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Short Communication

# Intensive versus low-input cropping systems: What is the optimal partitioning of agricultural area in order to reduce pesticide use while maintaining productivity?

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ABSTRACT

Pesticide use should be reduced for sustainable agriculture. Low-input cropping systems, centered on hardy varieties that maintain their yield in the presence of pests, allow pesticide use to be reduced. Since yield potential is generally lower for hardy varieties than for high-yielding varieties, a balance must be found between production and pesticide reduction. In order to compute the optimal partitioning of agricultural area between intensive and low-input cropping systems, we present a model that allows yield and gross margins to be computed at the landscape scale, as a function of the proportion of the area under intensive and low-input systems. The model shows that two cases must be distinguished, depending on inoculum production by each of the coexisting systems. If the low-input system produces less inoculum (e.g. because resistant varieties are used), coexistence can be optimal, whereas if the low-input system produces more inoculum (e.g. because tolerant varieties are used), it is best to devote the whole area to a single system. The model gives the gross margin for each cropping system as a function of the proportion of low-input systems – and so predicts the proportion to which the farmers' choices will lead – and illustrates the use of different (simplified) policies that would ensure that the optimum proportion is reached.



## 1. Introduction

Pesticides have been one of the major technological advances that allowed food production to increase spectacularly over the past half-century, along with breeding for high-yielding varieties, the use of fertilizers and irrigation. Thus world cereal productivity increased by almost 44 kg ha$^{-1}$ every year between 1961 and 2006, and doubled in the 40 years, between 1966 and 2006 (source: FAOstats, 2008). However this model of agricultural development has shown its limitations as its harmful effects have been recognized more fully (Aubertot et al., 2005). Pesticides pose a risk to human and environmental health, including toxicity to non-target organisms such as pollinators and wildlife, environmental contamination of soil, water, and air affecting ecosystem functions, selection of resistant pests, and acute and chronic toxicity to humans (Pimentel et al., 1992). Faced with the growing public concern about environmental and health hazards, governments of developed countries are starting to take action to reduce pesticide use: the French government has set as a goal to reduce pesticide use by 50% within the next 10 years (Paillotin, 2008), the European Union has proposed to "encourage the use of low-input or pesticide-free crop farming" as one of its priorities (Anonymous, 2006) while the US has decided to develop Integrated Pest Management (IPM) in order to reduce pesticide use (Epstein and Bassein, 2003).

One way of reducing pesticide use is the implementation of "low-input systems" (which include, but are not limited to, organic farming). These systems aim at reducing the consumption of all external inputs simultaneously (fertilizers, pesticides, growth regulators, etc.) while maintaining the farmer's income: despite the reduced yield, the gross margin is kept constant or increased thanks to the lower cost of fertilization, seeds, growth regulator and crop protection (Bouchard et al., 2008). The conversion from intensive (spend more in order to produce more) to low-input agriculture (produce less in order to spend less) necessitates redesigning the whole crop management system, from the choice of cultivar to the cultural practices. Low-input crop management systems, based on hardy varieties and low-input crop management, have been designed and tested with positive and significant results on pesticide use (Bouchard et al., 2008; Loyce et al., 2008).

Hardy varieties used in low-input systems are characterized by resistance to abiotic stresses (in particular low levels of nitrogen) and biotic stresses (pests). Two types of resistance to biotic stresses can be selected: genetic resistance (either complete or partial) or tolerance. Resistance means that the pathogen or pest insect cannot multiply on the crop (complete resistance) or has a lower reproduction rate than on the susceptible crop (partial resistance)

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(Vale et al., 2001). Tolerance means that the crop can endure severe disease or pest infestation without showing severe yield loss (Schafer, 1971), thanks to compensatory mechanisms. Unfortunately, there is often a trade-off between productivity and hardiness (Brown, 2002; Foulkes et al., 2006).

The question can therefore be asked whether these low-input systems should completely replace intensive cropping systems. If both systems coexist, one can ask what proportion of the land should be devoted to each system in order to maximize profit and/or minimize environmental risks, given that interactions between systems exist at the landscape scale through the dispersal of pests from field to field. Public policy concerning pesticide use in agriculture can benefit from insights coming from models that integrate ecological and economic constraints into cropping decisions (Janssen and van Ittersum, 2007).

This paper presents a simple model representing the effect of the proportion of land cropped under a low-input system on yield and gross margin at the landscape scale. The model computes the optimal proportion that maximizes profit (including externalities such as the environmental costs of pesticide use (Pretty et al., 2000)) at the landscape scale as well as the equilibrium resulting from farmers' choices, with and without simple economic incentives. The model is described using terms that apply to fungal diseases (e.g. "inoculum") but it is also relevant for insect pests, and more generally for any pest that disperses at the landscape scale and whose multiplication depends on the cropping system in each field. Similarly, actual parameter values used in the figures were chosen to be roughly representative of wheat management, but the model analysis is not specific to a particular system.

