Title: Bioeconomic model for optimal control of the invasive weed Zea mays subspp. (teosinte) in Spain

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Abstract

Teosinte is an invasive weed which emerged recently in Northeastern Spain, an important corn-growing region in Western Europe. It is causing substantial agronomic and economic damages and is threatening the availability of corn in the region. Farmers and regulatory agencies can choose from a number of strategies to control for teosinte infestations including adoption of specific cultural practices such as manual control constructing false seedbeds, as well as adopting corn rotations with other annual and perennial crops. In spite of the potential negative impacts of this weed, little is known about what the optimal control strategies are, both from the private (e.g. the farm) and social (e.g. regulatory agencies) perspectives. In response, we develop a dynamic optimization model to identify the sequence of control strategies that minimize private and social costs under low- and high-infestation level scenarios, for a fifteen-year planning horizon. We calibrate the model using biological data from experimental trials and economic parameters collected from farmers in the region. Our results suggest the economic losses of teosinte infestation can reach up to 7444 and 8421 €/ha for low- and high-infestation scenarios if nothing is done to control it. In addition, results show that optimal private and social strategies are different. For example, under high-infestation levels, private losses are minimized at 26.5% by not controlling in years 1-2, use false seedbeds in year 3, planting alfalfa in years 4-8, and planting corn thereafter in the total area. In contrast, social cost are minimized at 27.9% by adopting rotations starting year, return to corn mono-cropping in half the area after year four. Results show false seedbed and manual controls, currently recommended by the regulatory agency in low-infestation cases, are not socially optimal.

Keywords: dynamic programming, weed management, control strategies, economic impact, public costs.

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1. Introduction

Teosinte, an invasive species native to South America, recently appeared as weed in corn fields throughout Northeastern Spain. This species is the wild ancestor of corn *(Zea mays* L.) and they share a similar growth cycle in this region. That is, teosinte germinates in May and needs high temperature and humidity to develop. Next, it reaches the flowering stage between August and September and its seeds fall to the ground from October to December, remaining latent until the next cropping season.

Teosinte is a serious competitor of corn for several reasons. It is capable to produce a large number of seeds which remain viable in the soil for future cropping periods and can also be hybridized with commercial corn. A heterogeneous set of undesirable plants can be observed in the fields as a result. A recent genetic study has determined that this so-called "Spanish teosinte" *"does not group with any of the currently recognized teosinte taxa"* (Tritikova *et al.*, 2017). Moreover, at present, there is no herbicide control method that distinguishes between corn and teosinte, so chemical control is still unfeasible.

Although the first reports of teosinte in Spanish fields come from Aragon in 2014, some farmers have declared that rare, corn-like plants were observed some years before. At the same time, infestations in neighbouring areas of Catalonia have also been reported and teosinte infestations were already reported in 2013 in the French area of Poitou-Charentes causing maize yield losses of more than 50% (ARVALIS, 2013).[1]

Teosinte has become the main agronomic concern in important corn-producing regions of Aragon. Corn is the third most important crop in Spain with 4.6 million tonnes annually, covering 17% of the total Spanish agricultural land, of which 20% is produced in Aragon (Mapama, 2016). Additionally, corn mono-cropping is common in many

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[1] At present, it is not confirmed if the teosinte plants from France are genetically connected with plants from Spain.

affected areas, so teosinte has a high potential for spreading rapidly and could cause severe yield losses and economic costs to farmers.[2]

Examining the optimal control of a new invasive species like the Spanish teosinte requires considering temporal and spatial dimensions simultaneously. The temporal aspects of the invader require careful understanding of its life cycle to identify the most appropriate timing for the control method (Zimdahl, 1988; Recasens et al. 2005). This warrants research efforts to understand the demographic behaviour of this invasive species, the teosinte-corn competition for resources, and the effectiveness of potential control strategies. Research conducted at experimental trials can be used to estimate the expected economic benefits of weed control in the short- and long-run taking into account the infestation incidence in fields and the costs of available control methods (Recasens et al. 2005). With respect to the spatial dimension of teosinte control, it is important to consider the weed's diffusion ability and how the farmer's behaviour could affect neighbouring fields, i.e., the identification of positive and negative externalities. This paper focuses solely on the temporal aspects of teosinte control, deferring the spatial dimension to future research because this requires different methodological approaches (although some of them will be pointed out here).

In addition to affecting farms, a regulator dealing with the management of a new invasive weed in arable fields faces several policy issues, including: i) uncertainty about the biological behaviour of the invasive in the new agroecosystem area and its effects on yields; ii) limitations regarding in the available control methods and the regulator's budget constraints; and iii) uncertainty about the economic efficiency of control methods. To overcome these uncertainties, designing dynamic mathematical models that combine biological and economic aspects of invasive species control are useful

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[2] A research project to study the biology and control strategies has been proposed to the Spanish National Agriculture Research Institute (INIA) and accepted in 2015 including both Aragon and Catalonian Research Centres and Plant Protection Services.

tools to identify the most appropriate control strategies and the costs associated with them. One of the advantages of bio-economic modelling is that economic and biologic equilibrium can be obtained simultaneously. Additionally, it is possible to design economic incentives for farmers to achieve a specific invasive species control target.

The aim of this paper is to construct a bio-economic dynamic model in order to identify profit-maximizing strategies and policies to manage the teosinte problem in Spanish areas of Aragón and Catalonia. In this setting, the dynamic model is used to explain the real farmers' behaviour from an economic perspective and to compare it with the optimal behaviour from the social point of view. This comparison sheds light on practical insights to improve the knowledge of teosinte weed and its optimal control.

The literature on invasive species management incorporating estimations on their economic damages is relatively abundant since the 1990s in the United States, South Africa, Australia and New Zealand (see Born et al. 2005 and Pimentel et al. 2005 for a review of diverse species). It is remarkable, however, the scarcity of research focusing on Europe, with the exception of a few studies addressing the management of invasive species in natural ecosystems in Germany (Reinhardt et al. 2003; Nehring, 2005) and in the UK (Dehnen-Schmutz et al. 2004). Surprisingly, studies estimating impacts of invasive weeds in agroecosystems are very scarce. To the best of our knowledge, Recasens et al. (2007) in Spain is the only exception. They estimate the impact of invasive weeds by calculating the sum of the annual losses in expected crop production caused by weeds and the costs of the corresponding herbicide controls.

Our approach to the problem is similar to that used by Odom et al. (2003) who used a bioeconomic dynamic model to determine the optimal combination of strategies to control an invasive weed in an Australian National Park. In our case, two different models are defined (private and social) and we incorporate a function of public costs.

2. Methodology

2.1. Study area

Although the exact moment of the initial infestations of teosinte in the region is uncertain, the first consultations were received in August 2014 at the Centro de Sanidad y Certificación Vegetal of Aragón (CSCV), which is the regional government's Plant Protection Service agency responsible for monitoring and control of plants pests and diseases, and it supports farmers with technical advice on these issues. From these consultations, the CSCV identified several invaded areas with different infestation levels (low and high) in three specific irrigation districts of the Huesca and Zaragoza provinces covering an area of approximately 400 has. Table 1 shows the distribution of affected lands and the initial infestation status.

