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Jesper S. Schou* and Frank Jensen

Ragweed in Denmark: Should We Prevent Introduction or Mitigate Damages?

Abstract: In this article, we conduct a number of benefit–cost analyses to clarify whether the establishment of ragweed in Denmark should be prevented (pure prevention) or if the damage from this invasive species should be mitigated (pure mitigation). The main impact of the establishment of ragweed in Denmark would be a substantial increase in the number of allergy cases, which we use as a measure of the physical damage from this species. As valuation methods, we use both the cost-of-illness and benefit transfer methods to quantify the total gross benefits of these two policy actions. Based on the idea of an invasion function, we identify the total and average net benefits under both prevention and mitigation and find that all are significantly positive regardless of the valuation method. Therefore, both prevention and mitigation are beneficial policy actions, but the total and average net benefits under mitigation are larger than those under prevention in all the scenarios we consider. This finding implies that the former policy action is more beneficial. Despite this result, we propose that prevention, not mitigation, may be the proper policy because of information externalities, altruistic preferences, possible catastrophic events, and ethical considerations.

Keywords: benefit–cost analysis; invasive species; mitigation; prevention.

JEL classifications: D61; Q51; Q58

1 Introduction

Invasive species can be defined as “alien species whose introduction and spread threatens ecosystems, habitats, or species with sociocultural, economic and/or environmental harm, and/or harm to human health” (Jay et al., 2003), and these species are causing major problems around the world. For example, the Office of Technology Assessment (2013) has estimated that the damage costs from 79 invasive species

***Corresponding author: Jesper S. Schou,** Department of Food and Resource Economics, University of Copenhagen, Rolighedsvej 25, 1958 Frederiksberg C., Copenhagen, Denmark, e-mail: jss@ifro.ku.dk
Frank Jensen: Department of Food and Resource Economics, University of Copenhagen, Rolighedsvej 25, 1958 Frederiksberg C., Copenhagen, Denmark

constitute approximately 1.4 % of the gross domestic product of the USA, and Gren et al. (2009) found large damage costs in selected countries around the world.

Given these problems, policy actions may be necessary to avoid the damages caused by invasive species, and according to Marbuah et al. (2014), three potential policy strategies can be imagined: (*a*) pure prevention (only prevention); (*b*) pure mitigation (only mitigation); and (*c*) a mixed strategy (combining mitigation and prevention). From an economic point of view, a mixed strategy is often optimal if the marginal costs of preventing the establishment of and/or mitigating the damage from the last unit of an invasive species are high (see, e.g., Baumol & Oates, 1988; Hanley et al., 1997). However, in practice, either pure prevention or pure mitigation are often chosen as policy strategies (see, e.g., Marbuah et al., 2014) and to investigate whether these actions are beneficial, it is useful to conduct a benefit–cost analysis (BCA). In this article, we will consider pure prevention and pure mitigation, and for simplicity, we term these two strategies prevention and mitigation, respectively.

One potential invasive species in Denmark is ragweed (*Ambrosia artemisiifolia*), which is a native species in North America and is classified as an invasive species in Europe. Ragweed is at risk of being established in Denmark but has not yet entered the country (Danish Nature Agency, 2014). The main impact of the establishment of ragweed in Denmark would be a substantial increase in the number of pollen allergy cases (Anzivino et al., 2011). Based on the existing literature (Asthma Allergy Denmark, 2014; Steinback & Ribes, 2014), we estimate that ragweed will generate 100,000 additional allergy cases if it becomes established in Denmark and reaches a steady-state equilibrium. Because pollen allergies can be treated, mitigation is a possible policy action. To prevent ragweed establishment, a content threshold in birdseed is fixed in an EU directive (European Commission, 2011). In 2012 and 2013, the Danish Veterinary and Food Administration held a campaign to control ragweed, demonstrating that imported birdseed is the only source for its introduction in Denmark. Because there are only a few birdseed importers in the country, prevention is also a feasible policy action.