## 2. Model derivation

The model considers two alternative cropping systems: one "intensive" system based on a high-yielding cultivar and high inputs (in particular pesticides), and one "low-input" system based on a hardy cultivar, which is either resistant (Fig. 1) or tolerant (Fig. 2) to the pests, and no or reduced pesticides. The model is based on the assumption that fields produce infectious propagules (e.g. airborne spores in the case of fungal aerial diseases) that spread uniformly in the landscape, so that fields interact via the inoculum pressure at the landscape scale. The production of inoculum per unit area is assumed to depend only on the cropping system (type of crop grown and pesticides used) of this unit; as a result inoculum production of the whole area depends linearly on the proportion of land under the low-input system (Figs. 1a and 2a). Finally, a linear relationship is assumed between actual yield in each unit and inoculum pressure (Figs. 1b and 2b). The variable that we want to maximize is the mean, over the whole area, of the gain per unit area ($G$); it is equal to the economic value of the harvested product minus the environmental cost of pesticide use. The equations for inoculum pressure and yield are given in the Appendix A. The resulting mean gain ($G$, Figs. 1c and 2c) as a function of the proportion of land cropped under the low-input system ($P$) is:

$$G = a \cdot P^2 + b \cdot P + c \tag{1}$$
$$a = \kappa(I_L - I_I)(\varepsilon_I - \varepsilon_L) \text{ with}$$
$$b = \kappa(2 \cdot \varepsilon_I \cdot I_I - \varepsilon_L \cdot I_I - \varepsilon_I \cdot I_L + \delta_L - \delta_I) + \lambda(\gamma_I - \gamma_L)$$
$$c = \kappa(\delta_I - \varepsilon_I \cdot I_I) - \lambda \cdot \gamma_I$$

A description of parameters is given in Table 1; $I_I = \alpha_I - \beta_I\gamma_I$ is the amount of inoculum produced per unit area under the intensive system and $I_L = \alpha_L - \beta_L\gamma_L$ is the inoculum produced by the low-input system. The gross margins obtained by the farmers adopting the different systems can be computed by multiplying yield by selling price (including premiums for low-input systems) and subtracting the costs of inputs (see Appendix A). Thus the gross margins ($M$) obtained per unit area under intensive and low-input systems depend linearly on the proportion of land cropped under the low-input system (Figs. 1d and 2d):

$$M_I = P[\kappa \cdot \varepsilon_I(I_I - I_L)] + [\kappa \cdot \delta_I - \kappa \cdot \varepsilon_I \times I_I - \rho_I \cdot \gamma_I - \sigma_I] \tag{2}$$

$$M_L = P[(\kappa + \mu)\varepsilon_L(I_I - I_L)] + [(\kappa + \mu)\delta_L - (\kappa + \mu)\varepsilon_L \cdot I_I - \rho_L \cdot \gamma_L - \sigma_L] \tag{3}$$

## 3. Model analysis

This section presents the analysis of the model in mathematical terms. The agronomic interpretation of the different cases derived from this analysis, as well as their consequences in terms of farmers' choices, will be presented in the last section. The shape of the mean gain over the whole area ($G$) as a function of the proportion of land under the low-input system ($P$) determines the existence of an optimal proportion, which maximizes the gain. If the function is concave and the maximum gain is obtained for $P$ between 0 and 1, it is best to maintain the coexistence of intensive and low-input cropping systems (Fig. 1c). Conversely if the function is convex, the maximum gain is obtained for $P = 0$ or $P = 1$ and the optimal landscape should either entirely be occupied by the intensive system or by the low-input system (Fig. 2c). The gain function is concave if and only if a $\leqslant 0$, i.e. $(I_L - I_I)(\varepsilon_I - \varepsilon_L) \leqslant 0$.