Table 1: Distribution of lands affected by teosinte (has)

Location	Low infestation	High infestation
Monegros district		
Candasnos	-	284
Bujaraloz	27	-
Peñalba	-	12
Ejea district	-	38
Torralba district	-	36
Total area (ha)	**27**	**358**

Source: CSCV (2017)

The origin of teosinte infestations and its propagation in Aragón are still unclear, but some initial hypotheses point to the use of non-certified seeds and later propagation with harvesters and stubble sheep grazing in affected areas. Based on its initial prospecting data the CSCV published a technical report with control recommendations for farmers (Pardo *et al.*, 2014). In addition, several experimental trials were started in 2014 to carefully investigate the biology of the invasive species under the growing conditions of Aragón. This was even prior to the INIA-funded research project mentioned above, due to the urgency in providing responses to the new problem. Results are starting to be published (Cirujeda et al. 2017; Pardo et al. 2017; Prado et al. 2017) and have been employed in this paper as an input to construct a model that combines biologic and economic components explaining the farmer behaviour facing a teosinte infestation and to evaluate the social costs associated with the invasive species.

2.2. Hypothesis used for the model construction

A particular concern about teosinte is how the mono-cropping practices of corn, so far common in the area, could affect its propagation. Before the teosinte was detected, most farmers in the study area were growing corn as mono-crop since their fields started to be irrigated in 1996. Lack of experience in other irrigated crops and high maize prices have given little incentives to use crop rotation in the area. However, the guidelines of the CSCV have required farmers to include other crops in their rotation and they have been assumed in the model explained below.

In this work, the effect of mono-cropping practices over the teosinte temporal expansion will be evaluated under different initial infestation degrees. For this purpose, two initial conditions are assumed: low and high initial infestation levels. A low infestation level is associated to the presence of isolated plants in the plot, while a high level implies the existence of plant patches or a general presence of plants in the affected plot. Hence, the model is intended to represent the farmer behaviour under low or high infestation levels when mono-cropping is permitted. In this first model, individual farmer decisions are considered, assuming that the field average size of 8 has, and it is solved to identify the control strategy that maximizes profits in the presence of teosinte.

On the other hand, the evaluation of social impacts of alternative control strategies considers a social planner which selects the strategy that minimizes aggregate social costs in the infested areas (i.e. private costs of affected farmers plus public costs incurred by the social planner). In this context, the social planner is the institution responsible for the control of teosinte in the infested area (in our case the CSCV). The public costs include research, divulgation activities and monitoring of the infested areas. In a second step this aggregated perspective has been chosen assuming region of 400 has and modelling the best control methods from a social point of view. In addition, we compare this solution with the best control strategy from the private problem in order to evaluate the impacts of regulatory measures introduced by CSCV to control teosinte since 2014. Data on the total area affected and the infestation incidence in monitoring plots from 2014 to 2016 have been used in order to validate our results.

2.3. Bioeconomic dynamic model

We consider an individual farmer representative of all farmers' behaviour to easily describe the initial state of the problem. Subsequently, we will extend the model to cover the problem by the regulator in the total area. Thus, in the presence of teosinte infestation, the representative farmer problem is stated as the maximization of the total net annual benefit obtained from agricultural production in year *t* ($B_{i,t}$) (in €) calculated as the difference between income (the market value of crop yields) (in €·ha^{-1}) and costs (in €·ha^{-1}) from weed control strategy *i*:

$$B_{i,t} = \left[v_{i,t}\left(w_{i,t}\right) - c_{i,t}\right] \cdot z_{i,t} \qquad [1]$$

where $v_{i,t}(w_{i,t})$ is the market value function which depends on teosinte density (w_t) (in plants·m^{-2}), $c_{i,t}$ is the cost of control strategy i (in €·ha^{-1}) and $z_{i,t}$ is the farm area (in has) under control measure i. Each strategy i is linked to a specific crop as described below.

2.3.1. Teosinte control measures

For simplicity, the only costs considered are those directly related to teosinte control and these depend on the control method denoted by sub-index i=1,…,7. Therefore, seven control options are defined following the recommendations of the CSCV of Aragón (Pardo et al., 2014). Such recommendations include a set of preventive and cultural measures to avoid field infestations. Prevention includes using certified seed, careful cleaning of equipment and water canals, and avoiding the use of crop residues of infested plots as feed for livestock. Within the possible cultural controls, three strategies are proposed: false seedbed technique, manual control and rotations without corn. The first two cultural control strategies are only recommended for plots with low infestation levels, while rotations are mandatory in highly-infested plots, where in addition cropping corn is prohibited until the complete elimination of teosinte seeds.[3] The use of crop rotations facilitates weed control because the identification in field is easier and non-selective herbicides of corn might be used, i.e. unspecific herbicides for grass weed control authorised for the corresponding crops (Pardo *et al.*, 2017). The alternative crops in rotations considered in the model are barley-sunflower, pea-sunflower, alfalfa and wheat-alfalfa.

Seven control strategies have been considered in the model, as both low and high infestation level plots have been registered in the area:[4]

1. No control (corn crop),

2. False seedbed technique (corn crop),

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[3] The compliance of mandatory strategies in highly-infested plots is enforced and verified by the CSCV.

[4] Preventive strategies are not considered in the model.

3. Manual control (corn crop),

4. Barley-sunflower rotation,

5. Pea-sunflower rotation,

6. Alfalfa,

7. Wheat-alfalfa rotation.

The costs of each control measure in period *t* have been previously calculated by Pardo *et al.* (2016). Specifically, the authors estimate the annual net benefit losses with respect to non-infested plots under alternative simulated infestation scenarios. The authors also underscore that under high infestations levels, manual control and false seedbed strategies are overly expensive and ineffective, thus these strategies are only considered under low infestations levels.

2.3.2. Value function

The market value represents the farmer net gains function from each crop linked to each control measure *i*. For the case of continuous corn crop with no rotations (i=1, 2, 3) the value function is defined as:

$$v_{i,t}\left(w_{i,t}\right) = p \cdot y_{i,t}\left(w_{i,t}\right) \text{ for } i = 1, 2, 3, \qquad [2]$$

where p denotes the market price of corn; and $y_{i,t}(\cdot)$ is the yield function of crop in strategy i, which depends on weed density ($w_{i,t}$). The corn market price is obtained from Lonja del Ebro (2011-2015) as the average of the last five years, in order to partially avoid the impact of the high variability in market prices on the results. The yield function represents the relationship between teosinte and corn. Following experimental evidence, we assume that yields of other crops different to corn are not affected by teosinte because common tillage and herbicides control it effectively. Thus barley, wheat, alfalfa, pea and sunflower market values are calculated as the average of previous cropping seasons from years 2010 to 2014 (Magrama 2011-2015).

For the particular case of the corn (when $i=1,2,3$), we estimate a yield-weed competition function by using experimental data in field trials collected during a 2-year period in the areas affected by teosinte.[5] The specification of yield-weed function is linear and it is estimated using the statistical package R,v-2-14.2 (R Development Core Team, 2014) as:

$$y_i(w_i) = a_0 + a_1 \cdot w_i \quad \text{for } i=1, 2, 3, \qquad [3]$$

where a_0 and a_1 are the intercept and slope coefficients of the function.

2.3.3. Weed dynamics

A schematic diagram of the teosinte annual population dynamics is shown in Figure 1.

Figure 1: Demographic diagram for teosinte.

