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Managing maize under pest species competition: Is *Bt (Bacillus thuringiensis)* maize the solution?

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Abstract. Transgenic crops that contain Cry genes from *Bt (Bacillus thuringiensis)* have been adopted by farmers over the last 17 yr. Unlike traditional broad-spectrum chemical insecticides, *Bt*'s toxicity spectrum is relatively narrow and selective, which may indirectly benefit secondary insects that may become important pests. The economic damage caused by the rise of secondary pests could offset some or all of the benefits associated with the use of *Bt* varieties. We develop a bioeconomic model to analyze the interactions between primary and secondary insect populations and the impact of different management options on insecticide use and economic impact over time. Results indicate that some of the benefits associated with the adoption of genetically engineered insect resistant crops may be eroded when taking into account ecological dynamics. It is suggested that secondary pests could easily become key insect pests requiring additional measures, such as insecticide applications or stacked traits, to keep their populations under the economic threshold.

Key words: *Bacillus thuringiensis*; bioeconomic model; *Bt* maize; dynamic optimization; insecticide use; pest management; population dynamics; secondary pest.

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INTRODUCTION

In 1996, the first generation of genetically engineered insect resistant (GEIR) crops expressing toxins (crystalline (Cry) proteins) from the soil bacterium *Bacillus thuringiensis* (*Bt*) were made commercially available. Since then they have been used worldwide for controlling insect pests of major crops such as maize and cotton (James 2013). So far, the benefits of commercialized GEIR crops have exceeded expectations (Carrière et al. 2010). It is now broadly accepted that any eventual detrimental impact on nontarget organisms (NTO) is lower for *Bt* crops than for conventional crops requiring broad-spectrum insecticides (Cattaneo et al. 2006). There is evidence from the use of a number of environmental impact indicators that GEIR crops have reduced (or at least have not increased) the impacts of agriculture on biodiversity through selective targeting and associated reductions in the use of broad-spectrum insecticides (Carpenter 2010, Areal and Riesgo 2015). Furthermore, the economic benefit of *Bt* crops associated with the regional suppression of specific pest populations appear to be significant (Gomez-Barbero et al. 2008, Carpenter 2010, Hutchison et al. 2010, Areal et al. 2013). The damage caused by stalk-boring feeding insects, such as the European corn borer (ECB) (*Ostrinia nubilalis* [Hübner] [Lepidoptera: Crambidae]), is enough to cause a significant reduction in maize yields (Malvar et al. 1993, Bohn et al. 1999).

Hutchison et al. (2010) estimated the cumulative benefits of controlling ECB with *Bt* maize over the last 14 yr at $6.8 billion for maize growers in the US Midwest, with more than 60% of this total accruing to non-*Bt* maize growers. On the other hand, in European countries where *Bt* maize has still not been employed, yield losses without control may reach 30% in areas highly infested with stalk-borer feeding insects (Meissle et al. 2010). According to Park et al. (2011) this represents a loss to farmers of between 157 million and 334 million Euros each year.

Despite its wide adoption, the sustainability of *Bt* crops is still a controversial topic among the scientific community. Two concerns are usually raised: (1) ecological shifts may take several years to manifest (Ho et al. 2009), hence, the long-term ecological interactions around GEIR crops are important to understand (Snow et al. 2005); and (2) the impacts of *Bt* crops on NTOs in field conditions may not reflect the results obtained in laboratory studies (Andow et al. 2006, Lövei et al. 2009). In particular, researchers have predicted that NTOs could appear in such numbers that they may become key secondary insect pests in *Bt* crop fields (Andow and Zwahlen 2006). (A secondary pest is a "nontargeted" pest that has historically posed a small or no economic threat, but which could be directly or indirectly affected by changes in insecticide use patterns, such as those caused by *Bt* cropping, associated with the management of a primary pest [FIFRA Scientific Advisory Panel 1998].) Citing Harper (1991:22), "ignoring secondary pests can lead to devastating crop damage that may continue over a considerable period of time". Such occurrence of secondary pests would require additional spraying with conventional broad-spectrum insecticides, which may erode (at least) some of the benefits of GEIR crop technology (Pemsl et al. 2011).

We develop a bioeconomic model to evaluate the impact of a number of pest management options on primary and secondary pest populations, as well as on insecticide use and related economic outcomes. We use a production function based on a system of two first order differential equations that represent the ecological interactions of the primary and secondary pests with the pest management practices. As far as we are aware, such an approach has not yet been considered in the literature. The model takes into consideration the dynamics of two surrogate pest species, the Mediterranean corn borer (MCB) (*Sesamia nonagrioides* [Lefebvre] [Lepidoptera: Noctuidae]), a target pest, and the true armyworm (TAW), (*Mythimna* [*Pseudaletia*] *unipuncta* [Haworth] [Lepidoptera: Noctuidae]), a secondary pest. Their effects on the production function are used to predict pest control decisions. Optimal insecticide applications under deterministic conditions are calculated through a Differential Evolution dynamic nonlinear optimization technique (Storn and Price 1997, Mullen et al. 2011). (Differential Evolution [DE] is a simple yet powerful global optimization method which belongs to the class of Evolutionary Algorithms [EA] [Storn and Price 1997, Price 1999]. This metaheuristic method attempts to find the optimum of the problem by iteratively refining the candidate solution with respect to the objective function [function to be optimized] value [Storn and Price 1997, Price et al. 2005]. Due to its convergence speed, accuracy, and robustness, it is often preferred to other optimization methods [e.g., genetic algorithm and evolutionary programming] in order to solve real-world problems over continuous domains [Vesterstrom and Thomsen 2004].) Furthermore, numerical simulations of various scenarios arising from different hypotheses are developed and analyzed. In particular, this focuses on farmers' net returns due to the changes in insecticide use and the development of secondary pests on *Bt* maize. We conclude by considering the management implications of the results as well as suggesting future research directions.

Secondary Pest Outbreaks in the Context of GEIR Crops

Bacillus thuringiensis toxins have a narrow efficacy spectrum aimed at controlling only the target pest. This offers a safe environment for the development of nontarget pests (Sharma and Ortiz 2000, Lu et al. 2010), which may lead to crop damage (Sharma and Ortiz 2000, Wu and Guo 2005). Depending on the magnitude of the impact, the adoption of *Bt* crops might convey unexpected negative effects on agricultural ecosystem interactions and consequently on farm profits (Wolfenbarger and Phifer 2000, Catarino et al. 2015).

In the context of GEIR crops, three main causes may trigger an outbreak of secondary pest species: (1) a reduction in broad-spectrum insecticide applications (Lu et al. 2010, Pemsl et al. 2011, Stone 2011); (2) a sufficient reduction in pests' natural enemies (Naranjo 2005*a,b*, Marvier et al. 2007); or (3) a decrease in interspecific competition with the lowering of target pest numbers (Catangui and Berg 2006, Dorhout and Rice 2010, Virla et al. 2010). These causes are not necessarily independent.

It is postulated that whatever the cause of the rise in secondary pest numbers, insecticide spraying would be the only immediate solution at a farmers' disposal. The most notorious case concerns sap-feeding bugs on *Bt* cotton plants in China. Presently, in order to control these secondary pests, Chinese *Bt* cotton farmers are applying about 20 sprayings per season (for more details see Lu et al. 2010, Pemsl et al. 2011). Such application rates are similar to those before *Bt* cotton adoption when insecticides were used mainly to control cotton bollworm (Wu and Guo 2005). Insecticide spraying on *Bt* crops may convey ecological disturbances with knock-on consequences, such as the destruction of the primary and/or secondary pest's natural enemies' complex. Hence, if nonsusceptible secondary pest populations exceed economic thresholds, the sustainability of *Bt* technology may be put in jeopardy. The bioeconomic model developed in the following section demonstrates the interaction and economic impact of such an event.