The purpose of this article is to conduct a number of BCAs to clarify whether the potential establishment of ragweed in Denmark should be prevented or the damage from the species should be mitigated. For both pure prevention and pure mitigation, we use the number of allergy cases as a measure of the physical damage, and cost-of-illness (avoided cost) and benefit transfer methods are used to value the net benefits of preventing and mitigating this damage. Due to considerable uncertainty, we operate with a benchmark case and upper/lower bounds for all included parameters. Our analysis departs from the idea of an invasion function for establishment of ragweed in Denmark, and in the main part of the article, we use a linear specification. However, we also investigate the robustness of our results by using a logistic specification of the invasion function. Furthermore, due to the way the net benefits are valued, the harm from treated allergies compared to no allergies is not taken into account. Even though it can be discussed, we choose to include the harm from treated allergies in the net benefits of prevention, and taking this factor into account may increase these net benefits. We identify critical levels for the harm from treated allergies by using a break-even condition where the net benefits under prevention and mitigation are identical.

We show that for ragweed in Denmark, the total and average (discounted) net benefits under both prevention and mitigation are likely to be positive in all the considered scenarios, implying that both policy actions are beneficial. However, we also show that the total and average net benefits under mitigation are likely to be larger than under prevention, implying that the former policy strategy is more beneficial. Despite this result, we argue that prevention is the proper policy strategy because of information externalities, altruistic preferences, possible catastrophic events, and ethical considerations.

There is a very limited amount of literature conducting BCA of policy strategies for addressing the problems with invasive species (Panzacchi et al., 2007; Rajmis et al., 2016; Reyns et al., 2019). Although it can be discussed whether our BCA study of ragweed in Denmark can be generalized to other invasive species, we address, at least, four major shortcomings in this literature: (*a*) the total and average net benefits of preventing the establishment of invasive species (prevention) are rarely identified (Beck, 2012; Naylor, 2000). To address this issue, we calculate the total and average net benefits from preventing the introduction of ragweed in Denmark; (*b*) even though ex ante considerations are important (see, e.g., Horan et al., 2018), they are seldom incorporated in BCA studies of invasive species management (see, e.g., Marbuah et al., 2014). In this article, we conduct an ex ante evaluation of policy alternative actions since ragweed has not yet been established in Denmark, so this research topic is also investigated; (*c*) although there is significant uncertainty regarding the physical and economic impact of invasive species (Epanchin-Nil & Hastings, 2010; Simms & Finnoff, 2013; Horan et al., 2018; Hanley & Roberts, 2019), this uncertainty is not normally considered in BCAs (see, e.g., Born et al., 2005). By considering upper/lower bounds for all included parameter values and alternative specifications of the invasion function, we also address this issue; and (*d*) the total and average net benefits under alternative policy actions are seldom compared (see, e.g., Perrings et al., 2000; Born et al., 2005). Because we investigate the total and average net benefits under prevention and mitigation, we also compare alternative policy strategies.

The remainder of the article is organized as follows. In Section 2, some theoretical issues are summarized, whereas Section 3 provides an overview of a number of practical assumptions behind the analyses in the article. In Section 4, the results of the BCAs are presented and the policy implications are discussed in Section 5. Section 6 concludes the article.

2 Theoretical considerations

In this section, we use economic theory to discuss how the net benefits of pure prevention and pure mitigation can be calculated, and we begin with the fact that although ragweed has not yet been established in Denmark, the plant would spread rapidly upon entry (Danish Nature Agency, 2014). Following Beck (2012), we capture the establishment of ragweed with an invasion function that expresses the development of an invasive species population over time until an equilibrium is reached (a steady-state equilibrium). In this section, we provide a general characterization of an invasion function while two empirical specifications are discussed in section 3.4. To describe the invasion function, let q_{t+1} be the ragweed population at time $t + 1$ while q_t is the ragweed population at time t. Now, we assume the following relation:

$$q_{t+1} = f(q_t) \tag{1}$$

In Equation (1), $f(q_t)$ is the invasion function and we assume that (on the adjustment path toward a steady-state equilibrium) a large ragweed population at a given point in time will generate a large population in the next point in time ($f'(q_t) > 0$). However, a maximum capacity for the population level is assumed to exist, and without policy interventions, this level is reached at time T. Formally, T is found by requiring that $q_{t+1} = q_t$, and we label the ragweed population fulfilling this condition as $q*$. Expressed in mathematical terminology, $q*$ is a steady-state equilibrium while $f(q_t)$ indicates an adjustment path toward this equilibrium (Conrad & Clark, 1987). An example of an invasion function is illustrated in Figure 1.