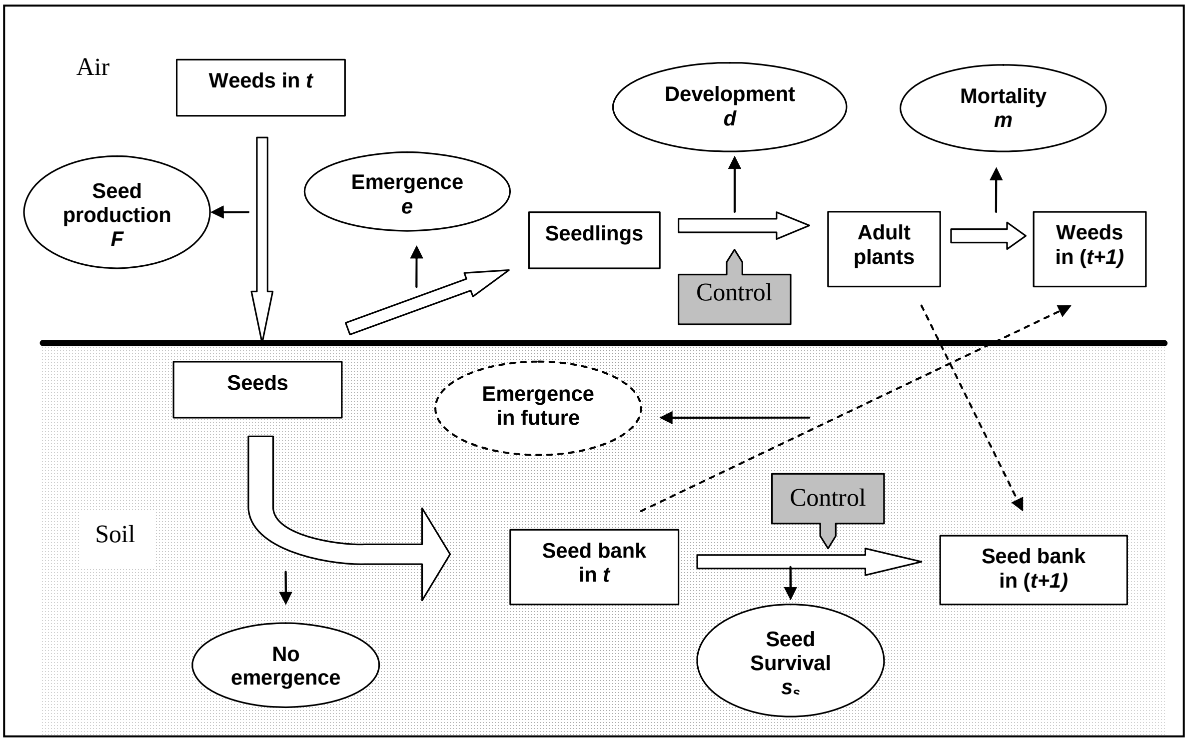

Figure 1 reflects the main biological processes and those plant stages considered in our bioeconomic model. The weed density in period *(t+1)* is affected by two variables: the

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[5] A detailed trial design description can be found in Pardo et al. (2017).

weed density in period *t* and the number of seeds in the soil from the previous period that emerge in period *(t+1)*. To model weed density in period *t*, we consider the number of seeds produced by plant (*F*) and the probability that seeds germinate (*e*) and become seedlings. The seeds that do not germinate in period *t* (1-*e*) become part of the seed bank in the soil. On the other hand, the seedling recruitment and survival is dominated by a linear function denoted by $d = d_0 + d_1 \cdot x$, where *x* is the number of seedlings. This function determines the number of adult plants. Finally, there is an observed mortality rate *(m)* affecting adult plants because of fungal diseases and corn borers.

The number of seeds in period *(t+1)* is affected by two variables: the amount of seed in the seed bank in period *t* (seeds that did not germinate in the previous period); and the weed density in period *t* (plants that have produced new seeds). With respect of seed bank in period *t*, some of the seeds are likely to survive in the next period, with s_s denoting the survival ratio. The production of new seeds from weeds in *t* is determined by the previously explained processes, i.e. seed production, emergence and development.

The dynamics of teosinte population growth described in Figure 1 is represented in the model through equations [4] and [5] below. Two variables are then considered relevant in the model: w_t affects agricultural output directly, whereas s_t affects the potential for the weed population to increase in future periods. The initial values for these variables will be denoted by w_0 and s_0 respectively. In addition, control strategy *i* will affect the dynamics of both variables. Mathematically:

$$w_{i,t+1} = f\left(w_{i,t}, s_{i,t}\right) \qquad [4]$$

$$s_{i,t+1} = g\left(w_{i,t}, s_{i,t}\right) \qquad [5]$$

where s_t is the size of the teosinte seed bank at time *t* (seeds·m^{-2}). The functions *f(·)* and *g(·)* represent the spread of w_t and s_t, and they depend on control strategy *i* selected by the farmer. They are estimated from the data collected in the field experiments. The function *f(·)* follows a Mitscherlich-Baule specification. This function allows for plateau growth and convex, but not necessarily, right angle isoquants. The intuition behind this specification is that weed density grows until a maximum value w^* and thereafter the density remains constant due to plant competition for space and nutrients. It imposes plateau growth which fits well with the observed behaviour of teosinte. This specification yields:

$$f(w_{i,t}, s_{i,t}) = w^* \cdot [1 - \exp(-\alpha_0(\alpha_1 + w_{i,t}))] \cdot [1 - \exp(-\alpha_2 \cdot (\alpha_3 + s_{i,t}))] \qquad [6]$$

The formulation in equation [6] is consistent with the view that the increase in teosinte density in period *(t+1)* due to a one-unit increase in the scarce state variable (w_t or s_t) is proportional to the difference between that state variable (w_t or s_t) and the maximum value w^*. After reaching a large enough level, the density will no longer grow due to high competition among teosinte plants and at this point the weed density reaches its maximum level w^*.

Function *g(·)* represents the evolution of the size of the seed bank.

$$g(w_{i,t}, s_{i,t}) = \begin{cases} \beta_1 \cdot s_{i,t} + \beta_2 \cdot w_{i,t} & \text{if} \quad s_{i,t} < s^* \\ \\ s^* \quad \text{if} \quad s_{i,t} \geq s^* \end{cases} \qquad [7]$$

The size of seed bank in period (*t+1*) depends linearly on the weed density in the previous period and also on the size of the seed bank in the preceding period provided that the seed number is lower than the maximum number s^* observed in experimental trials.

In other words, seeds in period (*t+1*) are calculated as the sum of the seeds surviving from the previous period and the seeds generated by adult weed plants in period *t* with the upper limit at s^*. In this case, the linear relationship among variables affecting the dynamics of the seed bank incorporates the demographic processes observed in experimental trials. The parameter of the population dynamics and coefficients values of functions are presented in Table 2.

Table 2: Biological parameters of the model.

Parameters	Value	Description	Source
F (plants·m^{-2})	414	Seed production	Cirujeda et al. (2017)
e (%)	47.7	Emergence	Cirujeda et al. (2017)
s_s (%)	7.38	Seeds survival ratio	Cirujeda et al. (2017)
m (%)	50.0	Mortality	Cirujeda et al. (2017)
w^* (plants·m^{-2})	22	Maximum value of weeds	Cirujeda et al. (2017)
s^* (plants·m^{-2})	31.8	Maximum value of seeds	Cirujeda et al. (2017)
d_0	0.0704	Coefficients of seedling	Cirujeda et al. (2017)
d_1	0.03933	survival function	
a_0	11.334	Intercept of yield-weed	Pardo et al. (2017)
a_1	0.5456	competence	
α_0	0.0704	Coefficients of weed spread	Pardo et al. (2017)
α_1	38.83	function	Cirujeda et al. (2017)
α_2	0.0704		
α_3	0.1876		
β_1	0.0738	Coefficients of seed bank	Pardo et al. (2017)
β_2	98.97	evolution function	Cirujeda et al. (2017)

Figure 1 also illustrates how the control methods alter the biological expansion of teosinte. Basically, control methods directly affect the seed survival parameter (s_s) and the development function (d). Following results from data analysis collected in the field, rotation strategies (i=4,5,6,7) can eliminate weed density and reduce seed bank size as already observed in selected commercial plots (Cirujeda et al., 2017). Table 3 shows the influence of control methods on the parameters of weed density and seed bank size expressed as multipliers or proportions of the initial parameter values in Table 2. For example, parameter values of 1.0 indicate no effect on initial values, i.e. no-control option. Also, parameter values 0.1 and 1.0 for manual control in Table 3 indicate that this strategy reduces the probability that a seedling becomes an adult plant to 0.9 of their original values, but there is no expected effect on seed survival. Values of the parameters in Table 3 were estimated on the basis of the logical relationship between the control method and the parameter and on the observations taken in field trials, i.e., whether the parameter is expected to increase or decrease with a particular control.