METHODS

Study context

Although several other events are under evaluation by the European Food Safety Authority (EFSA), the only *Bt* maize currently allowed for cultivation in Europe contains the transformation event MON810 (Monsanto Company, Brussels, Belgium), expressing Cry1Ab *Bt* toxin (EFSA 2010). This transgenic maize presents a high level of resistance to its primary pests—the two main maize borers present in the EU, the MCB and the ECB (González-Núñez et al. 2000). From a total of 441,000 hectares of maize cropped in Spain in 2013 (MAGRAMA 2013), about 1/3 was devoted to *Bt* maize. This makes Spain the largest European adopter, growing 94% of the total *Bt* maize hectarage in the EU (James 2013). Ex post economic analysis on the performance of *Bt* maize shows that Spanish adopters have obtained higher yields, higher gross margins, and better quality of harvested product, along with a significant decrease in insecticide applications compared with conventional farmers (Gomez-Barbero et al. 2008, Riesgo et al. 2012). In this region, two other Lepidoptera, the TAW, and the corn earworm, *Helicoverpa armigera* (Hübner), are considered to be important secondary pests causing occasional but severe damage to maize (Eizaguirre et al. 2010, Pérez-Hedo et al. 2012). While under normal conditions the MCB tends to outcompete the TAW (Eizaguirre et al. (2009), it has been suggested that the increase of transgenic maize could affect the population dynamics of these secondary Lepidopteran pests due to the high efficiency of *Bt* maize against its target pests (López et al. 2000, 2008, Eizaguirre et al. 2010). This would arise if TAW takes advantage of the absence of the major corn borers (Eizaguirre et al. 2010). These species are representative of the problem of secondary pests explored in this paper, as both species compete for the same food resource—maize—and the MCB, although biologically stronger than the TAW, is efficiently controlled by *Bt* maize.

Mediterranean corn borer

The MCB, is here used as an example of a primary pest due to its historical importance and present susceptibility—99%—to the Cry1Ab toxin (González-Núñez et al. 2000, Farinós et al. 2011). The MCB is a cosmopolitan multivoltine species with a wide range of host plants, including maize (Kfir et al. 2002, Eizaguirre and Fantinou 2012). It is considered to be the most important maize production pest in Spain and in other countries around the Mediterranean basin (Cordero et al. 1998, Malvar et al. 2002). Since maize production areas have increased in these areas during the past, the pest has consequently expanded (Eizaguirre and Fantinou 2012). Larvae cause damage by tunneling into stems or the ear until pupation, weakening the plants and consequently reducing yield (Malvar et al. 1993). Economic losses accrued to MCB in Spain have not been fully quantified, since the injury is undistinguishable from that caused by ECB (Eizaguirre and Fantinou 2012). The damage caused by MCB can reach 30% of the maize yield depending on the date of sowing and on the plant development stage when attacked (Butrón et al. 1999, 2009, Malvar et al. 2004, Velasco et al. 2004). The effect of photoperiod and temperature on MCB diapause induction and development has been extensively studied (e.g., Eizaguirre et al. 1994, Fantinou et al. 1995). In Spain, this species usually achieves two complete generations and one incomplete generation per year (Eizaguirre et al. 2002, 2008). According to Gillyboeuf et al. (1994), only about 5% to 25% of the overwintering larvae survive to pupate in spring, with the minimum threshold temperature for the pest being around 10°C (Eizaguirre et al. 2008).

In conventional maize cropping, MCB control through the use of insecticides is only moderately effective since larval development occurs mainly inside the stalk (Albajes et al. 2002). Depending on application timing, Clark et al. (2000) report an efficacy of between 67% and 80%. Natural enemies—generalist ground dwelling predators such as ground beetles, spiders, *T. busseolae* (Hymenoptera: Scelionidae), and parasitoides—of *S. nonagrioides* play an important role in the control of this pest (Alexandri and Tsitsipis 1990, Pons and Eizaguirre 2003, Farinós et al. 2008). Predation pressure comes mainly from egg parasitoides which may be responsible for up to 65% egg mortality depending on natural environmental conditions (Alexandri and Tsitsipis 1990, Figueiredo and Araujo 1996, Monetti et al. 2003).

True armyworm

The TAW is an important cosmopolitan secondary pest of the Noctuidae family in Europe and North America (Bues et al. 1986, McNeil 1987). It is an invasive species that was first noticed in Europe in the 19th century (Bues et al. 1986). The TAW feeds on the leaves of several nonagricultural and cultivated gramineous plants, including maize (Guppy 1961). Sporadic outbreaks, with large numbers of larvae marching across the landscape can have devastating economic impacts (McNeil 1987). In Europe, it is more prevalent in the Mediterranean basin due to the larvae's low ability to survive prolonged temperatures below freezing (Bues et al. 1987). In Spanish climatic conditions this species typically completes 4 generations (López et al. 2000). Despite conducive climatic conditions and their high capacity for mobility, the inconsistency of TAW prevalence is related to a combination of two other factors. Firstly, the existence of natural enemies, and secondly, the implementation of tillage practices and regular weed control (Willson and Eisley 1992, Clark et al. 1994). Contrary to MCB, this species is highly susceptible to natural enemies, Menalled et al. (1999) note an 80% mortality on field experiments. It is not uncommon to observe parasitism and other sorts of predation at rates capable of maintaining the population at endemic levels (Guppy 1967, Kaya 1985, Laub and Luna 1992). Although the devastating effects of armyworm larvae have been commonly documented, the impact on maize yields specifically is not clear due to the erratic nature of outbreaks (Douglas et al. 1981, Hill and Atkins 1982, Buntin 1986). Musick (1973) reported that six larvae were enough to destroy one plant, while Harrison et al. (1980) noted that an infestation level of one larva per plant was sufficient to cause a significant yield impact.

Several studies have evaluated the efficacy of different *Bt* maize transgenic lines against the TAW, reporting substantial plant damage on the varieties assessed (e.g., Pilcher et al. 1997, Schaafsma et al. 2007, Eizaguirre et al. 2010, González-Cabrera et al. 2013, Pérez-Hedo et al. 2013). Eizaguirre et al. (2010) found no difference in the number of TAW larvae per plant between *Bt* and isogenic varieties in the majority of field trials. Pérez-Hedo et al. (2013) noted that larvae complete their development, presenting similar growth rates, regardless of whether they are fed on a *Bt* or non-*Bt* diet. In laboratory experiments González-Cabrera et al. (2013) found TAW survival rates of approximately 80% when fed on a diet of *Bt* maize Cry1Ab. It is therefore possible that the increasing use of transgenic maize expressing Cry1Ab toxin might amplify TAW's economic importance (Eizaguirre et al. 2010).