In Figure 1, we have time is on the x-axis, and the y-axis captures the ragweed population. Because ragweed has not yet been introduced in Denmark, the population is zero at the initial point in time ($t = 1$). Over time, the ragweed population develops as illustrated by the invasion function, $f(q_t)$, and at $t = T$, we reach a steady-state equilibrium ($q = q*$) where the ragweed population is constant over time (Figure 1). However, the population of an invasive species often only converges toward a steady-state equilibrium asymptotically without reaching $q*$, and if this adjustment occurs, the steady-state equilibrium can be described as $f(q_t) \to q*$ when $T \to \propto$.

Now, let us consider pure prevention and pure mitigation as two alternative policy actions to combat the impacts of ragweed in Denmark. In this section, we will describe the total gross benefits, costs, and net benefits of these two policy actions in a general way while we discuss how these benefits and costs are measured in detail in Section 3. We begin by considering the net benefits of mitigation. Here, we assume

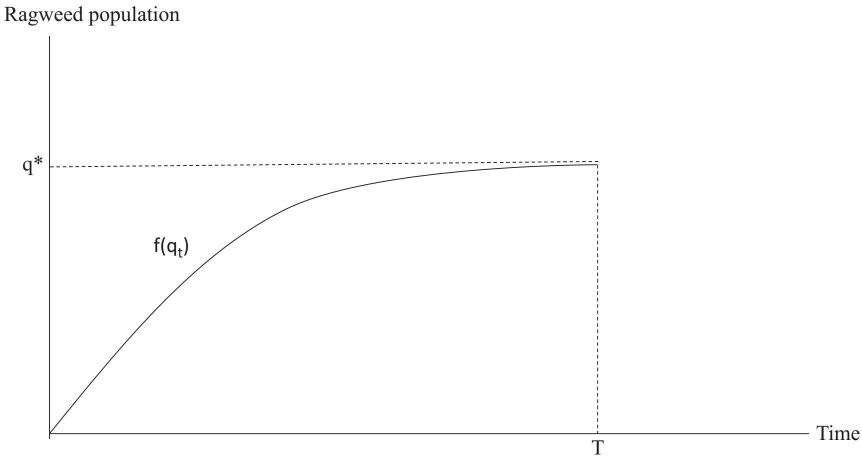

Figure 1 An example of an invasion function.

that ragweed immediately enters Denmark (at t = 1) and that the probability for introduction at this point in time is equal to one. Thus, a policy maker can only try to mitigate the damages of introduction. We denote the total gross benefits under mitigation as $B_{mt}(q_t)$ whereas the total costs under mitigation are $C_{mt}(q_t)$, where the subscript m indicates mitigation and t expresses a given time period. Thus, the total discounted net benefits under mitigation becomes:

$$NB_m = \sum_{t=1}^{S} \frac{[B_{mt}(q_t) - C_{mt}(q_t)]}{(1+r)^t} \tag{2}$$

where r is the discount rate, S is a terminal time period for measuring the costs and benefits, and NB_m is the total (discounted) net benefits under mitigation.

Note four facts in relation to Equation (2). First, in Equation (2), the gross benefits and costs depend on the ragweed population in Denmark. Second, because ragweed is assumed to enter immediately, the total gross benefits and costs can alternatively be defined by using the invasion function in Figure 1. Indeed, for each time period, we can substitute the invasion function into the benefit and cost expressions in Equation (2). Third, we assume a given time horizon for evaluating the total net benefits represented by S; therefore, the net benefits are assumed to be zero for $t > S$. Last, if mitigation is the only possible policy action, we shall mitigate if $NB_m > 0$ and do nothing provided $NB_m < 0$ (Boadway & Bruce, 1984 for a discussion of decision rules in BCAs).