Table 3: Effects of control strategies on parameter values.

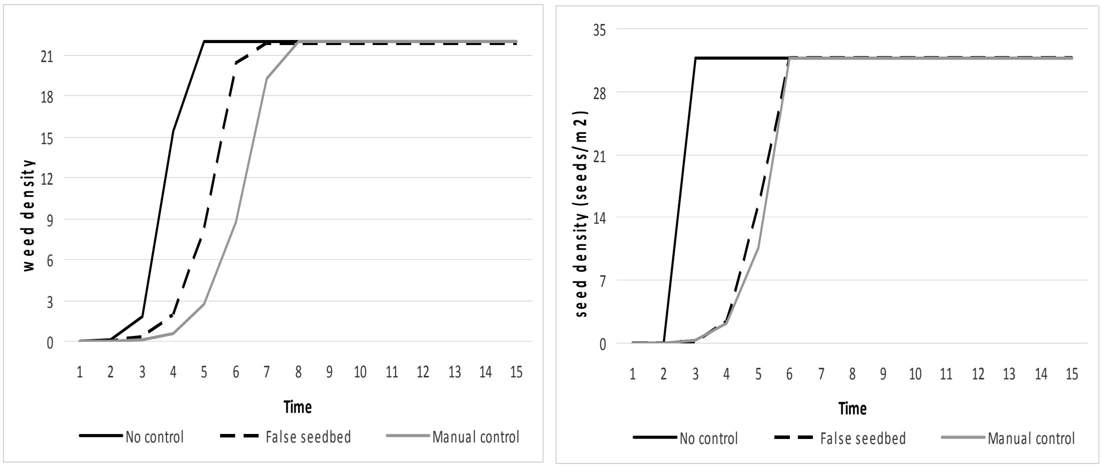
Control method	Multipliers	
	Weed (d)	Seed (s_s)
1. No control	1.00	1.00
2. False seedbed technique	0.20	0.90
3. Manual control	0.10	1.00
4. Barley-sunflower	0.00	0.30
5. Pea-sunflower	0.00	0.30
6. Alfalfa	0.05	0.50
7. Wheat-alfalfa	0.05	0.50

Source: Pardo et al. (2017), Cirujeda et al. (2017)

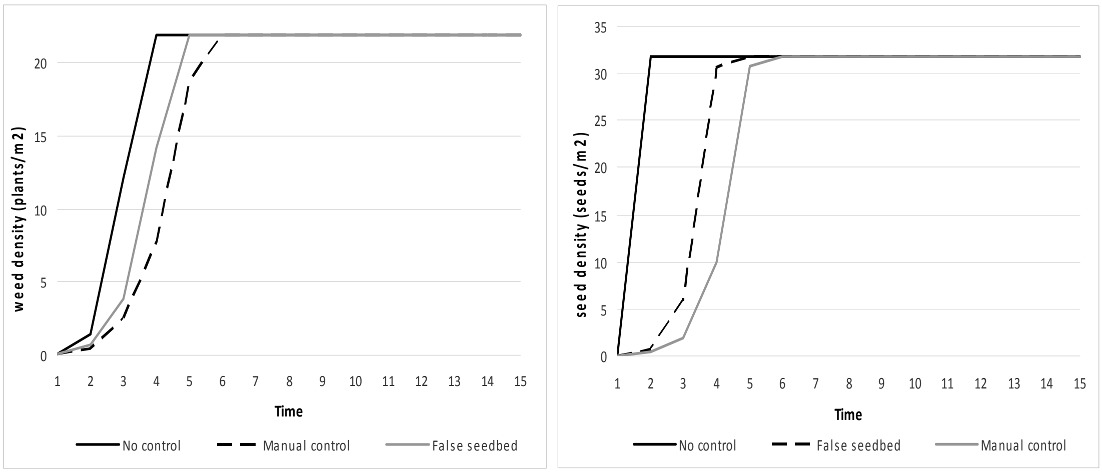
Figure 2 illustrates how the control strategies with continuous corn crop (controls 1, 2 and 3) affect weed and seed density dynamics when the same particular strategy is maintained in time throughout the considered period by applying the multipliers in Table 3. The initial values of weed density considered are w_0=0.001 plants·m^{-2} for the case of fields with low infestation and w_0=0.1 plants·m^{-2} for high infestation. The initial situation of low weed density and no-control causes that the invasive species to attain the maximum weed density value in five years and the maximum seed density in period four, given that the entire corn crop is lost due to teosinte competition. The false seedbed technique delays the total loss of corn production to period seven, while manual control delays it until period eight.

Figure 2: Evolution of weed and seed dynamic depending on control and infestation degree.

Low infestation (w_0= 0.001 plants·m^{-2})



High infestation (w_0=0.1 plants·m^{-2})



When the initial density of teosinte in a plot is high, then the evolution is similar but the total loss of the corn crop in plots occurs one period earlier (fourth year). The dynamics of weeds and seeds under manual control and false seedbed strategies show that none of them can eradicate the infestation completely because they only delay the total loss of corn production by one or two years. Thus, these strategies recommended by CSCV are supposed to delay the teosinte infestation both in low and high-density situations but need additional control methods to be able to reduce infestations.

When crop rotations are considered combining winter and summer crops (controls i=4 and 5) teosinte is completely eliminated in the second period (multipliers in table 3 are 0.0) while the incorporation of alfalfa (i=6 and 7) eliminates infestations in the third period as a consequence of the use of herbicides and their specific tillage (data not shown).

This confirm that only strategies that imply rotating corn with other commercial crops are effective in eradicating teosinte, while cultural control methods (false seedbed and manual control) have a partial effect on seed bank and limited effect in reducing weed dynamics.

2.3.4. Economic model

The economic model is stated as the maximization of benefits from agricultural production activities, subject to the dynamics of teosinte in the field. In the model, a farmer selects the sequence of control strategies (*i*) linked to a crop strategy without considering any other costs different to the cost of the control strategy (e.g. negative externalities and public costs to regulatory services). Under discrete time, the dynamic private profit maximization model is defined as follows:

$$B_{private} = \underset{i}{Max} \sum_{i=1}^{7} \sum_{t=1}^{T} \frac{1}{(1+r)^{t}} \left[v_{i,t}\left(w_{i,t}\right) - c_{i} \right] \cdot z_{i,t} \qquad [8]$$

subject to:

$$w_{i,t+1} = f\left(w_{i,t}, s_{i,t}\right) \qquad [9]$$

$$s_{i,t+1} = g\left(w_{i,t}, s_{i,t}\right) \qquad [10]$$

$$\sum_{i=1}^{7} z_{i,t} = \overline{Z} \qquad [11]$$

where r is the discount rate (3%); the planning horizon T is 15 years; c_i is the cost per ha associated with each control stratey, z_i is the amount of land allocated to control strategy i. The objective equation [8] is the net private benefit through the planning horizon expected from each control strategy. Constraints [9] and [10] capture the weed and seed bank density dynamics explained in the previous section, and equation [11] is the total land (in has) constraint. The model incorporates two state variables (w_t, s_t). The objective of the analysis is to choose the sequence of control strategies (i) that maximise the present value of net benefits given an initial state of teosinte incidence (w_0, s_0). This private problem reflects a farmer' behaviour when no mandatory control strategy is imposed and they do not take into account the public costs assumed by regulatory services due to establishing a program to control the teosinte problem (which include divulgation, surveys in affected areas, monitoring and enforcing mandatory strategies). Thus, it captures the situation in the initial states of the teosinte infestations.