Bioeconomic model

Following Lichtenberg and Zilberman (1986), we designed a bioeconomic model where pest interactions are incorporated into a production function. (For a detailed review on the Lichtenberg and Zilberman [1986] damage control approach see Sexton et al. [2007].) The damage-abating role of insecticide is taken into account explicitly in the production function through an asymmetric treatment of "productive" inputs (z) and "damage-abating" insecticide (x): $y = F(x, D(z))$. $D(x)$ is the so called damage-abatement function, representing the role of insecticide in the model, which do not have the potential to increase the output but indirectly mitigate yield loss through pest elimination. The effect of pest impact on the output is based on the Lotka–Volterra model which defines the population dynamics of two species competing for the same resource. Although the Lichtenberg and Zilberman (1986) damage control approach is not free from criticism (Lansink and Carpentier 2001, Zhengfei et al. 2006), it has been successfully used in other bioeconomic models of GEIR crops (Huang et al. 2002, Pemsl et al. 2008, Qaim 2009) and to model the management of invasive alien species (Ceddia et al. 2009).

The initial model assumptions are as follows. The agricultural product is attacked by two rather different pests: the MCB—primary pest (N_1)—is a highly competitive pest that is also highly susceptible to *Bt* toxin; and the TAW—secondary pest (N_2)—is negatively affected by the first species, but has a higher tolerance to the *Bt* toxin. Both have the same negative impact upon the yield. The dynamic behavior of both species, with and without pest control, is analyzed below. It is assumed that the farmer has only two means to suppress pests, by adopting *Bt* varieties and spraying insecticide when pest densities exceed an economic threshold (ET). (Economic threshold is defined as the "density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury level." The economic injury level (EIL) was defined by these authors as the "lowest population that will cause economic damage" [Stern et al. 1959].)

Actual output

Let $G(Z)$ denote the aggregate potential maize output over a landscape, which includes both conventional maize (G_c) and GEIR maize (G_{Bt}), where Z represents a vector of non-insecticide inputs (i.e., labor, seeds, fertilizers etc.). The damage control framework models the actual output, Y, as a function of potential output, $G(Z)$, damage, $D(N_1, N_2)$, and proportion of the total landscape planted with *Bt* maize (Ω). The actual output is given by:

$$Y = G(Z)\left[1 - D\left(N_1, N_2\right)\right] \tag{1}$$

with:

$$G(Z) = (1-\Omega)G_c(Z) + \Omega G_{bt}(Z)$$
$$G' > 0, G'' < 0$$

Damage is a function of the density of both pest populations—N_1 and N_2—and expresses the fraction of yield lost (D_y) due to the sum of damage caused. It is assumed that both pests can act simultaneously and the nature of the damage is species independent:

$$D = D_{N_1} + D_{N_2} \tag{2}$$

with:

$$D_{N_1} = \frac{\mathrm{IN}_1}{\text{Plant density}} \tag{2a}$$

$$D_{N_2} = \frac{\mathrm{IN}_2}{\text{Plant density}} \tag{2b}$$

Economic threshold

The ET is a practical operational rule difficult to assess theoretically, hence we have set the ET at a fixed level—25%—below the EIL, as suggested by Pedigo et al. (1986). Following the same author, the EIL is composed of five primary variables: w, the cost of management per unit (€/ha); p, the product market value per ton (€/ton); D_y, yield lost per larvae (tons/ha); and s, the proportion of larvae killed (%).

$$\mathrm{ET} = \frac{\mathrm{EIL}}{4} \tag{3}$$

with:

$$\mathrm{EIL} = \frac{w}{pD_y s} \tag{3a}$$

Population dynamics

The pest populations grow according to a classical logistic growth equation where population dynamics without control are influenced by: the growth rate, r_i, the species' intrinsic carrying capacity, k_i; intra-competition, b_{ii}; inter-competition, b_{ij}; and by mortality attributed to natural enemies, m_i (i = 1, 2; $i \neq j$):

$$\begin{cases} \frac{dN_1}{dt} = r_1 N_1 \left(1 - b_{11}\frac{N_1}{k_1} - b_{12}\frac{N_2}{k_1} - m_1\right) \\ \frac{dN_2}{dt} = r_2 N_2 \left(1 - b_{22}\frac{N_2}{k_2} - b_{21}\frac{N_1}{k_2} - m_2\right) \end{cases} \tag{4}$$

Within this basic framework, two forms of pest control are introduced: the adoption of *Bt* seeds (Ω) and the application of broad-spectrum insecticide (x). The parameter q_i (i = 1, 2) indicates the effectiveness of *Bt* in controlling each pest population. The pest dynamics become:

$$\begin{cases} \frac{dN_1}{dt} = r_1 N_1 (1 - b_{11}\frac{N_1}{k_1} - b_{12}\frac{N_2}{k_1} - u(x)m_1 - q_1\Omega - h(x)) \\ \frac{dN_2}{dt} = r_2 N_2 (1 - b_{22}\frac{N_2}{k_2} - b_{21}\frac{N_1}{k_2} - u(x)m_2 - q_2\Omega - h(x)) \end{cases} \tag{5}$$

Farmers' adoption of *Bt* technology is assumed to be exogenous and develops according to the following logistic function:

$$\Omega = \frac{\lambda_f \lambda_i e^{r_\Omega t}}{\lambda_f + \lambda_i (e^{r_\Omega t} - 1)} \tag{6}$$

The insecticide's effectiveness is specified by $h(x)$ which is a function of the number of insecticide applications (x), and by φ, a dummy variable, assuming the value of one if $N_1 \geq \mathrm{ET}_{N_1}$ or $N_2 \geq \mathrm{ET}_{N_2}$, and zero otherwise. Both pests are equally affected by the insecticide. It is important to note the insertion of the new component into the natural enemies' variability parameters $\varphi u(x)$ which reflects the negative impact of insecticide applications on natural enemies (Eq. 8).

Following Shoemaker (1973) and Bor (1995), mortality rate is an exponential function of insecticide dosage because high insect mortality requires a large dosage of insecticide. Consequently, the following kill efficiency function is written as:

$$h(x) = (1 - e^{-x(t)s_p}) \tag{7}$$

$$x(t) = a + bt + ct^2 + dt^3 \tag{7a}$$

$$u(x) = (1 - e^{-x(t)s_{ne}}) \tag{8}$$

$h(x)$ is assumed to be monotonically increasing in $x(t)$, which represents the application of insecticide at time t, and satisfies

$$h(0) = 0, \lim_{X \to \infty} h(x) \leq 0.$$

We assume the farmer applies insecticide as a preventative measure (Sexton et al. 2007). Under this approach, the farmer makes a long-term educated guess about the possibility of pests occurring according to their known biological dynamics. The parameters a, b, c, and d in this expression are estimated through the maximization of the farmer's net present value as specified below. Insecticide applications assume a cubic form in order to provide a higher degree of freedom when carrying out the optimization process.

Net present value

An agricultural landscape (whose area is normalized to one ha) populated by a profit maximizing farmer is used to explore the economic implications of different pest management decisions. The problem is formulated in terms of the maximization of NPV after 25 yr of aggregate landscape profits, subject to the pest management problem over a time interval $[0, T]$. This is accomplished by choosing the appropriate amount of insecticide to apply throughout the cropping season according to the economic threshold given the above pest dynamic scenario. The farmer determines his optimal insecticide application at the beginning of the planning horizon by choosing the values of parameters a, b, c, and d in Eq. 7a so as to maximize his NPV over the given time horizon. To make the problem more treatable, it is also assumed that all other inputs (Z) in the equation below are applied in fixed proportions.

