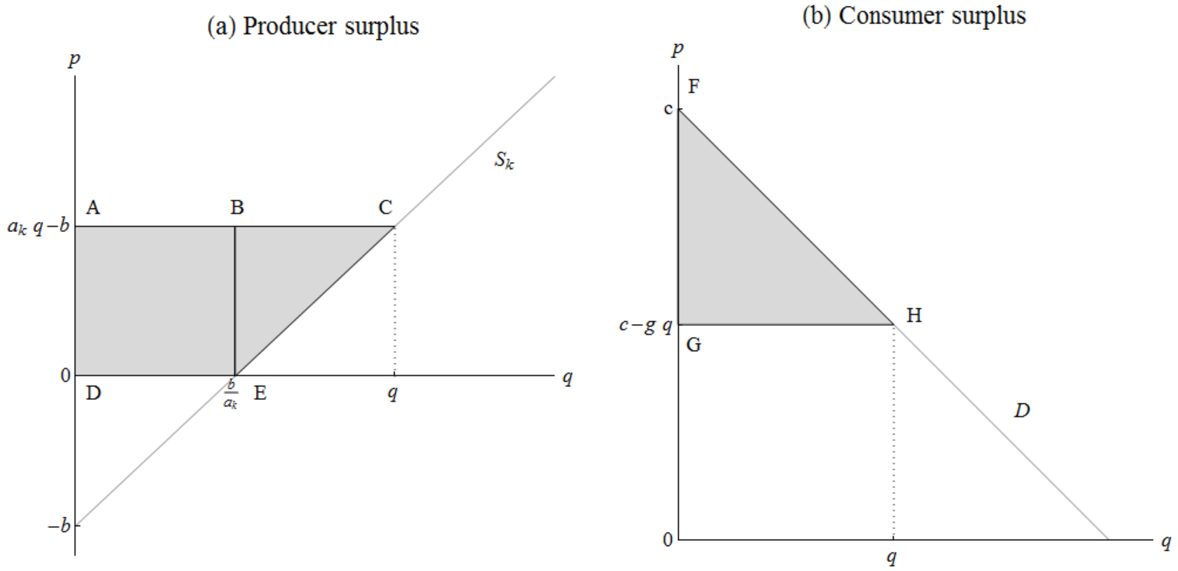


Figure 3. Equilibrium with perfectly inelastic demand

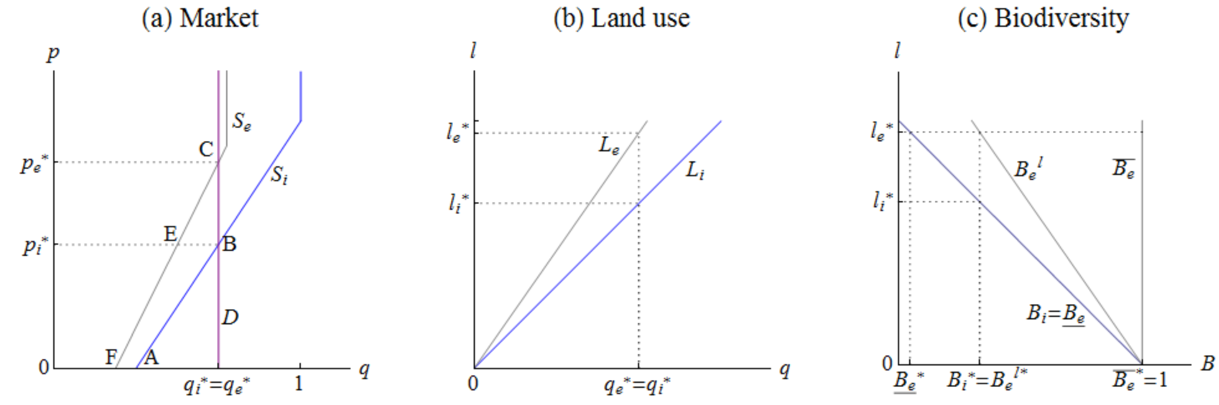