The economic model defined in equations [8] to [11] can be extended to represent the problem of a social planner who maximizes the social benefit (SB) by including some additional equations. Following current land-use patterns on the study area, it is assumed that a total area of 385 has is affected by teosinte infestations (CSCV, 2017), which was the affected area in 2014.

We assume that there are two types of perfectly competitive farmers j, (j= 1, 2). Both types of farmers have identical characteristics, i.e. they can be described by the same market value functions $v^j(\cdot)$, the same control costs c^j and the same functions governing weed and seed dynamics. The main differences between farmer types are the initial teosinte infestation levels in field, the number of farmers n^j that belong to group *j* and the total area $\overline{Z}^j$ of group *j*. Mathematically, the SB is given by:

$$SB = \underset{i,j}{Max} \sum_{j=1}^{2} \sum_{i=1}^{7} \sum_{t=1}^{T} \frac{1}{(1+r)^t} \left[v^j_{i,t} \left(w^j_{i,t} \right) - c^j_i \right] \cdot z^j_{i,t} \cdot n^j - D\left(z^j_{i,t} \right) \cdot n^j \qquad [12]$$

subject to:

$$w^j_{i,t+1} = f\left(w^j_{i,t}, s^j_{i,t} \right) \qquad [13]$$

$$s^j_{i,t+1} = g\left(w^j_{i,t}, s^j_{i,t} \right) \qquad [14]$$

$$\sum_{i=1}^{6} z^j_{i,t} = \overline{Z}^j \qquad [15]$$

$$z^j_{i,t} \leq \sum_{k=1}^{5} z^j_{k,t-1} \text{ with } i \neq k \quad \forall i,k = 1,....,5 \qquad [16]$$

$$\sum_{j=1}^{2} \overline{Z}^j \cdot n^j = H \qquad [17]$$

The SB is defined as the total incomes from production activities in the region minus the sum of the private production costs and the public costs resulting from the control program to manage teosinte infestations that have not been considered by farmers. In order to capture these public costs we formulate a linear function *D(·)*, which depends on the number of hectares under control strategy *i* by each type of farmers *j*. The function incorporates the information on actual spending from the CSCV in affected areas (CSCV, 2017).[6] The public costs function is defined as follows:

$$D(z^j_{i,t}) = b^j_0 + b^j_{i,1} \cdot z^j_{i,t} \qquad [18]$$

where b^j_0 represents a fixed cost (in €) due to establishing the control program (divulgation, research on plant biology, etc), and $b^j_{i,1}$ is a variable cost which depends

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[6] The control program includes the monitoring of more than 7,000 ha of crops in the areas where the presence of teosinte was detected.

on control strategy i (in €·ha^{-1}) and is related with the amount of land under control (surveys in infested plots, monitoring farmer' strategy, etc). It is assumed that the first derivative of function $D(\cdot)$ is positive ($D'>0$) when control strategies include corn crop, i.e. $i=1,2,3$. In the case of rotations ($i=4,5,6,7$), then $D'<0$. This means that the costs of monitoring the infested areas increase when corn crop is maintained in fields but decrease when rotations are introduced. The values of function coefficients and economic parameters of the model and their sources are included in Table 4.

Table 4: Economic parameters of the model

Parameters	Value	Description	Source
ci (€·ha^{-1}) $i=1,4,5,6,7$	0	Control costs	Pardo et al. (2016)
$i=2$	547		
$i=3$	142.8		
p (€·t^{-1})	152.3	Market price of corn	Lonja del Ebro (2011-2015)
b_0	1600	Coefficients of public costs function	Pardo et al. (2016)
$b_{i,1}$; $i=1,2,3$	134.43		
$i=4,5,6,7$	-25.80		
$\overline{Z}^j$ (ha) ; $j=1$	27	Area with low infestation	CSCV (2017)
$j=2$	358	Area with high infestation	
H (ha)	385	Total infested area	CSCV (2017)

Equations [13] to [15] and [17] are extended versions of equations [9] to [11] for the case of different groups of farmers. Finally, equation [16] is a crop succession restriction that affects all rotations, except for those that include alfalfa. This restriction is incorporated to the model for agronomic reasons (improvement of soil fertility, control of diseases or pests). This crop succession restriction is a mandatory measure is introduced by CSCV in the affected areas when plots are highly infested but not for plots with low infestations.

The solution of the social planner problem [equations 12 to 17] allow us to obtain the optimal choice of control strategies in the area taking into account all the private and social costs associated with the dynamics of the invasive species. Both individual and social problems were programmed with GAMS (General Algebraic Modeling System, Brooke et al., 1998) and solved with the CONOPT2 algorithm.

3. Results

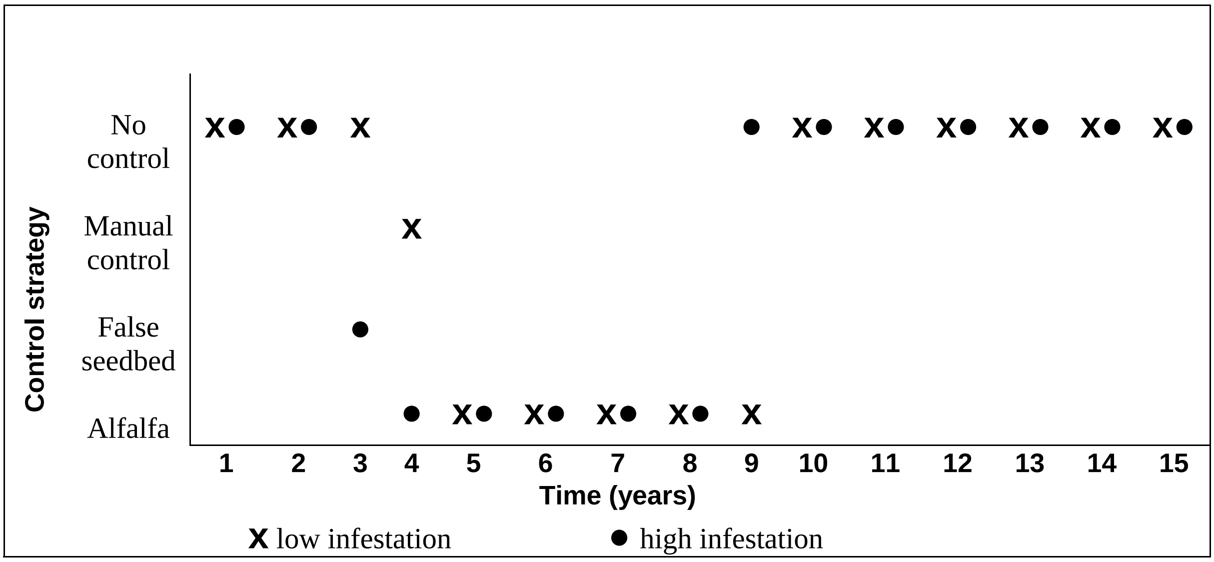
3.1. The optimal individual farmer decision

The individual farmer problem defined in equations [8] to [11] is solved to provide the optimal decision rule for farmers with low and high initial infestation degrees. These optimal decisions are specified in a ‘package’ of control measures that can be used to tackle the individual problem each year depending on the current weed density and seed bank.

Figure 4 shows the optimal control measures suggested by the model for the individual farmer problem. From the economic point of view, farmers with low infestation levels would select a no control strategy during the first three years, and then adopt manual control during year four. The corn crop is then substituted by alfalfa for five years and then the farmer would return to the corn mono-cropping in the tenth year.