Letting p denote output price, u_c and u_{Bt} the prices of conventional and GEIR maize inputs unrelated to damage control, w the price of a unit of insecticide (x), then the problem is:

$$\max_{\{a,b,c,d\}} \int_0^T e^{-\delta t} \Big\{ pg(Z)[1 - D(h(N_1, N_2, q, X))] - Z[(1-\Omega)u_c + \Omega u_{bt}] - \phi w x \Big\} dt \tag{9}$$

s.t.

$$\frac{dN_1}{dt} = r_1 N_1 \left[1 - b_{11}\frac{N_1}{K_1} - b_{12}\frac{N_2}{K_1} - (1-\phi)m_1 - \Omega q_1 - \phi h(x)\right]$$

$$\frac{dN_2}{dt} = r_2 N_2 \left[1 - b_{22}\frac{N_2}{K_2} - b_{21}\frac{N_1}{K_2} - (1-\phi)m_2 - \Omega q_2 - \phi h(x)\right]$$

with

$$\phi = \begin{cases} 1, N_1 \geq \mathrm{ET}_{N_1} \\ 1, N_2 \geq \mathrm{ET}_{N_2} \\ 0, \text{otherwise} \end{cases}$$

The model therefore computes aggregate maize output as the potential yield minus the fraction of the crop that is lost due to the damage caused by both pest species. The model excludes external social and environmental costs of insecticide use for both society and the farmer. Two different scenarios are analyzed: before and after *Bt* maize adoption. Each scenario includes the two cases: (1) the use of insecticides; and (2) the nonuse of insecticides.

Model parameterization

Population growth rates for the pests were derived from laboratory data given in peer-reviewed scientific publications (see Appendices S1 and S2). The laboratory conditions in these experiments represent the typical temperature and photoperiod conditions of the Mediterranean basin area.

In Spanish conditions, researchers have found not more than five larvae of MCB and TAW larvae per plant (Velasco et al. 2004, 2007, López et al. 2008, Eizaguirre et al. 2010). Hence this value was assumed as the maximum larvae number, for each species, per maize plant. Consequently the carrying capacity (k_1 and k_2) is equal to the maximum possible density of larvae within the cropped field, assuming a plant density of 90,000 per ha. Due to the large available habitat, we incorporate the intraspecific competition parameter within the carrying capacity, $b_{ii} = 1$. Considering a maximum carrying capacity of five larvae per plant and a maximum damage of 30% (as indicated above), we assume that each MCB and TAW larvae is able to reduce yields by 6% per plant. It has been suggested that the due behavioral characteristics, MCB may influence negatively the TAW, however until now this effect has not been quantified (López et al. 2003, Eizaguirre et al. 2009). We studied the case in which MCB has a strong negative effect on TAW ($b_{21} = 0.9$), while the reciprocal effect is relatively small ($b_{12} = 0.1$).

The parameters m_1 and m_2 take into account the impact of natural enemies on MCB and TAW populations respectively, and the random effect of variable external factors that can affect predatory activity, such as temperature, humidity, or agricultural practices (Kaya and Tanada 1969). Since we have little information about these, we have assumed that m_1 and m_2 follow random uniform distributions with m_1 varying between 0.1 and 0.65 and m_2 between 0.1 and 0.9. The difference between the ranges of m_1 and m_2 is explained by the cryptic nature of the MCB larvae which reduces its vulnerability to predation (see sections *Mediterranean corn borer* and *True armyworm* for further details). Small values of m_i, reflect a bad year for the occurrence, abundance, and subsequent predatory activity of natural enemies; high values of m_i reflect high levels of pressure by natural enemies and efficiency in capturing the pest. The parameter q_i ($i = 1, 2$) which indicates the effectiveness of *Bt* in controlling each pest population takes values $q_1 = 0.99$ and $q_2 = 0.2$. These values indicate the different pest susceptibility to the *Bt* toxin. It is assumed that N_1 is highly susceptible and that N_2 is weakly susceptible to *Bt* technology. It is hypothesized that full adoption of the *Bt* variety happens within 10 yr ($r_\Omega = 0.8$). Initial adoption for our model is 10% ($\lambda_i = 0.1$) and the maximum adoption is 80% ($\lambda_f = 0.8$) reflecting the minimum 20% refuge commonly advised. When adoption reaches a plateau, it means that 100% of the agricultural land is under a GEIR crop scheme.

In this study, although potentially very important, we did not take into consideration any eventual impact of *Bt* toxin on the natural enemies of our case study pests. Nonetheless, it should be noted that at least for Cry1Ab, no significant impacts have been reported especially when compared with insecticides (Naranjo 2005*a*, Cornell

2010). It is assumed that the farmer applies insecticide with optimal timing, obtaining an 80% (s_{ne}) pest control efficiency per application (Hyde et al. 1999, Folcher et al. 2009). We further assume that insecticides have a 100% efficiency on the natural enemies' complex ($s_p = 1$) since it has been reported that the effect of insecticides on natural enemies is greater than the effect on pests (Longley and Jepson 1996, Van Emden 2014). Insecticide applications change over time according to the Eq. 7a.

The parameters for the economic and ecological components of the model are presented in Appendix S3: Tables S1 and S2, respectively. The time horizon considered in the analysis extends over 25 yr after the initial (hypothetical) adoption of *Bt* varieties (so $T = 25$). The model is numerically solved with R software (R-Core-Team 2012) with support from the packages "deSolve" and "RcppDE" (Soetaert et al. 2010, 2015, Eddelbuettel 2015). After calibration, the numerical results appear consistent with data reported in recent studies (e.g., Gomez-Barbero et al. 2008, Meissle et al. 2010, Areal et al. 2013). The model sensitivity analysis is presented in the following section.

Sensitivity analysis

To assess the influence and importance of the biological parameters $\{r_1, r_2, m_1, m_2, b_{12}, b_{21}, b_{11}, b_{22}\}$ on the model results, we conducted a global sensitivity analysis (GSA) using the Morris (1991) method (Saltelli et al. 2000*b*). (The GSA was conducted in R software using the "sensitivity package" [Pujol et al. 2015].) The Morris method has been used in several dynamic agroecosystem modeling projects (e.g., Confalonieri et al. 2010, DeJonge et al. 2012, Ben Touhami et al. 2013). The use of this method of sensitivity analysis aids the selection of which parameters have greater influence on the model's final output variability. The parameter's uncertainty distribution values are shown in Appendix S3: Table S3. The Morris analysis has been used in several dynamic agroecosystem modeling projects (e.g. Confalonieri et al. 2010, DeJonge et al. 2012, Ben Touhami et al. 2013). The generated results give two measures of sensitivity, firstly the final output mean variation (μ^*) in relation to the computed values (horizontal axis), and secondly the correspondent effect standard deviation (σ) (vertical axis). Parameters with higher μ^* will have a stronger influence on the final output, while parameters with a high σ implies dependency through nonlinear responses and/or interactions with other parameters (Saltelli et al. 2000*a*, 2004). The sensitivity analysis using the Morris method showed that interspecific competition between primary and secondary pest (b_{12}) is the most influential parameter (Fig. 1). Four other parameters: natural enemies on secondary pest $\{m_2\}$, primary and secondary pest intraspecific competition $\{b_{11}, b_{22}\}$, and the effect of the primary pest on secondary pest $\{b_{21}\}$ are as well noticeably influential, while the remaining parameters have a sensitivity which is about threefold lower (Fig. 1).