Figure 4. Equilibrium with perfectly elastic demand

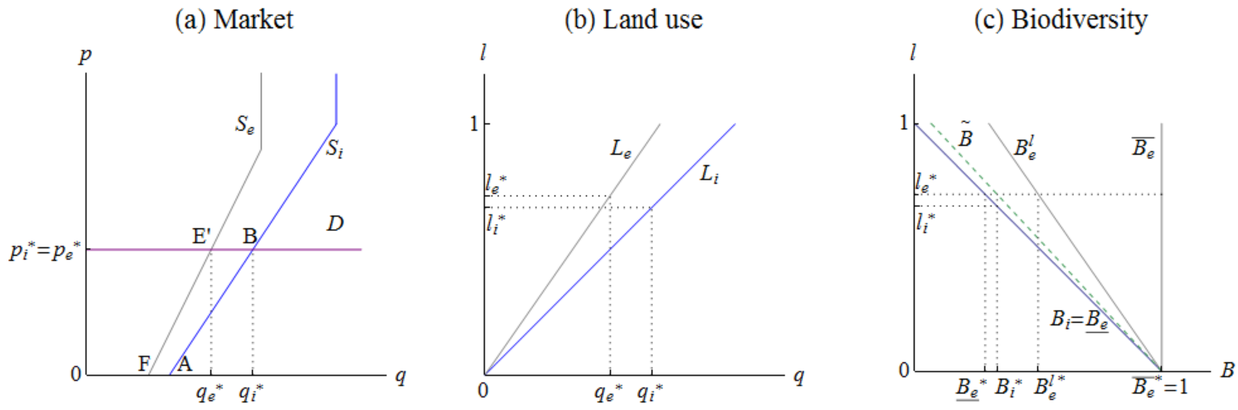
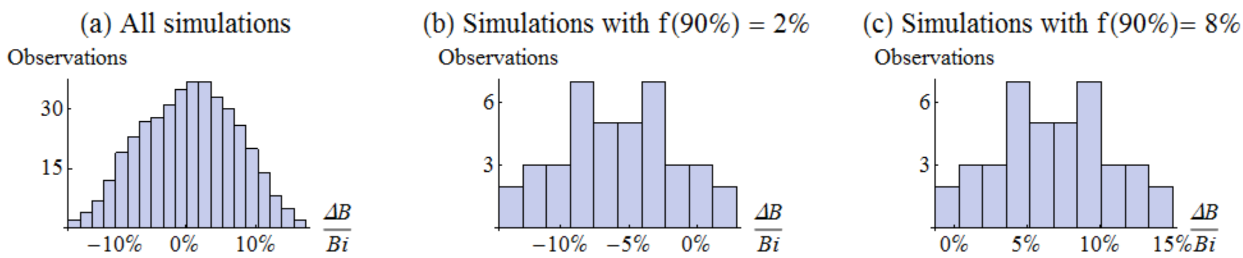
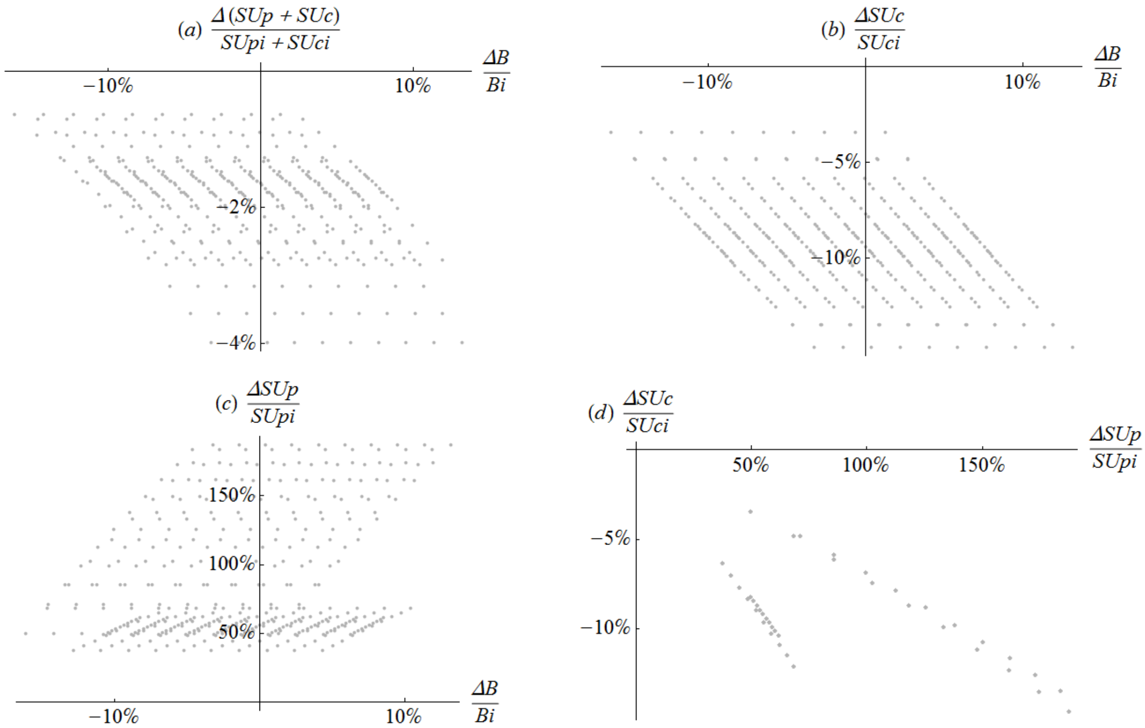