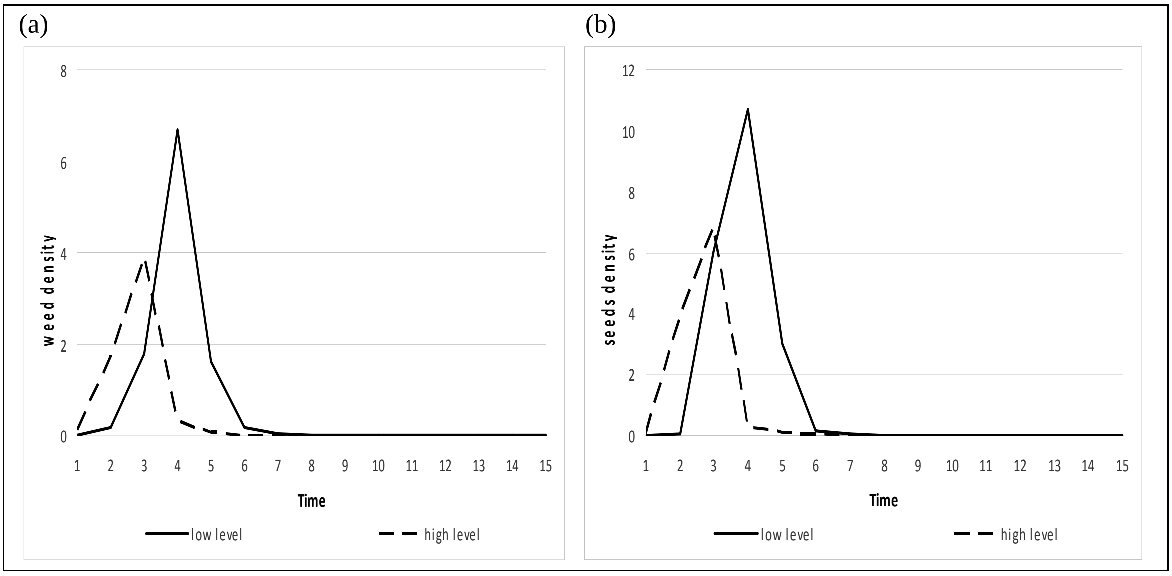
When farmers have highly-infested plots, the model suggests that they would select no control during the first two years, false seedbed technique in the third year followed by alfalfa during its total cropping cycle. The corn mono-cropping would be restored from year nine since rotations are not mandatory.

Figure 4: Optimal control strategies of individual farmer under different initial infestation incidence.



These decisions maximize benefits and they also result in optimal transitions for state variables (w_t and s_t), i.e. the relationship between the state at period *t* and the state at *t+1* when control strategies are employed. Figure 5 illustrates the optimal weed and seed densities path under low and high infestations if the optimal control strategies are followed by an individual farmer.

Figure 5: Optimal trajectory of the state variables for the representative farmer problem: weed density (a) and seed density (b) with optimal control strategies.

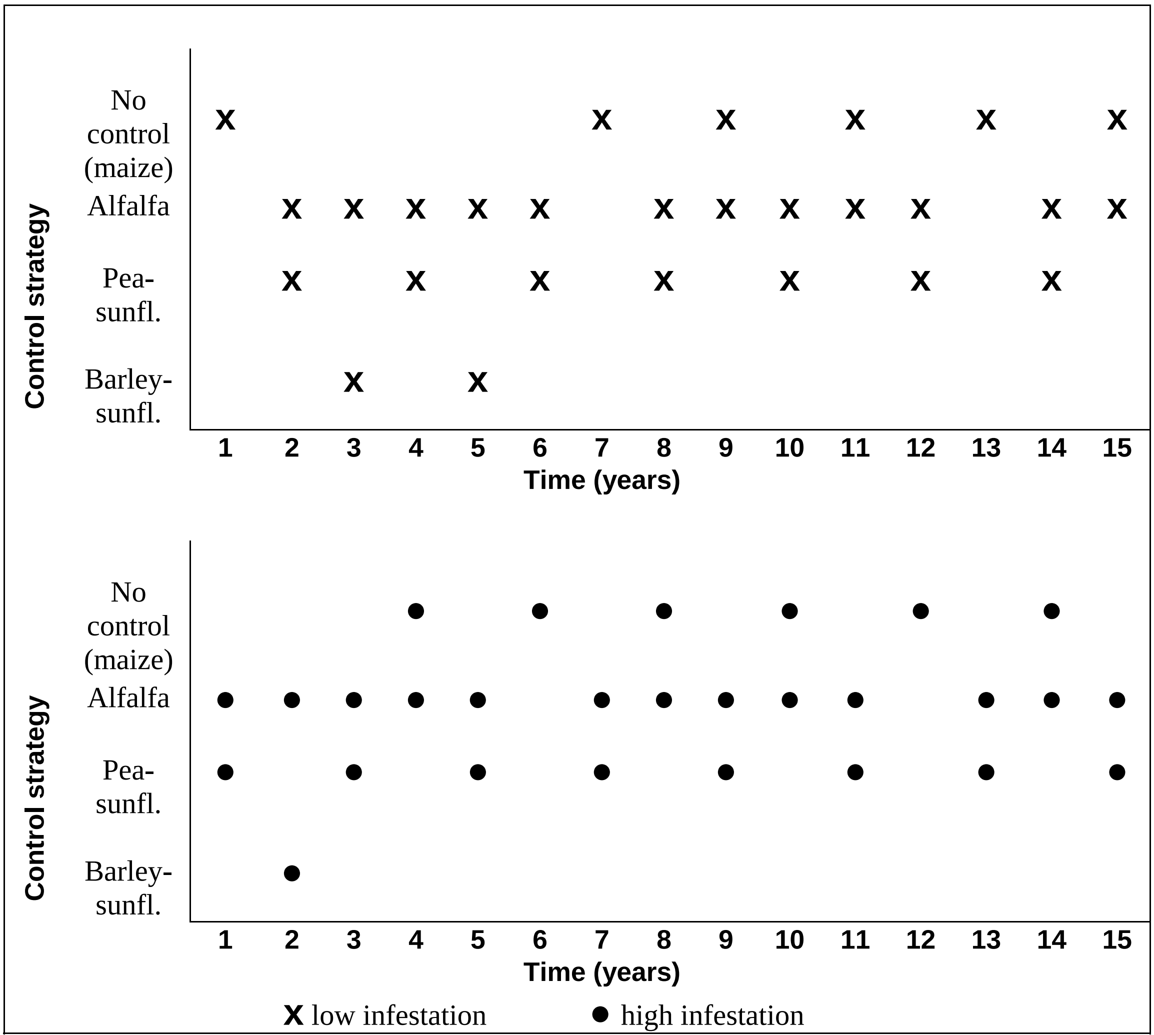


Trajectories for the state variables indicate that farmers owing plots with low infestation levels tend to adopt rotations later than those owing plots with high initial infestation levels. This causes that weed and seed density to grow up to period five, when rotation with alfalfa is introduced. In contrast, highly-infested plots adopt the alfalfa rotation one year earlier, which allows the elimination of invasive species already in the eighth period.

3.2. The optimal social control strategies

Figure 6 presents results for the optimal set of control measures when the social problem is solved. In the case of plots with low infestation levels, the model suggests that rotations are adopted in the second year, after the first period of no control. Half of the infested area (13.5 ha) would then be devoted to alfalfa which is a crop that will remain for five years in field. The rest of the area will rotate with pea-sunflower or barley-sunflower until period seven, when fields could return to corn crop since weeds and seed bank have been eradicated by then. In contrast, results suggest that fields with high levels of infestation should adopt rotations starting in the first year of the period and could return to corn crop in half the area (179 ha) by the fourth year.