Next, we consider prevention and assume that, if this policy strategy is chosen, the introduction of ragweed can be prevented with a probability of one. This

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definition implies that the gross benefit of prevention can be measured as the monetary value of avoiding a ragweed population in Denmark, and this population can be described with an invasion function. We assume that the invasion function is unaffected by the prevention strategy, implying that an identical invasion function can be used for both prevention and mitigation. This definition of the gross benefits and costs of prevention is chosen because we want to compare prevention and mitigation through BCAs. To make this comparison as simple as possible, it is useful to impose similar assumptions for the two policy strategies. The total gross benefit under prevention is labeled $B_{pt}(q_t)$, where the subscript p indicates prevention. We also need a total cost function under prevention, given as $C_{pt}(q_t)$, and the total discounted net benefits under prevention become:

$$NB_p = \sum_{t=1}^{S} \frac{\left[B_{pt}(q_t) - C_{pt}(q_t)\right]}{(1+r)^t} \tag{3}$$

In relation to Equation (3), note that the gross benefits and costs depend on the ragweed population in Denmark, and we can substitute the invasion function in Equation (1) into the cost and benefit functions for each time period. Furthermore, we assume a given time horizon for evaluating the total net benefits represented by S, so the net benefits are assumed to be zero for $t > S$.

In this article, we assume that r and S are identical when applying Equations (2) and (3) to make NB_p and NB_m directly comparable. If prevention is the only policy action, it shall be chosen if $NB_p > 0$, whereas nothing should be done provided $NB_p < 0$. If a manager can choose between prevention and mitigation, we shall choose prevention if $NB_p > NB_m$, whereas we shall mitigate provided $NB_m > NB_p$. Note that since ragweed has not yet been established in Denmark, NB_m and NB_p are ex ante total net benefits. Thus, by comparing NB_p and NB_m, we conduct a full ex ante BCA of two pure policy actions for addressing the problem of an invasive species.

In Section 3 below, we discuss how the invasion function and parameter values for calculating NB_p and NB_m are determined for ragweed in Denmark, whereas Section 4 presents the results of these calculations of the total net benefits. However, we also calculate the average, yearly (discounted) net benefits under prevention and mitigation, defined as $AB_p=NB_p/S$ and $AB_M=NB_M/S$, respectively. Because S is identical under prevention and mitigation, the decision criteria for the total net benefits mentioned above also hold when investigating AB_p and AB_M, which we label the average net benefits under prevention and mitigation, respectively.

In the introduction, we mentioned that pure prevention, pure mitigation, and a mixed strategy can be used to address the problems with invasive species, and now we will briefly discuss how an optimal mixed strategy can be determined for ragweed in Denmark. Here, it is useful to follow, for example, McCarthy et al. (2001), Leung et al. (2002), and Finnoff et al. (2005) and construct a stochastic dynamic programming model. In this model, we can let the development of the ragweed population depend on the mitigation and prevention efforts. Furthermore, a probability can be assigned to invasion in a given time period that may depend on the prevention effort. By solving this problem, we reach an optimal level of prevention and mitigation effort, and these effort levels may change over time on an adjustment path toward a steady-state equilibrium. The optimal prevention and mitigation efforts represent a first-best optimum, and the two effort levels will be correlated (interrelated). However, we will only investigate pure mitigation and pure prevention in this article, so we assume that the two policy strategies can be treated separately. From the introduction, we have argued that pure mitigation and pure prevention are commonly used in practical policy, and these two strategies represent a second-best optimum.

3 Measuring the net benefits

Based on the considerations in Section 2, we now discuss how to measure the total and average net benefits under the prevention and mitigation of ragweed invasion in Denmark. Tables 1–3 provide an overview of the parameter values used in the calculations.