The model can be used to compute the proportion of land under the low-input system towards which the landscape will naturally evolve in the absence of regulation or cooperation between farmers, assuming that farmers choose the system that maximizes their own gross margin in the given context of landscape composition. Gross margins per unit area are equal in both systems when $P$ is equal to the equilibrium proportion $P^*$:

$$P^* = \frac{\kappa(I_I(\varepsilon_I - \varepsilon_L) + \delta_L - \delta_I) + \mu(\delta_L - \varepsilon_L \cdot I_I) + \rho_I \cdot \gamma_I - \rho_L \cdot \gamma_L + \sigma_I - \sigma_L}{(I_I - I_L)(\kappa(\varepsilon_I - \varepsilon_L) - \mu \cdot \varepsilon_L)} \tag{4}$$

If the slope of $M_I$ Eq. (2) is steeper than that of $M_L$ Eq. (3), the equilibrium is stable (Fig. 1d): when $P < P^*$, the gross margin is higher for the low-input system so the area under the low-input system tends to increase while when $P > P^*$, the gross margin is higher for the intensive system so the proportion of low-input crops tends to decrease. On the other hand, when the slope of $M_I$ is less than that of $M_L$, the equilibrium is unstable (Fig. 2d): when $P < P^*$, the gross margin is lower for the low-input system so the area of low-inputs crops tends to decrease, and $P$ becomes lower and lower whereas when $P > P^*$, the gross margin is higher for the low-input crop so the area of low-input crops tends to increase, up to 1.

Two cases can be distinguished, as a function of the production of inoculum by each type of cropping system ($I_I$ and $I_L$):

In the case where $I_I > I_L$, the inoculum pressure decreases with the proportion of low-input crops in the landscape (Fig. 1a). Since the harmfulness ($\varepsilon$) is less for the low-input crop than for the high input crop, by definition of a hardy variety (Fig. 1b), $a = \kappa(I_L - I_I)(\varepsilon_I - \varepsilon_L)$ is negative and the gain function is concave (Fig. 1c). The gain is maximum for $P_{\max}$:

$$P_{\max} = -\frac{b}{2a} \tag{5}$$

Since $\varepsilon_L < \varepsilon_I$ and $(I_I - I_L) > 0$, $\kappa \cdot \varepsilon_L(I_I - I_L) < \kappa.\varepsilon_I(I_I - I_L)$, if $\mu$ is small or if $\varepsilon_L = 0$, the slope of the gross margin for the low-input system is smaller than for the intensive system, and so $P^*$ Eq. (4) is a stable equilibrium (Fig. 1d). $P^*$ is equal to $P_{\max}$ only in exceptional cases.