RESULTS AND DISCUSSION

The NPV maximization over 25 yr (Eq. 9) was solved numerically using the following postulated pest management option scenarios. In our first assessed scenario (*Scenario 1: Prior to Bt maize adoption*), we modeled the pest dynamics and NPV after 25 yr, with and without insecticide control, assuming that the farmer did not have access to *Bt* maize seeds. In the second scenario (*Scenario 2: Bt maize adoption*), a new control technology—*Bt* maize expressing Cry1Ab toxin—becomes available. The adoption rate is not linear (Eq. 6). It is assumed that at time $T = 0$, 10% of the area is covered with *Bt* maize, reaching an 80% plateau after approximately 11 yr. Assuming that the farmer may lack a full understanding of the capacity and limitations of *Bt* technology, we tested two different cases: the first assumes that the farmer will rely on GEIR technology completely and all insecticide applications are stopped; the second assumes the farmer utilizes both of the pest control means at his/her disposal, with the *Bt* maize adopted at the projected rate and insecticide applications used whenever pest numbers exceed the ET. We also compared the results obtained with a conjectural case where both pests are highly susceptible to *Bt* toxin. In *Further scenarios* below, we have explored two additional scenarios: (1) a ±25% variation in seven parameters shown to influence pest dynamics $\{r_1, r_2, b_{12}, b_{21}, q_1, q_2, \lambda_i\}$; and (2) due to the importance of natural

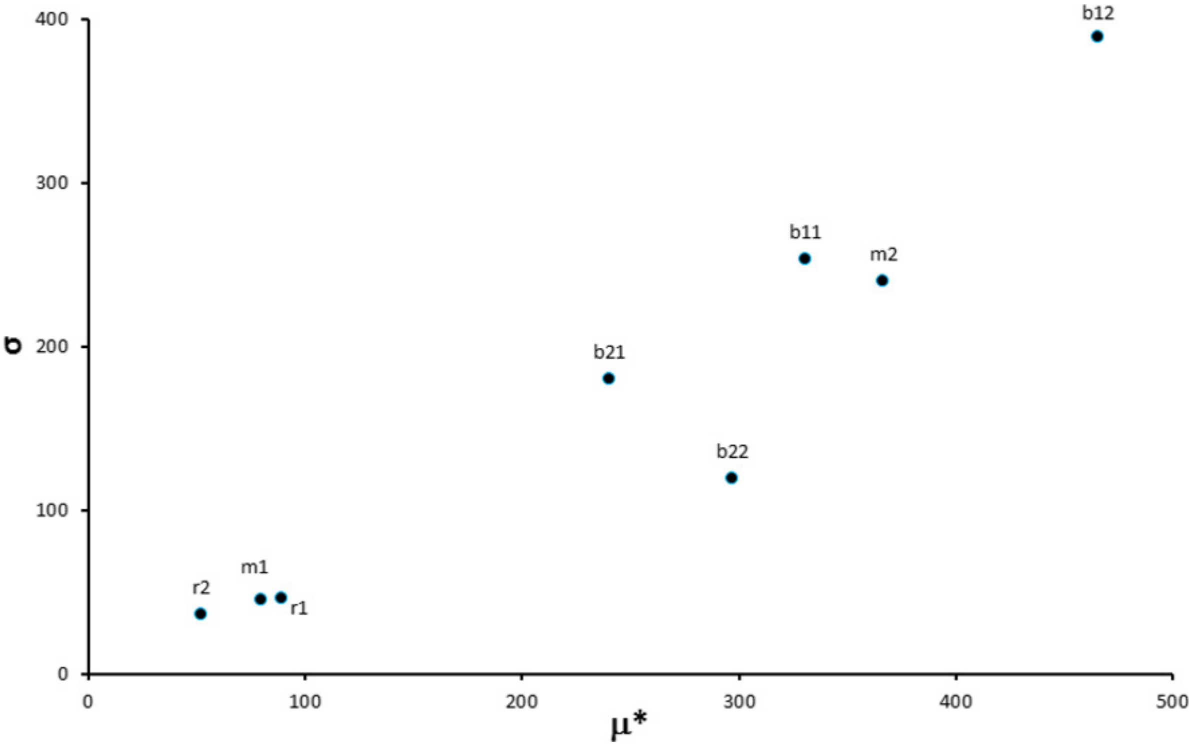

Fig. 1. Results of the Morris method (across 30 trajectories, 16 levels, and 8 grid jumps) on mean (μ*) and standard deviation (σ) associated with the NPV after 25 yr. Parameters were automatically scaled before computing the elementary effects so that all factors would vary within the range [0, 1]. It was implicitly assumed here that the uncertain model parameters were uniformly distributed. For each parameter, the tested range before scaling is shown in Appendix S3: Table S3.

enemies, we have assessed five additional cases of different natural enemies' densities (representing different levels of ecosystem disruption) with the assumption that the farmer uses a selective insecticide harmless to these enemies. In both additional scenarios, we have compared the resulting NPV after 25 yr and the number of insecticide applications with the results obtained in the optimal pest management control strategy (when insecticide is used along with *Bt* maize).

Scenario 1: Prior to Bt maize adoption

This scenario reflects a situation in which conventional maize is grown and *Bt* maize is not adopted (e.g., technology is not accessible), and primary and secondary pests are present in the agro-ecological system. Results under this scenario show the evolution of the population dynamics during a period of 25 yr for the primary (MCB) and secondary (TAW) pest without (Fig. 2) and with (Fig. 3) pest control (i.e., insecticides). Without pest control, the TAW density passes unnoticed for most of the period due to strong competition from the MCB and pressure from natural enemies (Fig. 2). This leads to high crop damage and a low NPV after 25 yr, and is therefore not desirable to the farmer (Appendix S3: Table S4). Fig. 3 shows the results under a conventional maize cropping system with the farmer applying insecticide. In this case, over 25 yr, an average of 3.55 insecticide applications per ha are made (SD = 0.61), obtaining a total NPV of 8563 €/ha (Appendix S3: Table S4).

The small variability in the amount of insecticide used occurs because the farmer is not able (and not economically willing) to completely eradicate the pest, but seeks to keep it under the EIL. Having the latter goal in mind, the farmer