For all parameter values, a benchmark case and upper/lower bounds are identified (Tables 1–3), but it is useful to discuss several considerations regarding their selection, which is done in the following subsections. Furthermore, we discuss empirical specifications of the invasion function from Figure 1, and how the costs and benefits under prevention and mitigation can be identified. Finally, by using the model from Section 2, we investigate how the harm from treated allergies can be taken into account.

3.1 Ragweed population

Following the theoretical model in Section 2, we must measure the ragweed population at each point in time if this species were to be introduced in Denmark.

Table 1 General parameter values.

Parameter	Scenario	Value
Allergy cases	Benchmark	100,000
Steady-state equilibrium, q^* (number of cases)	Upper and lower bounds	150,000 and 50,000
Adjustment time	Benchmark	10
Steady-state equilibrium, T (number of years)	Upper and lower bounds	15 and 5
Time horizon, S (number of years)	Benchmark	50
	Upper and lower bounds	75 and 25
Discount rate, r (%)	Benchmark	3
	Upper and lower bounds	0, 5, and 9

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Table 2 Parameter values for the net benefits under prevention.

Measure	Parameter	Scenario	Value
Total gross benefit	Average medical cost	Benchmark	1.99
Cost-of-illness	(1000 DKK per case)	Upper and lower bounds	2.68 and 1.30
	Average staff cost	Benchmark	0.631
	(1000 DKK per case)	Upper and lower bounds	0.82 and 0.44
	Average working time	Benchmark	20
	(hours per case)	Upper and lower bounds	26 and 14
	Average leisure time	Benchmark	96
	(hours per case)	Upper and lower bounds	125 and 67
	Average cost of working time	Benchmark	0.28
	(1000 DKK per hour)	Upper and lower bounds	Lost working time
	Average cost of leisure time	Benchmark	0.143
	(1000 DKK per hour)	Upper and lower bounds	Lost leisure time
Total gross benefit	Average WTP	Benchmark	4.8
Benefit transfer	(1000 DKK per case)	Upper and lower bounds	6.2 and 3.4
Total cost	Fixed control cost	Benchmark	196
	(1000 DKK)	Upper and lower bounds	247 and 133

Table 3 Parameter values for the net benefits under mitigation.

Measure	Parameter	Scenario	Value
Total gross benefit	Average working time	Benchmark	51
Cost-of-illness	(hours per case)	Upper and lower bounds	66 and 36
	Average leisure time	Benchmark	245
	(hours per case)	Upper and lower bounds	319 and 171
Total gross benefit	Average WTA	Benchmark	52
Benefit transfer	(1000 DKK per case)	Upper and lower bounds	68 and 36
Total cost	Total treatment cost	Benchmark	Total gross benefit
	(1000 DKK)		Cost-of-illness
			Prevention
		Upper and lower bounds	Total gross benefit
			Cost-of-illness
			Prevention

The population shall be related to several damage measures if the impact of ragweed affects several damage-generating variables (multidimensional damage). However, because the main impact of having ragweed in Denmark is an increase in the number of pollen allergy cases, we can use this as a one-dimensional measure of the physical damage (Anzivino et al., 2011).

3.2 Number of pollen allergy cases

We also require information about the time path of the number of pollen allergy cases. However, because ragweed has not yet been established in Denmark, we choose to use

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the steady-state equilibrium number of pollen allergy cases caused by the potential establishment of the plant (q^*). To identify q^*, note that Burbach et al. (2009) have conducted a pan-European study showing that an average of 10 % of European citizens are allergy sensitive to ragweed, but at the same time, the incidence of allergic reactions is very heterogeneous across Europe. Specifically, the highest sensitivity rates are found where a ragweed population has already been fully established. Because a ragweed population has not yet been fully established in Sweden and the climate conditions in this country and Denmark are identical, we can use an estimate of pollen allergy cases caused by ragweed for Sweden. For Sweden, Steinback & Ribes (2014) estimate that approximately 6 % of citizens are allergy sensitive to ragweed. Because the number of citizens in Denmark in 2014 was 5,570,027 (Statistics Denmark, 2015b), this figure corresponds to a q^* value of 100,000 pollen allergy cases, and we use this number in the benchmark scenario (Table 1). Note that this number corresponds to the estimated number of allergy cases reported by Asthma Allergy Denmark (2014). However, this number is uncertain, so we also consider a lower bound of 50,000 cases and an upper bound of 150,000 cases (Table 1).