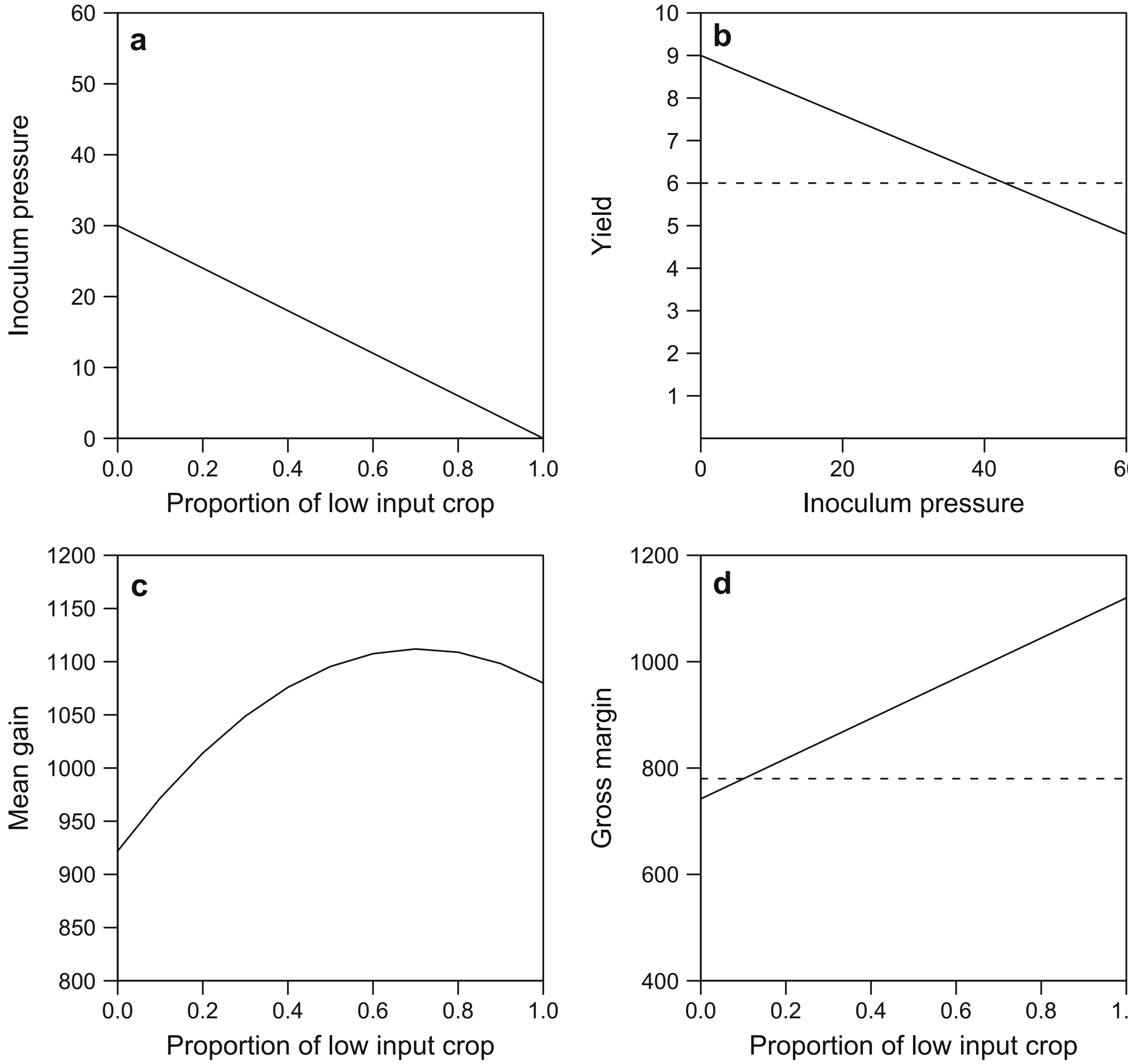


**Fig. 1.** Expected effect of the use of a resistant cultivar in low-input cropping systems. (a) Effect of the proportion of landscape area under the low-input system on inoculum pressure (arbitrary units). (b) Effect of the inoculum pressure on the yield (t ha$^{-1}$) produced per unit area under the intensive (solid line) and low-input (dashed line) cropping system. (c) Effect of the proportion of area under the low-input system on the mean gain (€ ha$^{-1}$) over the whole area. (d) Effect of the proportion of area under the low-input system on the gross margin (€ ha$^{-1}$) obtained per unit area under the intensive (solid line) and low-input (dashed line) cropping system.

In the case where $I_L > I_I$, the inoculum pressure increases with the proportion of low-input crops in the landscape (Fig. 2a). $(\varepsilon_I - \varepsilon_L)$ is still positive (Fig. 2b) and so $a \geqslant 0$ and the gross margin function is convex (Fig. 2c). The adoption of the low-input system can be beneficial for society as a whole only if $P_{\max}$ Eq. (5) is lower than 0.5, because a parabola is symmetric across a vertical axis going through its maximum so if $P_{\max} < 0.5$ then $G(0) > G(1)$ . For the same reason, low-input systems start being worthwhile at the landscape scale for $P$ values above $2P_{\max}$, i.e. $-b/a$.

Since $\varepsilon_L < \varepsilon_I$ and $(I_I - I_L) < 0$, $(\kappa + \mu)\varepsilon_L(I_I - I_L) > \kappa.\varepsilon_I(I_I - I_L)$ so $P^*$ is an unstable equilibrium (Fig. 2d), and the system towards which the landscape will naturally evolve under farmer's choices depends on the initial proportion of the landscape under low-input crops being above or below $P^*$.

## 4. Discussion

The model presented here, albeit very simple (a quadratic function for the gain over the whole area and linear functions for the gross margins), offers insights concerning the effect, on yield and gross margin, of the proportion of low-input systems in a landscape. Although studies comparing intensive and low-input systems at the field level usually try to identify which of these is the "best" (in terms of yield, economic result and/or environmental impacts) (Bouchard et al., 2008), our model shows that in some cases, the coexistence of both systems at the landscape level leads to higher yield and gain for society as a whole than either system separately. Of course, the results obtained here are valid only under the assumptions of the model, which greatly simplify the system by assuming linear relationships between proportion of low-input crops and inoculum pressure, and between inoculum pressure and yield per unit area. This is not necessarily the case, in particular if secondary infections play an important role in the epidemics. For example, the rate of disease increase in oat stem rust was found to have a linear relationship with the logarithm of proportion of susceptible plants in a mixture of resistant and susceptible oat varieties (Leonard, 1969). More complex (maybe more biologically relevant) assumptions could result in different optimum and equilibrium proportions or even several possible optimal proportions.