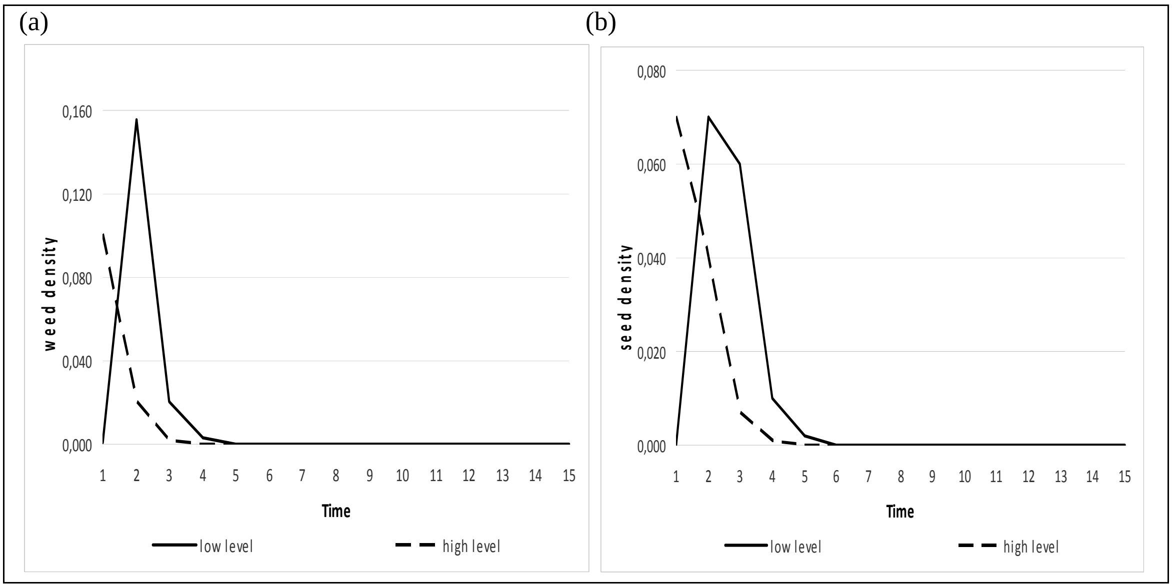
Figure 6: Optimal control strategies for the total area w.r.t. infestation degree[*]



[*] Symbols in two cells in the same year indicate that half of the total area is dedicated to each strategy.

Figure 7 illustrates the optimal trajectories of state variables (i.e., weed and seed densities) in the case of adopting the optimal control strategies from the social problem point of view. In this case, plots with low infestation levels would be permitted to attain weed density of 0.15 plants·m^{-2} which is considered a high level of infestation. Next, alfalfa would occupy half the area and rotations with annual crops would occupy the rest of the area until teosinte is eradicated in period five. Under set of optimal control strategies, the seed bank is totally eliminated in period six, when maize crop could be planted again. The evolution of weeds for the plots with high infestation decreases until total eradication in the fourth period, after which corn crop is planted in half the area. The seed bank would decrease until disappearing in period five.

Figure 7: Optimal trajectory of the state variables in the social problem: weed density (a) and seed density (b)


(a) (b)

3.3. Estimation of economic impacts

Economic impacts of the invasive weed can also be estimated by calculating the benefits obtained over the period for the case of no infestation and comparing them with the benefits under infestation. The evaluation of the economic losses caused by teosinte is made by computing the total discounted benefit for 15-year period and the average annual per hectare benefits. Table 5 shows the results obtained in the context of the private problem, where mono-cropping practices are permitted and also for the social problem, where rotations are mandatory.

When optimal individual control strategies are adopted by farmers, results indicate that the private annual average benefits of low- and high-infested plots is 1,045 and 1,009 €·ha^{-1} for the 15-year period, respectively. This implies a revenue reduction of 24% and

26.5% with respect to the non-infestation case (1374 €·ha^{-1}), respectively. When optimal strategies from the social point of view are adopted then these values are substantially lower, reaching 695 and 663 €·ha^{-1} for the low- and high-infestation level scenarios respectively. This implies revenue reductions of 24.4% and 27.9% with respect to the no-infestation scenario (920 €·ha^{-1}). These results explain the reluctance of farmers to adopt rotations when public costs are not considered in their behaviour (i.e. the research and monitoring costs incurred by the regulatory agency).

The impact of teosinte is quite different when public costs are taken into account. In this case, public costs for the total period yield 170,096 € (20,918 € and 149,178 € corresponding to low- and high-infestation levels, respectively), and only 5,230 € for the social problem. Interestingly, if annual average per hectare public costs is considered in the private optimization problem, then we observe that low-infested plots cause higher economic costs than highly-infested plots (51.65 €·ha^{-1} versus 27.77 €·ha^{-1}, respectively) because corn is produced during a longer in plots with initial low-infestation levels. Thus, if public costs are taken into account, then the average annual per hectare benefit from the individual strategies diminishes by 28.5% (with respect to the non infestation context, while the social strategies diminishes it by 27.7%.

The estimates for the case of non-infestation permit us calculating the total economic cost of invasive species in the infested area for the period considered, which amount to 2.26 million euros in the case of the individual strategies versus 1.4 million euros for the social optimal strategies.

According to our model, if no-control strategy is followed by a farmer, then corn production is totally lost in period four and three for the low- and high-infestation levels respectively (Figure 4) which implies private economic losses of 178,991 and 556,462 € with respect to the socially-optimal strategies. Moreover, the no-control strategy in presence of teosinte infestations increases public costs to 27,228 € for the total period (data not shown in table 5).

Table 5. Estimates of economic impacts in the study area.

	Total discounted value (in 10^3 €)		**Average annual benefit per ha (€/ha)**	
	Private problem	**Social problem**	**Private problem**	**Social problem**
(1) Benefits, No-Infestation	7,933	5,314	1,374	920
(2) Benefits, Low-Infestation Area	423.2	281.3	1,045	695
(3) Public costs, Low-infestation Area	20.9	5.2	51.6	12.9
(4) Benefits, High-infestation Area	5,418	3,562	1,009	663
(5) Public costs, High-infestation Area	149.2	-	27.8	-
(6) Benefits, Total Infested Area* (6)=(2)+(4)-(3)-(5)	5,671	3,839	982	665
(7) Losses relative to No-Infestation (7)= (1)-(6)	2,262	1,475	392	255

*The low-infestation area is 27 has, and the high-infestation area is 358 has.

4. Discussion

The definition of individual and social benefit maximization problems facilitates a comparison between the strategies currently used by farmers to control teosinte in the focal area and the socially optimal strategy. The analysis of optimal private versus social control strategies indicate that individual farmers who are not forced to introduce rotations will maintain corn crop until period six (under low infestation degree) and four (under high infestation degree) (see Figure 4). This behaviour was in fact observed in many monitored plots of the study area during the initial stages of teosinte detection in the study area: farmers with low-infested plots did not control weeds, nor used cultural controls (manual or false seedbed controls) because of high corn market prices and lack of knowledge regarding the potential competition of teosinte with corn. Afterwards, most farmers introduced rotations because the invasion was out of control and they realized that other cultural control methods were costly and ineffective.

Socially optimal control strategies require that corn is planted only in the first year with low-infestation levels; and rotations are used afterwards to avoid teosinte propagation and public costs caused to society (Figure 6). The mandatory inclusion of rotations implies that farmers in the affected area would diversify crops with half the land allocated to alfalfa and the other half allocated to rotations with winter and summer crops. This proposed behavior reduces the public costs for low-infested plots and eliminates them for highly-infested ones. These results suggest that the introduction of rotations could have prevented the teosinte propagation and the associated economic costs, as has been often claimed by scientists for other plant and pest diseases (Altieri and Liebman, 1988).