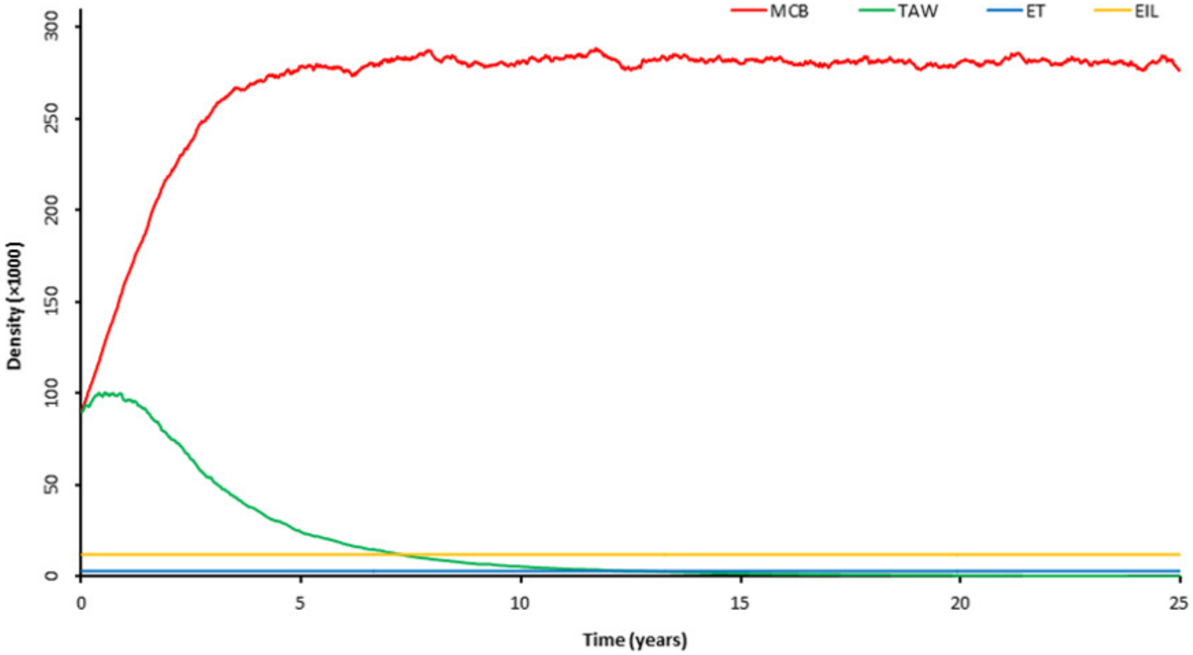

Fig. 2. Pest dynamics prior to *Bt* adoption with no control.

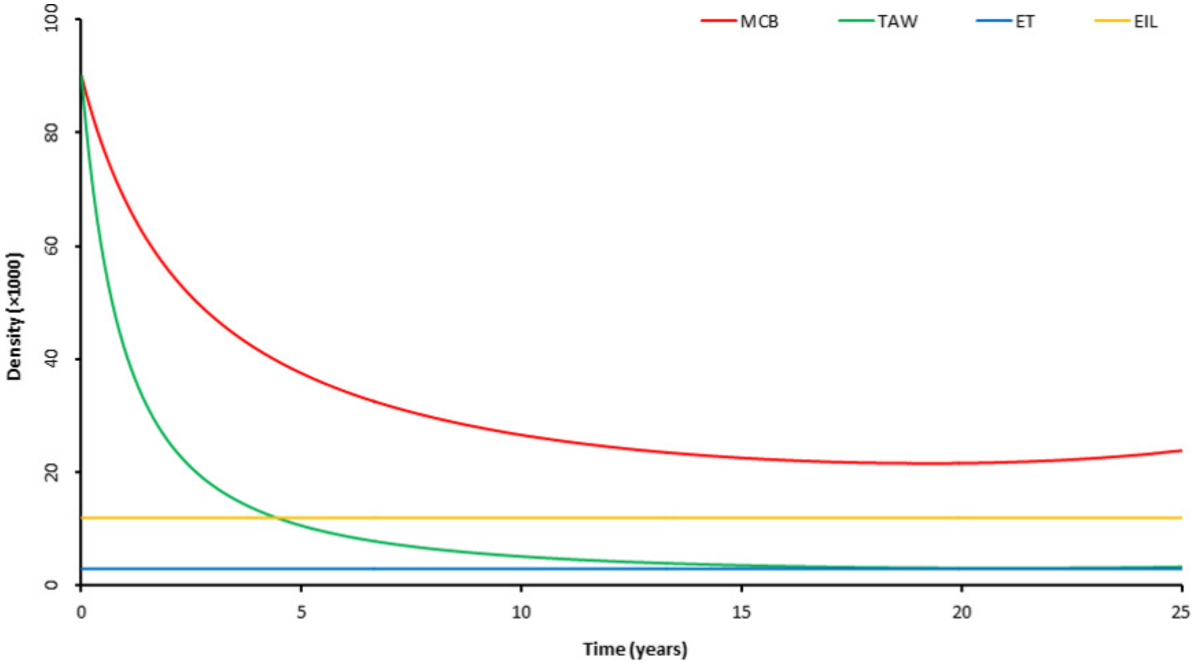

Fig. 3. Pest dynamics prior to *Bt* adoption with insecticide control.

only reacts when a pest reaches the ET. Because the MCB's proliferation capacity is high, its density will always rebound above the EIL obliging the farmer to keep constant attention on the fields. Assuming that resistance factors are constant, pest populations will then oscillate consistent with population numbers in previous years. Accordingly, it is expected that this insecticide

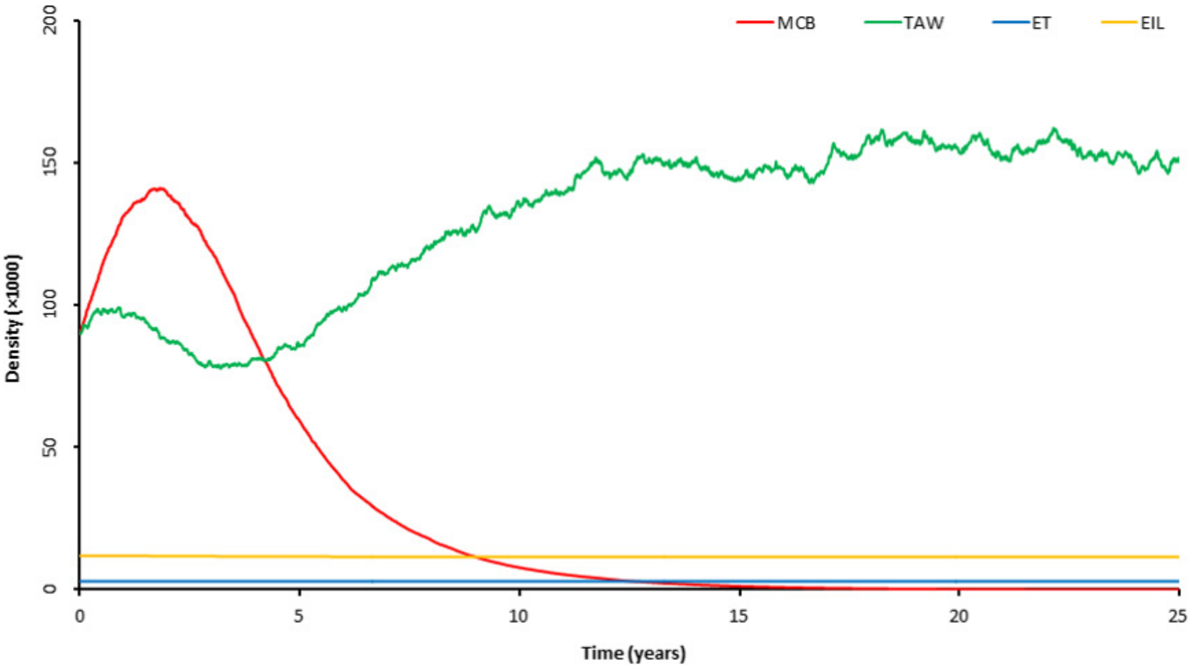

Fig. 4. Pest dynamics after *Bt* adoption, with *Bt* control only.

application pattern continues. In this scenario, the farmer may have no "knowledge" of the economic impact of TAW because it is always kept under the EIL by either the effect of insecticide or MCB competition pressure.