The question of the proportion of landscape that should be devoted to different types of agriculture had already been asked

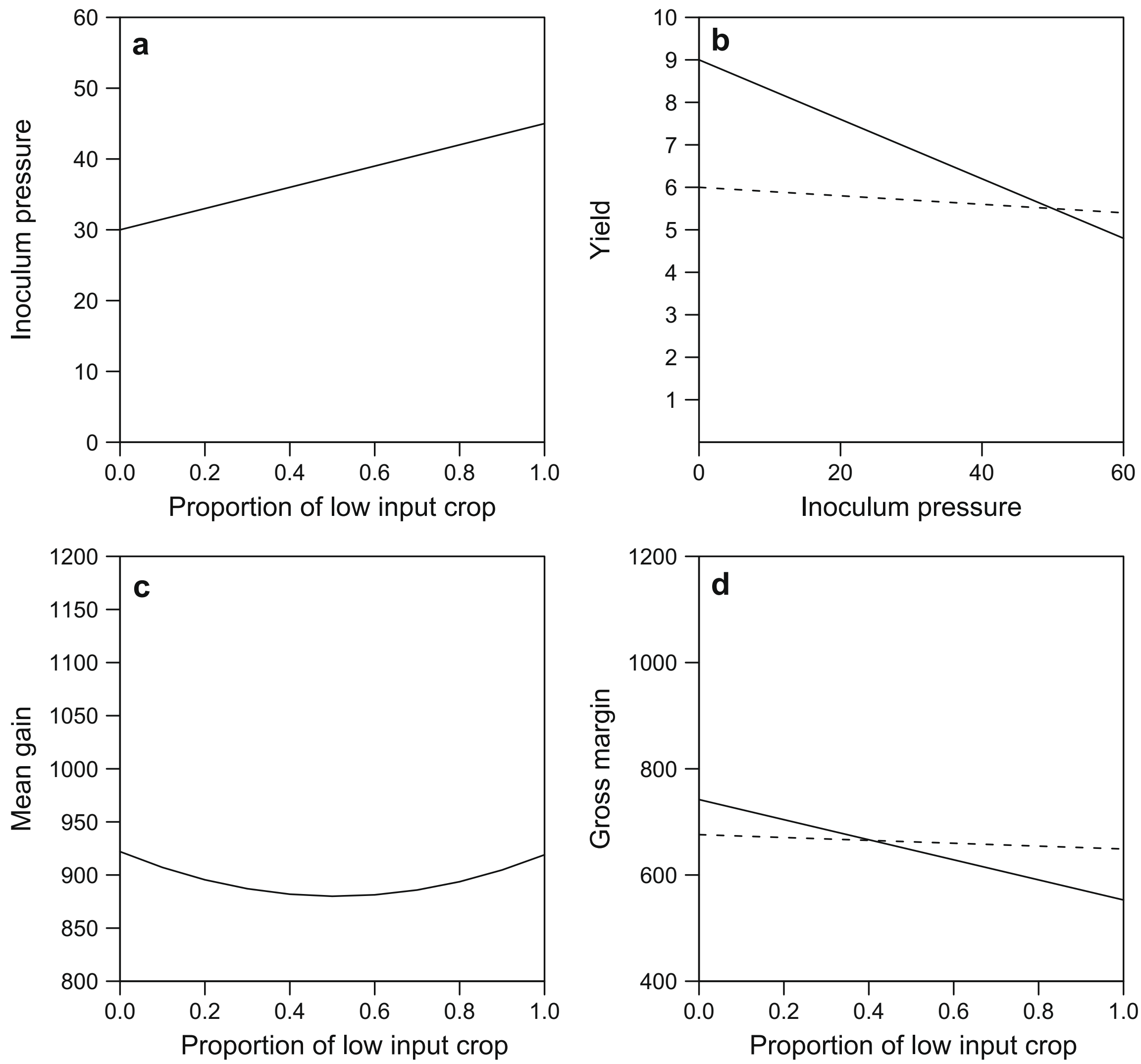


**Fig. 2.** Expected effect of the use of a tolerant cultivar in low-input cropping systems. (a) Effect of the proportion of landscape area under the low-input system on inoculum pressure (arbitrary units). (b) Effect of the inoculum pressure on the yield (t ha$^{-1}$) produced per unit area under the intensive (solid line) and low-input (dashed line) cropping system. (c) Effect of the proportion of area under the low-input system on the mean gain (€ ha$^{-1}$) over the whole area. (d) Effect of the proportion of area under the low-input system on the gross margin (€ ha$^{-1}$) obtained per unit area under the intensive (solid line) and low-input (dashed line) cropping system.

regarding the conservation of biodiversity (Green et al., 2005). Their model showed that, for a given production level, it was best either to devote the whole area to wildlife-friendly farming or to spare natural land by using high-yield agriculture on part of the area, depending on the shape of the relationship between agricultural yield and biodiversity. However this study did not take into account the interactions between both types of land use. In the case of pesticide reduction, one cannot disregard the flows of pests and propagules between fields, which cause the yield and gross margin of a crop to depend not only on the cropping system applied to the crop but also on the cropping systems applied in the whole area.