3.3 Time until a steady-state equilibrium is reached

The time period before the steady-state equilibrium number of pollen allergy cases is reached is also important. In particular, T may affect the results of a BCA (particularly for high discount rates) because the duration of the time period affects the net benefits from $t = 1$ to $t = T$. We have no information on T for Denmark, but in European countries where ragweed is a non-native species, Burbach et al. (2009) find that the time period before ragweed is fully established is approximately 10 years, and Steinback and Ribes (2014) find a similar T value for Sweden. This result is consistent with Asthma Allergy Denmark (2014), which argues that the amount of ragweed in Denmark will approach q^* reasonably quickly. Therefore, we have chosen to set T equal to 10 time periods (years) in the benchmark case, but due to the unknown value, we have also conducted calculations for a lower bound of $T = 5$ and an upper bound of $T = 15$ (Table 1).

3.4 Invasion function

We also need empirical specifications of the invasion function from Figure 1, which describe the adjustment path of the number of pollen allergy cases toward the steady-state equilibrium on 100,000 cases. Given that ragweed has not yet been established in Denmark, this function cannot be estimated using statistical procedures. However, Steinback and Ribes (2014) have assumed a linear and positively sloped invasion function until a steady-state equilibrium amount of

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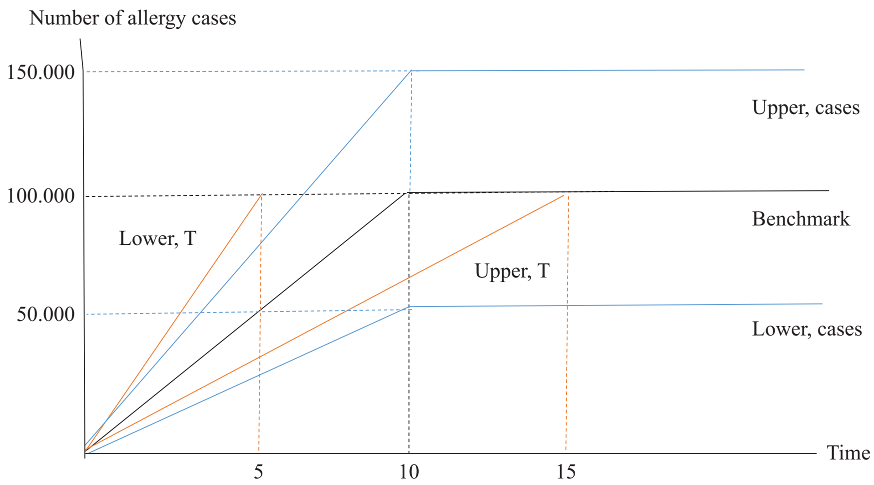

Figure 2 A linear invasion function for ragweed in Denmark.

allergy cases is reached in Sweden, and Burbach et al. (2009) use a similar specification for other European countries where ragweed is a non-native species. Therefore, we choose a linear invasion function in the benchmark case in this article, and this function is illustrated in Figure 2.

In Figure 2, we have the number of allergy cases on the y-axis, and the black line shows the linear invasion function for the benchmark case ($T = 10$ and $q^* = 100{,}000$). The red lines indicate the linear invasion functions with the upper and lower bounds for T ($T = 15$ and $T = 5$, respectively) whereas the blue lines show the linear invasion functions for the upper and lower bounds for the number of allergy cases ($q^* = 150{,}000$ and $q^* = 50{,}000$, respectively). Note that T directly affects the slope of the increasing part of the linear invasion functions whereas the number of allergy cases affects the value on the y-axis and, therefore, indirectly influence the slope.