Scenario 2: Bt maize adoption

In the first case, the farmer relies solely in the efficiency of *Bt* maize putting aside insecticides (Fig. 4). After an initial rise in both pest densities, the TAW population is slightly suppressed by the MCB. However, due to the increasing presence of *Bt* toxin, after the MCB population peaks, its density steadily declines. MCB population levels below the EIL are reached after the 9th year of adoption. The ET is reached around the 12th year of adoption and with 80% of the maize area planted with *Bt* varieties. This translates into a decrease in the MCB's competition capacity and with a corresponding ascension in TAW numbers. In this case, the TAW population becomes the main pest being always above the EIL, causing serious damage to the crop. The oscillation in TAW numbers is due to the variable pressure of environmental factors and natural enemies affecting it. After 25 yr, MCB population is marginal and its complete eradication is never achieved. However, a quick recovery of the population will occur in the case of *Bt* seeds being used is stopped. In this case, where *Bt* maize is used without insecticide, the farmer obtains an NPV of just 7052 €/ha after 25 yr, which is about 82% of what was achieved when relying solely on insecticide (Appendix S3: Table S4). This scenario is slightly unrealistic as it fails to take into consideration the insecticide applications of non-adopting farmers. Nonetheless, it clearly demonstrates the problem of relying on a single pest control technique and illustrates what happens when a farmer is not aware of the secondary pest problem.

More realistically, farmers can be expected to utilize both the pest control means at their disposal (Fig. 5), with the *Bt* seeds adopted at the projected rate (as in Eq. 6) and insecticide applications used whenever pest numbers exceed the ET. In this case, due to the rapid insecticide action, both the pests' populations suffer an immediate decrease. Competition pressure is evident during the first 3 yr when TAW's population surpasses MCB population. TAW's population is kept below the EIL but above the ET until the

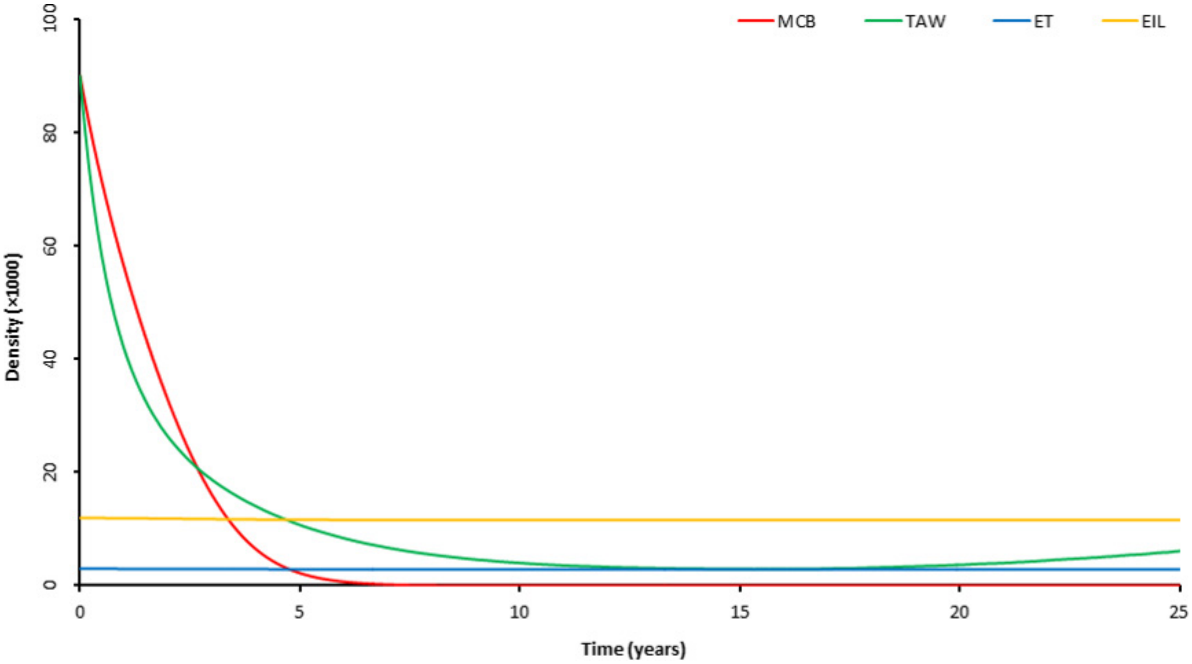

Fig. 5. Pest dynamics after *Bt* adoption, with *Bt* and insecticide control.

end of the time period in study. MCB population reaches the EIL after 3 yr of adoption, and the ET 1 yr later, with 54% and 69% of maize area planted with *Bt* maize, respectively. At this point due to both control measures pressure, the MCB density steadily falls below the ET until it is entirely eradicated after approximately 12 yr. It is the MCB decline, hence the lack of competition, that causes a plateauing of TAW within the ET and EIL. Here, the farmer continues to apply insecticides, but now in order to control TAW. The insecticide application frequency falls to an average of 2.01 applications per ha (SD = 0.68) (Appendix S3: Table S4). This amount represents a reduction of about 43% in the number of insecticide applications compared with conventional maize use. This noteworthy decline is accrued to the use of *Bt* and its efficiency in controlling MCB, and its provision of a safer environment for the natural enemies of TAW. In the section *Further scenarios*, the impact of natural enemies is discussed. The reduction in insecticide applications found here is sufficient to compensate the farmer for the extra cost of *Bt* seeds (roughly 10% more expensive than conventional seeds). After 25 yr, the farmer would realize an NPV of 10,353 €/ha (Appendix S3: Table S4), which is higher than what is realized with both conventional seeds and using only *Bt* maize (Appendix S3: Table S5).

For comparison, in a case of *Bt* maize with stacked traits conferring a perfect control to MCB and TAW, insecticide applications steadily decrease until the farmer stops applying insecticide altogether after the 5th year of adoption (at which point 70% of the total maize cropping area is planted with stacked *Bt* maize). The farmer achieves the goal of entirely eradicating both pests and, logically, realizes a higher NPV of 10,906 €/ha after 25 yr (see stacked traits line in Fig. 6). Realistically however, this situation is unlikely for two reasons: firstly agriculture is not a closed system, migration into crop fields by either known or unknown pests must be taken into consideration; secondly, as happened in our assessment, a species whose population is significantly subdued so as to in effect be “concealed” by the present insecticide or by the effect of a strong competitor, could unexpectedly reappear.

Further scenarios

In this section, we explore two further scenarios in which the five key parameters implicated in pest dynamics are varied: growth