As a result, the optimal proportion of land under the low-input system depends on the inoculum production in each system. The model analysis distinguished two cases, leading to very different consequences, depending on whether the low-input system produced less (case 1) or more (case 2) inoculum than the intensive system. Biologically, the two cases arise under different situations. The first case, where the coexistence of both intensive and low-input systems can be optimal, occurs when the cultivar used in the low-input system is resistant to the disease: the pathogen cannot multiply on the crop ($\alpha_L = 0$) so $I_L = 0$ (or at least $I_L$ is small if the resistance is partial), and cannot infect the crop so $\varepsilon_L = 0$. The second case, leading to a homogeneous landscape being optimal, arises when the cultivar used in the low-input system is tolerant to the disease: the pathogen can develop on the crop but since it causes less loss, the farmers use less pesticide ($\gamma_L < \gamma_I$), which induces the multiplication and the spread of inoculum. This highlights the importance of distinguishing between resistance and tolerance when assessing varieties.

In our model, the most favourable case is resistance, as it has a beneficial effect not only on the resistant crop but also on the intensively managed area, through the reduced inoculum production. However the model is very simple and does not take into account the genetic evolution of the pathogen populations and for this reason cannot be used to evaluate the durability of resistance and thus the sustainability of the low-input system. Resistant crops create a strong selection pressure on the pathogen populations which often leads to resistance breakdown (Rouxel et al., 2003). The coexistence of resistant and susceptible crops has been proposed as a means of increasing the durability of plant resistance (Gould, 1998), by providing refuges on which avirulent fungal strains, or insect pests susceptible to the toxin released by the plant, can reproduce and thus maintain the proportion of virulent

**Table 1**
Parameters of the model. Parameter values were chosen in order for the figures to be illustrative but were inspired by wheat management.

| Symbol[a] | Name | Unit | Values used in the illustrations[b] | | |
|---|---|---|---|---|---|
| | | | $I$ | $L_R$ | $L_T$ |
| $\alpha_I$, $\alpha_L$ | Inoculum production per unit area in absence of phytosanitary control | Inoculum unit ha$^{-1}$ | 50[c] | 0 | 50 |
| $\beta$ | Inoculum reduction per dose of pesticide | Inoculum unit dose$^{-1}$ | 5[c] | | 5 |
| $\gamma_I$, $\gamma_L$ | Dose of pesticide | Dose ha$^{-1}$ | 4[d] | 0 | 1 |
| $\delta_I$, $\delta_L$ | Potential yield (i.e. yield in the absence of disease or pest) | t ha$^{-1}$ | 9[e] | 6 | 6 |
| $\varepsilon_I$, $\varepsilon_L$ | Harmfulness (i.e. yield loss per unit of inoculum) | t inoculum unit$^{-1}$ | 0.07[f] | 0 | 0.01 |
| $\kappa$ | Selling price of the crop | € t$^{-1}$ | 180[g] | 180 | 180 |
| $\lambda$ | Environmental cost of pesticide use | € dose$^{-1}$ | 80[h] | | 80 |
| $\mu$ | Price premium for products from the low-input system | € t$^{-1}$ | | 0 | 0 |
| $\rho$ | Price of pesticide | € dose$^{-1}$ | 50[i] | | 50 |
| $\sigma_I$, $\sigma_L$ | Cost of other cultural practices | € ha$^{-1}$ | 300[j] | 300 | 300 |

The cost of pesticides was 188 € ha$^{-1}$ on average in the intensive crop management plan used in Loyce et al. (2008), which corresponds to 47 € dose$^{-1}$ in our model.

[a] Subscript $I$ corresponds to the intensive system, $L$ to the low-input system,

[b] $I$ = intensive system using high-yielding variety, $L_R$ = low-input system using a resistant variety, $L_T$ = low-input system using a tolerant variety.

[c] Inoculum pressure is in arbitrary units so the values do not have any agronomic meaning other than in relation to yield loss.

[d] Intensive crop management of wheat includes several kilograms of active ingredients in pesticides (e.g. 3.65 kg ha$^{-1}$ in Loyce et al. (2008) and number of treatments ranged from 3 to 8 in France in 2006 (Agreste, 2008). In low-input systems pesticides are used only if the estimated cost of lost production is higher than the price of pesticides (with the values used here, the economic threshold for spraying is 54 €, i.e. one dose of pesticide in the case where the proportion of low-input system is almost zero).

[e] Attainable yields are higher in intensive systems than in low-input systems, both because of the difference in the varieties' yield potential and the reduced fertilization and sowing density in low-input systems (e.g. attainable yield was set to 10 t ha$^{-1}$ for an intensive wheat crop and 7 t ha$^{-1}$ for an organic crop (Willocquet et al., 2008).