In an online appendix (available at https://ifro.ku.dk/the-invasion-function/), we describe the method that is used to identify a time profile for the number of pollen allergy cases with the linear invasion functions in Figure 2. However, a linear specification is only one possible empirical specification of the invasion function from Figure 1. Because ragweed has not yet been established in Denmark, it is useful to investigate the robustness of our results by considering another specification. As an alternative, we have used a logistic invasion function, which is illustrated together with a linear specification in Figure 3.

The logistic function is carefully described in Conrad and Clark (1987), and details about the logistic function for ragweed in Denmark can be found in the online appendix. We only use the logistic invasion function on the benchmark parameter

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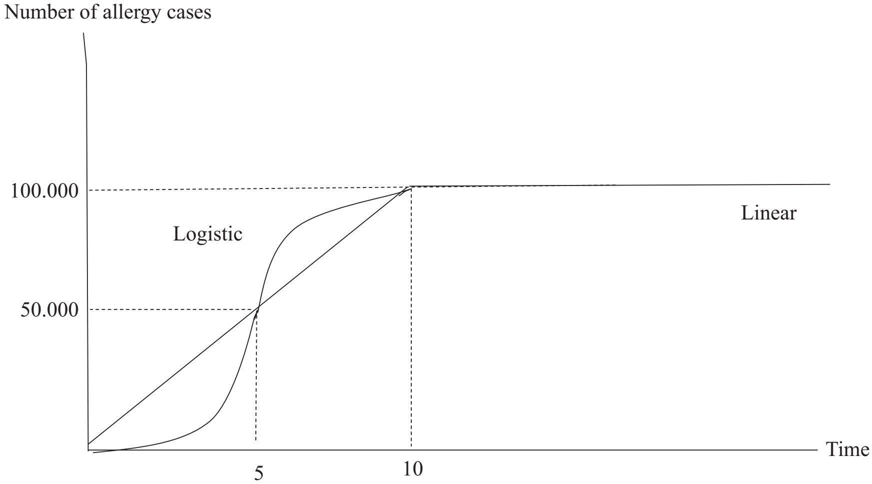

Figure 3 A logistic invasion function for ragweed in Denmark.

values from Tables 1 to 3, and two properties are important for our results: (*a*) the number of pollen allergy cases with a logistic function is lower than with a linear function for $T < 5$ while the opposite occurs for $5 < T < 10$; and (*b*) the choice between the linear and logistic function only matters for $T < 10$ because the number of allergy cases is approximately identical in a steady-state equilibrium with the two invasion functions.

3.5 Terminal time period

The terminal time period for evaluating the gross benefits and the costs (S) represents the time horizon of the BCAs. As with T, we have no information on S, but S is probably not very important for the results of the BCAs because the effect of an increase in S is reduced due to discounting (see, e.g., Pearce et al., 2006). Following Pearce et al. (2006), we choose to use $S = 50$ in the benchmark case but conduct calculations for a lower bound of $S = 25$ and an upper bound of $S = 75$ (Table 1).

3.6 Discount rate

The discount rate, r, captures the weight attached to future gross benefits and costs. In the BCA literature, the choice of a discount rate is a controversial topic (Freemann, 1993). A high discount rate implies that a large weight is attached to the total net

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benefits in a current time period compared to future time periods. We follow the recommendations of the European Commission (2015) by using $r = 0.03$ in the benchmark case, but we introduce a lower bound of $r = 0$ and two upper bounds of $r = 0.05$ and $r = 0.09$ (Table 1).

3.7 Total gross benefits under prevention

Our measure of the total gross benefits under prevention begins with two observations. First, ragweed has not yet been established in Denmark, and second, the main impact of potential ragweed introduction would be an increase in the number of pollen allergy cases. From Section 2, we assume that: (*a*) the introduction of ragweed can be prevented with a probability of one; and (*b*) the invasion function is not affected by the prevention strategy. Given these two assumptions, our definition of the total gross benefits under prevention is the monetary value of moving from no pollen allergies to treated pollen allergies. Based on this definition, we compare the following two methods for valuing the total gross benefits under prevention: (*a*) the avoided cost method (see, e.g., Pearce et al., 2006 for an introduction); and (*b*) the benefit transfer method (see, e.g., Johnston et al., 2015 for an introduction). Table 2 provides an overview of the parameter values used when valuing the gross benefits under prevention with these two methods. In the following two subsections, we discuss the assumptions behind these parameter values.