Figure 5. Effects on biodiversity of a shift from intensive to extensive farming



Note: $\Delta B/B_i = (B_e - B_i)$ is the percent variation of biodiversity resulting from a shift from intensive to extensive farming. Mean m and standard deviation s of the percent biodiversity change are: (a) in all simulations: $m = -1.1\%$, $s = 6.1\%$; (b) in simulations where $f(90\%) = 2\%$: $m = -7.4\%$, $s = 2.8\%$; and (c) in simulations where $f(90\%) = 8\%$: $m = 5.3\%$, $s = 2.7\%$.

Figure 6. Welfare effects of a shift from intensive to extensive farming



Note: $\Delta(Su_p + Su_c)/(Su_{pi} + Su_{ci})$, $\Delta B/B_i$, $\Delta Su_c/Su_{ci}$ and $\Delta Su_p/Su_{pi}$ represent respectively the percent variations of total surplus, biodiversity, consumer surplus, and producer surplus resulting from a shift from intensive to extensive farming.

Figure 7. Equilibrium with protected areas

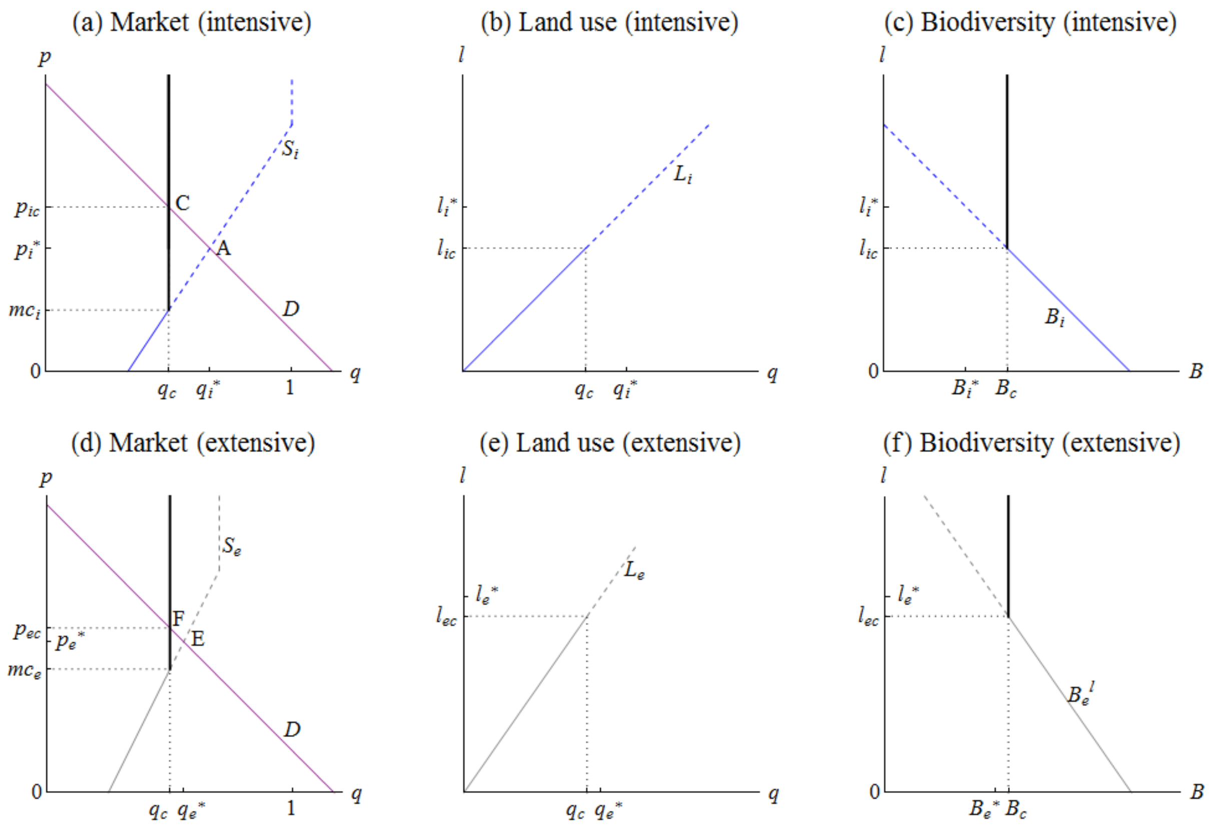


Figure 8. Food, feed, and biofuel outlets

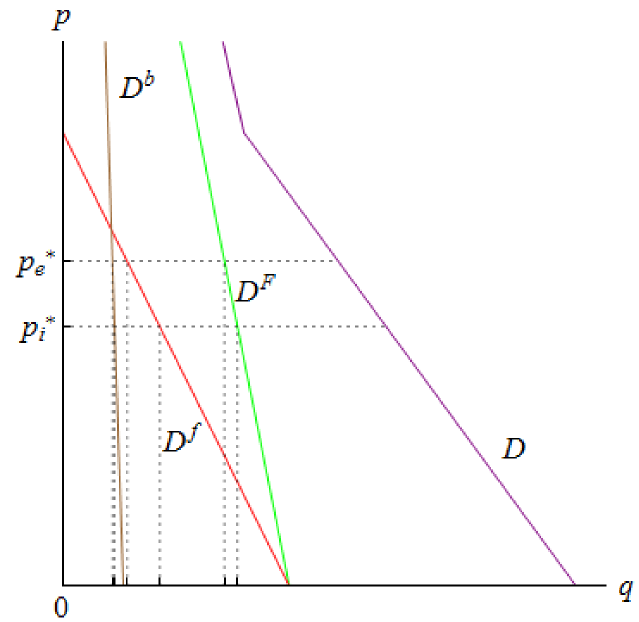
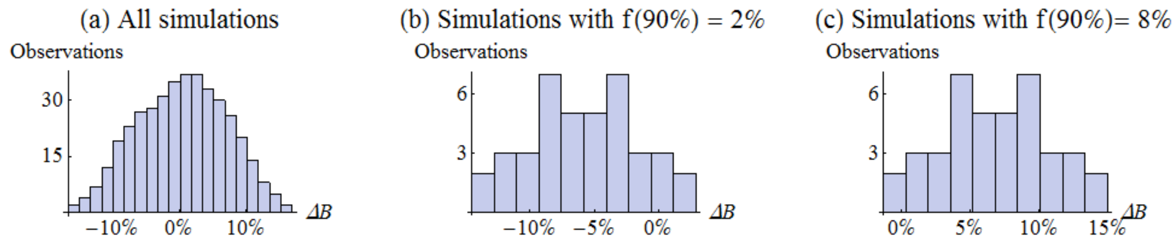
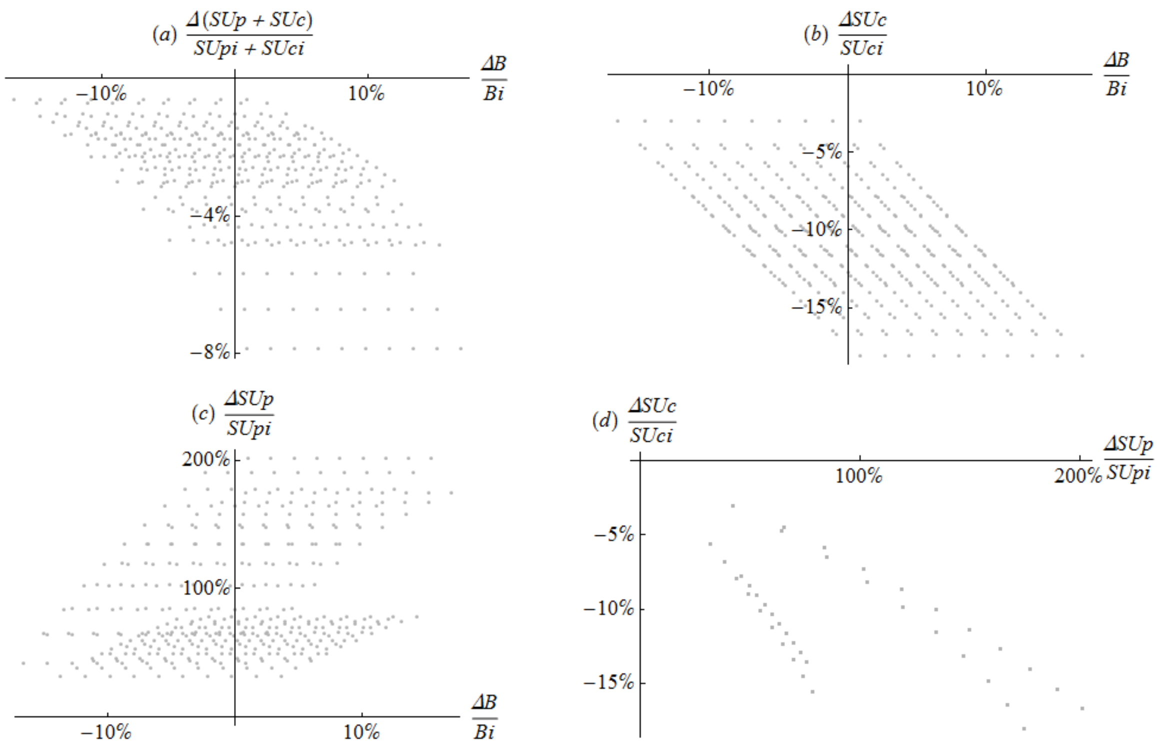


Figure A1. Effects on biodiversity of a shift from intensive to extensive farming with a parallel supply shift



Note: $\Delta B/B_i = (B_e - B_i)$ is the percent variation of biodiversity resulting from a shift from intensive to extensive farming. Mean m and standard deviation s of the percent biodiversity change are: (a) in all simulations: $m = 5.0\%$, $s = 6.7\%$; (b) in simulations where $f(90\%) = 2\%$: $m = -5.8\%$, $s = 4.2\%$; (c) in simulations where $f(90\%) = 8\%$: $m = 6.8\%$, $s = 3.9\%$.

Figure A2. Welfare effects of a shift from intensive to extensive farming with a parallel supply shift



Note: same as Figure 6.