The examination of optimal trajectories obtained for weed and seed bank as a result of the optimal individual strategies application (Figure 5) shows that the total elimination of teosinte infestation in low-infested plots is attained later than in high-infested plots. The reason is that rotation strategies are adopted later in low-infestation plots because farmers expect higher benefits from adopting no-control strategies in the short-run and underestimate the potential of this weed to compete with corn. As a consequence, low-infested plots become highly-infested plots after three years of no weed control, and farmers have to adopt rotation strategies thereafter. The optimal trajectories of state variables (Figure 5) also confirm that cultural control methods do not eradicate teosinte infestations. In addition, data from experimental trials reveal that the survival of teosinte seeds is drastically reduced by crop rotations. Thus, data used in this paper regarding the survival capacity contrast with the hypothesis of long survival rate stated in Tritikova et al. (2017) and Pardo et al. (2016).

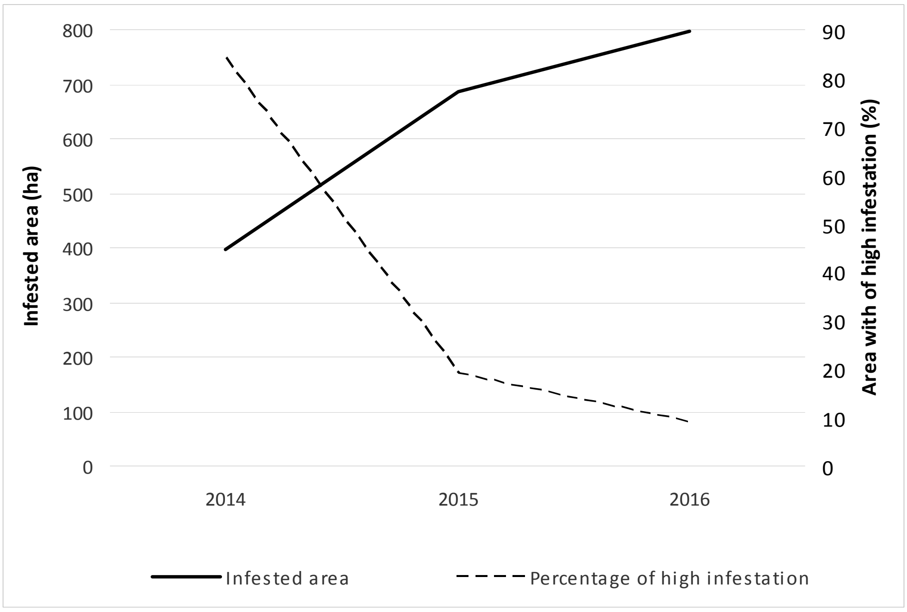
When social strategies are applied, the eradication of weeds is attained in year five because rotations are adopted earlier and public costs are taken into account (Figure 6). The comparison of private and social trajectories suggest that control methods based in false seedbed and manual means are not optimal from the social point of view since the eradication of teosinte will be only attained with rotations. Hence, this result indicates that the regulatory authority must reconsider these measures also in the case of low-infested plots.

With respect to the estimation of the economic impacts of the optimal strategies, results suggest that private strategies are not optimal from a social perspective and impose a total public cost of 170,096 €. The reason is the private optimization problem, corn is produced in infested plots during the first three or four years, given that the public costs are not considered by the farmers. In contrast, when socially optimal strategies are adopted, public costs are reduced dramatically because control strategies planting corn in the presence of an infestation are only selected in the first year, and monitoring costs are not incurred when rotations are introduced.

The economic estimates of average losses show that the socially-optimal strategies reduce private benefits by 33%. Therefore, farmers have no incentive to adopt them voluntarily in the short-run because public costs are not taken into account in their private decisions. These results highlight the importance of considering the public costs in the social problem and underscore the importance of mandatory rotations to avoid negative externalities generated in the form of public costs.

Regarding the temporal and spatial evolution of teosinte in the region, Figure 8 summarizes the available data obtained by the CSCV on the monitored area and the infestation levels from 2014 to 2016. The figure indicates that although the total infested area has increased since 2014, the number of plots with high infestation levels has decreased rapidly from 93% (358 ha) to 9% (72 ha) of the total area due to mandatory rotations. According to the data we have analyzed (consistent with CSCV technicians' assessment), the new infected areas located in 2015 and 2016 were plots with previous infestations but not yet identified in 2014. The observed temporal evolution confirms that rotations have been effective in reducing the infestation incidence in the affected plots.

Figure 8: Data on the real evolution of infested areas.



Of course, the results depend heavily on the ability of the models to represent reality and on the values of the parameters used to calibrate them. The economic model incorporates actual data obtained by the CSCV on invested areas, farmer behavior, actual evolution of the invasive species in the affected regions, and actual costs of monitoring. This feature of the model provides face validity to the economic impact estimates in the focal region of this investigation.

If some of the economic parameters change (e.g., the crop prices), the economic value of the control strategies is would change because some of the crops may become more economically attractive with respect to others. For example, higher (lower) prices for alfalfa could make this strategy more (less) desirable compared to corn and this could affect the period when corn would be substituted by this rotation. However, in order to partially avoid the excessive impact of this effect on the validity of the results, the average prices of the last five years have been used in our calculations. Hence, although the estimates of losses associated to the optimal strategy path would change, some of the conclusions on individual versus social decisions remain valid since the changes would affect all farmers in the same way and biological processes are not affected.

With respect to the population dynamics, results have been validated using data obtained in experimental trials from 2014 to 2016. These data confirm that the crop rotations are the preferred effective measure to eradicate weeds and seed bank of Spanish teosinte.

5. Conclusions

The bio-economic model developed here integrates a dynamic model of teosinte's population growth and an economic model selecting control strategies to optimise private and social benefits. The teosinte biology is characterized by its formidable ability to compete with corn and its fast propagation rates. In contrast, the survival capacity of the seed bank has proved to be limited (Cirujeda et al. 2017). The dynamic model developed here takes into account these characteristics by introducing two state variables. The specification of both private and social optimization problems allows a comparison of teosinte impacts between the actual farmers' decisions and the adoption of socially-optimal control strategies. In addition, considering of two infestation levels (low and high) allows modeling the effect of control strategies in a more realistic way and estimating the public costs of the regulatory authority.

A key result of our analysis is that controls based in false seedbed and manual control are not optimal strategies to eradicate teosinte. Therefore, the regulatory authority must reconsider recommending these control strategies in low-infested plots. Our results indicate that, if the proposed social optimal strategies are introduced in all infested plots, the invasion will be totally eradicated after six cropping periods and public costs would disappear completely thereafter. Of course, this estimate depends on farmers' compliance with the technical advice of the regulatory authority in terms of control and prevention strategies.

Our results also shed light on approaches to completely eradicate teosinte. First, it is crucial that incipient infestations are monitored, due to the fast propagation capacity of the weed. In addition, the corn mono-cropping has contributed to the rapid expansion of initial infestations in the area. Both aspects reveal the importance of farmers to be involved in the control measures, and be informed about the effects (both economic and agronomic) of not following the recommendations of the regulatory authority seriously.

Although the spatial diffusion of teosinte has not been analyzed in this paper, field observations indicate that preventive actions play an important role in the spatial dispersion of this invasive species. Therefore, future research should incorporate the spatial dimension in the model to evaluate the influence of preventive actions on the optimal control strategies. Future research can also incorporate of other externalities in teosinte control. For example, what the benefits of cleaning harvesters after using them are (in terms of reduced weed spread), considering that farmers in the same district share the same harvester.

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