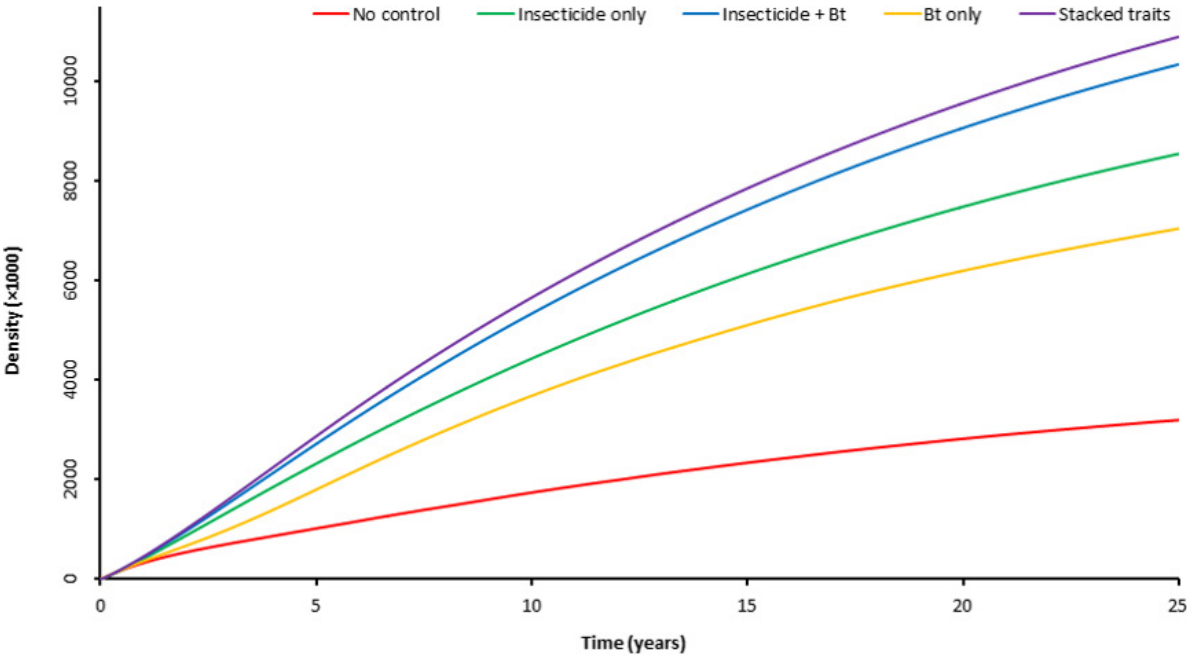

Fig. 6. Optimized NPV after 25 yr for the 5 cases (no control; only insecticide is used; only *Bt* maize is used; insecticide and *Bt* maize are used; stacked *Bt* maize conferring perfect control to both pests is used).

rate (r_i), interspecific competition (b_{ij}), susceptibility to *Bt* toxin (q_i), initial *Bt* adoption (λ_i), and natural enemies (m_i). The full results are presented in Appendix S3: Tables S6 and S7. When decreasing the parameters $\{b_{ij}; q_i; \lambda_i\}$ by 25%, we expect the NPV to decrease and insecticide applications to increase. Similarly, when increasing these parameters by 25%, we expect the NPV to increase and insecticide applications to decrease. It was also expected that r_i would respond in the opposite direction to its counterparts. From the 16 results obtained, 14 had expected outcomes. The two unexpected outcomes have relatively small deviation values (see values marked with * in Appendix S3: Table S6); although the mean insecticide applications varied as expected, the NPV varied in the opposite direction. These unexpected outcomes are believed to represent an active response from the farmer to lower/higher pest density in the initial cropping period, initiating insecticide applications accordingly.

Due to the high importance of natural enemies, we have assessed the individual impact of this parameter in model uncertainty. We explore five cases representing various levels of disturbance in the ecosystem, assuming that the farmer uses a selective insecticide which does not cause harm to natural enemies (Appendix S3: Table S7). In the first, the impact of natural enemies' on pest dynamics varies randomly as in the baseline cases in Scenarios 1 and 2; in the second, there are no natural enemies present; and in the third, fourth, and fifth, the impact of natural enemies is low, medium, and high respectively. All results are as expected, the higher the natural enemies' impact the lower the need for insecticide applications, yielding a higher NPV. It is interesting to note that the previous optimal outcome in terms of NPV (derived from the use of *Bt* maize with a broad-spectrum insecticide) lies between a scenario in which natural enemies are absent, and one where the impact of natural enemies on pest populations is low. This results suggests that boosting the population of natural enemies through selective use of insecticide, rather than broad-spectrum, has a knock-on positive impact on NPV. Assuming the utopia around the last scenario, we would like to point out the scenario where m_i = 0.8, reflecting a substantial constant presence of natural enemies. Here, the farmer would ultimately cease the insecticide applications, while increasing the NPV after 25 yr by 9%. These results indicate that pest populations are highly sensitive to natural means of control, and that pest populations could be managed with a relatively small increase in natural enemy numbers.

Conclusion

We use a bioeconomic model to analyze different pest control approaches—*Bt* technology and insecticides—on secondary pest outbreaks, a problem that has been largely ignored until now, and subsequent effects on farm profits. Optimized insecticide applications under deterministic conditions were achieved through a dynamic nonlinear optimization technique. The model developed in this study is capable of effectively evaluating the impact of GEIR crops on two pest species that compete for the same resource. As shown in *Results and discussion: Further scenarios*, the model enables the incorporation of different scenarios, such as insecticide restrictions, new transgenic traits, and other means of pest control.

Results from the sensitivity analysis showed that when holding prices, costs, and other input parameters constant, the results suggest that, the parameters related with the secondary pest are more influential on the final output than those related with primary pest. The uncertainty in the results arises from two main areas: (1) it is unlikely that available data and model parameters are error-free; and (2) no simulation model is an entirely true reflection of the physical process being modeled. Results show the need to be conscious of the possibility of an outbreak from a secondary pest and the consequences of such an event upon yields and farm profits. We found that it may take several years for secondary pests to proliferate to relevant levels of importance, thus the need to understand pest dynamics (Ho et al. 2009). We defined a model where the outbreak of a secondary pest in *Bt* fields is not a random event. It can arise as a natural result of the use of *Bt* technology, and may be predicted with access to accurate data. The model shows that insecticide applications and the presence of natural enemies, contribute most to achieving a higher NPV. The presence of natural enemies is intrinsically related to environmental conditions, and agricultural procedures, which in turn will certainly influence the number of insecticide applications needed each year. This is an important insight to take into consideration, given future climate shifts that are expected. Hence, alongside the deployment of GEIR crops, it is therefore highly advisable to also promote agricultural practices that could enhance the presence of natural enemies. When farmers effectively comply with certain procedures, such as having a refuge strategy and using extra selective insecticide applications (Meissle et al. 2011), the economic, environmental, and social benefits can be substantial (Wesseler et al. 2007, Skevas et al. 2010).

Our work corroborates the hypothesis that secondary pests might emerge due to a significant reduction in insecticides applications (Lu et al. 2010, Pemsl et al. 2011, Catarino et al. 2015). We have shown that (1) a secondary pest can become the key insect pest in unsprayed *Bt* maize compared with sprayed *Bt* fields, due to the high specificity of Cry1Ab toxin; and (2) the damage to crops from secondary pests can increase with the expansion of *Bt* technology if no additional measures, such as insecticide applications or stacked traits, are taken. One of the claimed benefits of *Bt* crops is that they decrease the use of insecticides, in turn diminishing contamination of food and the environment, as well as increasing farm profits. Indeed the use of *Bt* maize has a knock-on positive impact on NPV as well as in the environment by decreasing the need for insecticides. Furthermore, the farmer would have accomplished the goal of entirely eradicate the MCB after 14 yr. Nonetheless, insecticides applications would not cease due to the outbreak of TAW, the secondary pest.

Models of pest dynamics are a valuable tool, especially within a world affected by strong environmental and agricultural shifts. For example, forecasted global warming and increases in GEIR cropping could enable insect pests to spread into new habitats (Maiorano et al. 2014). We have shown that a profounder knowledge of how agro-ecological systems work is needed to evaluate the full benefits of *Bt* crops. If new agricultural technologies aim to be used as a viable IPM solution, understanding insect dynamics is vital, requiring an integration of ecosystem services into management decisions. For that, further research should accurately estimate, either in field trials or in the laboratory, the nature of intra- and inter-specific pest competition.

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