[f] The chosen values of harmfulness lead to relative yield losses of 23% and 5% for the intensive and low-input (tolerant variety) systems in the case where the proportion of low-input system is almost zero, which is plausible (e.g. estimated yield losses ranged from 1.9% to 30.7% between 1977 and 2005 (Wiik, 2009).

[g] French channel wheat prices ranged from 110 € t$^{-1}$ to 310 € t$^{-1}$ between 2004 and 2009 (Agrimer, 2009), and the mean price for 2008 was 173 € t$^{-1}$ for Soft Red Winter from the Gulf of Mexico and 183 € t$^{-1}$ for Russian wheat from the Black Sea (Carrelet, 2008).

[h] Environmental cost of pesticide use was estimated to be 13.8 € kg a.i.$^{-1}$ in England (Pretty et al., 2000), but the authors warned that it was a conservative estimate and furthermore, costs that could not be estimated were not taken into account (e.g. loss of agricultural biodiversity, chronic effects of pesticides on human health).

[i] The cost of pesticides was 188 € ha$^{-1}$ on average in the intensive crop management plan used in Loyce et al. (2008), which corresponds to 47 € dose$^{-1}$ in our model.

[j] The cost of other cultural practices was 290 € ha$^{-1}$ on average in the intensive crop management plan used in Loyce et al. (2008).

genotypes relatively low in the pest population. However this strategy will be efficient only if there is a fitness cost for pests overcoming the host resistance. In the absence of such costs, durability, measured as the time for the virulent genotype's appearance and establishment, can be lowest when the susceptible and resistant hosts coexist (van den Bosch and Gilligan, 2003). The reason for that is that having both the susceptible and the resistant cultivars allows both a large population of pathogen (out of which virulence appears by mutation) and a strong selection pressure (allowing the virulent genotype to establish quickly once it has appeared). Thus, although the best approach in the short-term to increase yield or gross margin might be to allocate an intermediate proportion of land cropped with resistant cultivars, the optimization would be much more complex if durability was taken into account. Much effort is being devoted by scientists to study the durability of resistance and design Integrated Avirulence Management strategies (Aubertot et al., 2006) that aim at reducing both the selection pressures and the size of the pest population by combining cultural, physical, biological or chemical methods of control.

Conversely, tolerant varieties do not face breakdown due to evolution of the pest population, as their efficacy resides not in reducing the fitness of the pest but on compensating for damage. However, their use in low-input systems can be harmful at the landscape scale by increasing the quantity of inoculum that can then infect the susceptible cultivars used in the intensive system. Fortunately, several non-chemical control methods can be used to reduce the multiplication of pests, such as changing the dates of sowing/harvest to desynchronize the host's and the pest's life cycles, modifying cropping practices to enhance biological control or increasing the variety and/or species richness at the field scale and beyond. Still, these control methods have a cost for the farmer while they may well benefit others (the farmers using intensive systems which will receive less inoculum, and society as a whole, as less pesticide is used) because the yield of tolerant cultivars does not increase much when inoculum pressure is decreased (Fig. 2b).

This raises the question of the most efficient way to reach the desired proportion of low-input crops (crop management ratio). Studies in ecological economics have provided detailed models and methodologies to determine which policy mechanisms are most effective (Pannell, 2008, or Parra-Lopez et al., 2009 for an example of application, taking into account not only land use but also management practices). Our objective here is not to compete with such comprehensive models but rather to illustrate, with very simple assumptions, the mechanisms driving the system's evolution. Since the gross margin per unit area can be lower in the low-input system than in the intensive system when the area under low-input system is small (Fig. 2d), farmers will not choose the low-input system unless external benefits are internalised. The question is also valid when a resistant cultivar is used, as the optimum proportion is generally different from the equilibrium proportion. The model can illustrate several policy mechanisms aimed at reaching a target proportion of low-input systems: taxing pesticide use (increasing $\rho$) or adding a price premium ($\mu$) for products from the low-input system (e.g. through eco-labelling schemes). For the purpose of illustration, we can use the values of parameters used in Fig. 1. In this example, in order to make the equilibrium proportion $P^*$ and the optimal proportion $P_{\max}$ coincide, a tax on pesticide should be set at 57.5 € per dose (which might not be acceptable, since it represents 115% of the initial cost); alternatively, a price premium of 38 € t$^{-1}$ could be granted to the products from the low-input system, which could be more acceptable since it represents an increase of only 21% in the price, and consumers are willing to pay (a little bit) more for greener products (Galarraga Gallastegui, 2002). The question of whether regulatory or incentive-based instruments could be appropriate for assuring sustainability is a major research question in ecological economics, in particular concerning the environmental impacts of agriculture (soil and water pollution, erosion, greenhouse gas emission, loss of biodiversity, etc.). These impacts are manifold (trade-offs might exist between different objectives), and economic considerations are not the only obstacle to the adoption of low-input systems (Vanloqueren and Baret, 2008). Furthermore, it is difficult to design cost-effective economic or regulatory incentives able to ensure the coexistence (and appropriate spatial location) of several land use or agricultural systems: it is difficult to negotiate contracts with each individual farmer and uniform contract schemes are less cost-effective when there are differences between farmers, as some of them get more than what would be strictly necessary for them to change their management decisions (Havlik et al., 2008). Moreover, the objectives of the individual farmers might be antagonistic to the objectives of agricultural development agencies working on a wider scale. For example, it is in the best interests of a farmer to sow partially resistant cultivars in a contiguous block in order to protect them from contamination by susceptible crops, while a more intimate mixing of susceptible and resistant fields is best for area-wide disease control, because it reduces the total pathogen population (Holt and Chancellor, 1999).

This model offers a first step towards pesticide management at the landscape scale, as it considers only the proportion of the different systems (and also simplistic biological and economic assumptions); further work will focus on taking into account not only landscape composition but also landscape configuration, and more realistic interactions in terms of population dynamics and management practices.

## Appendix A

Model equations (all variables are expressed per unit area).

- Inoculum produced by intensive ($I_I$) and low-input ($I_L$) crops:

$$I_I = \alpha_I - \beta \cdot \gamma_I \tag{A1}$$
$$I_L = \alpha_L - \beta \cdot \gamma_L \tag{A2}$$

where $\alpha$ is the inoculum production per unit area in the absence of phytosanitary control, $\beta$ the reduction in inoculum per dose of pesticide, and $\gamma$ the dose of pesticide.

- Mean inoculum pressure over the whole area:

$$I = P \cdot I_L + (1 - P)I_I \tag{A3}$$

where $P$ is the proportion of land under low-input crop.

- Yield as a function of inoculum pressure in intensive ($Y_I$) and low-input ($Y_L$) crops:

$$Y_I = \delta_I - \varepsilon_I \cdot I \tag{A4}$$
$$Y_L = \delta_L - \varepsilon_L \cdot I \tag{A5}$$

where $\delta$ is the potential yield in the absence of disease and $\varepsilon$ the yield loss per unit of inoculum.

- The mean gain per unit area ($G$) over the whole area is equal to the economic value of the harvested product minus the environmental cost of pesticide use:

$$G = \kappa(P \cdot Y_L + (1 - P)Y_I) - \lambda(P \cdot \gamma_L + (1 - P)\gamma_I) \tag{A6}$$

where $\kappa$ is the selling price of the harvested product and $\lambda$ the cost of pesticide use per dose of pesticide.

Substituting Eqs. (A3)–(A5) into Eq. (A6) gives the mean gain as a function of the proportion of area under the low-input system:

$$G = P^2 \cdot \kappa(I_L - I_I)(\varepsilon_i - \varepsilon_L) + P(\kappa(2\varepsilon_i \cdot I_i - \varepsilon_L \cdot I_i - \varepsilon_i \cdot I_L + \delta_L - \delta_i) + \lambda(\gamma_i - \gamma_L)) + \kappa(\delta_i - \varepsilon_i \cdot I_i) - \gamma_i \cdot \lambda \tag{A7}$$

- Gross margin obtained with the intensive ($M_I$) and low-input ($M_L$) crops:

$$M_I = Y_I \cdot \kappa - \gamma_I \cdot \rho_I - \sigma_I \tag{A8}$$

$$M_L = Y_L(\kappa + \mu) - \gamma_L \cdot \rho_L - \sigma_L \tag{A9}$$

where $\mu$ is the premium on the price of the product from the low-input system, $\rho$ the cost of one dose of pesticide, and $\sigma$ the other production costs. Substituting Eqs. (A3)–(A5) into Eqs. (A8) and (A9) gives:

$$M_I = P \cdot \kappa \cdot \varepsilon_I(I_I - I_L) + \kappa \cdot \delta_I - \kappa \cdot \varepsilon_I \cdot I_I - \rho_I \cdot \gamma_I - \sigma_I \tag{A10}$$

$$M_L = P(\kappa + \mu)\varepsilon_L(I_I - I_L) + (\kappa + \mu)\delta_L - (\kappa + \mu)\varepsilon_L \cdot I_I - \rho_L \cdot \gamma_L - \sigma_L \tag{A11}$$

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