3.7.1 Avoided cost method

When using the avoided cost method, the total gross benefits under a policy action are defined as the total costs that are avoided if the action is adopted. In our case, the avoided costs arise due to treatment of pollen allergies, and valuing the total gross benefits by the costs of sickness is normally labeled as the cost-of-illness method (Tarricone, 2006 for a discussion). Petersen et al. (2005) calculate the average costs of a standard pollen allergy treatment in Denmark and show that the most important monetary consequences are related to medical costs, staff costs, lost working time, and lost leisure time. By adjusting the numbers in Petersen et al. (2005) to our case, we find that the average (annual) medical cost is 1.995 (1000 DKK per case), while the average staff cost is 0.631 (1000 DKK per case). Furthermore, treatment of pollen allergies implies a loss in the average working time of 20 hours and a loss in the average leisure time of 96 hours. The average cost of lost working time is found by using the loss in marginal productivity; here, the cost is approximated by the average wage for skilled labor of 0.28 (1000 DKK per hour; Statistics Denmark, 2015a). The average cost of lost leisure time is approximated by the average income per hour after

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taxes. With a marginal tax rate of 51.7 % (Danish Ministry of Taxation, 2014), the average cost of lost leisure becomes 0.1432 (1000 DKK per hour). These values are applied to the benchmark case (Table 2), and by using simple multiplication, we reach a measure of the gross benefit under prevention. By using simple multiplication, we assume constant marginal and average costs of medicine, staff, lost working hours, and lost leisure hours.

However, because these numbers are uncertain, we introduce upper and lower bounds by varying the average medical costs, staff costs, lost working time, and lost leisure time (Table 2). We do not consider upper and lower bounds with respect to the average cost of lost working and leisure time because these costs have the same impact on the results as the average lost working and leisure time due to the use of simple multiplication. Despite the upper and lower bounds, one major problem with the cost-of-illness method is that it is inconsistent with traditional welfare economics in the sense that the benefit measure has no relation to the preferences of the pollen allergy patients (see, e.g., Tarricone, 2006). However, a justification for using the cost-of-illness method in our case is significant uncertainty regarding the potential future impacts of ragweed in Denmark (Danish Nature Agency, 2014). Therefore, using more advanced preference-based valuation methods, such as contingent valuation or hypothetical choice (see, e.g., Pearce et al., 2006), will also generate a very uncertain estimate for the gross benefits under prevention, so we may use a simple method such as the cost-of-illness approach. Finally, the data are used on the entire adjustment path toward a steady-state equilibrium, so we must calculate the total gross benefits under prevention from the avoided pollen allergies along the entire linear invasion function in Figure 2.

3.7.2 Benefit transfer method

A theoretically correct preference-based measure of the gross benefit under prevention is the willingness-to-pay (WTP) for a pollen allergy treatment. By using a portion of the Danish population of patients with a pollen allergy as respondents, Petersen et al. (2010) find that the average WTP for a treatment is 4.8 (1000 DKK per case). For our case, one possibility is to conduct a benefit transfer by using this average WTP value. We chose to conduct a simple unit root benefit transfer, where the average WTP value from Petersen et al. (2010) is directly transferred to our case (see, e.g., Johnston et al., 2015), but this method provides an uncertain WTP estimate. Therefore, we consider upper and lower bounds by using WTP values of 3.4 (1000 DKK per case) and 0.2 (1000 DKK per case), respectively (Table 2).

One problem with the simple unit root benefit transfer method is that dissimilarities between the study region/case (the region/case from which the WTP is transferred) and the policy region/case (the region/case to which the WTP is transferred) are not considered (Johnston et al., 2015). However, significant uncertainty regarding the invasion function may justify using a simple unit root benefit transfer method. Notably, the average WTP values are used on the entire adjustment path toward the steady-state equilibrium described by the linear invasion function (Figure 2).

3.8 Total cost under prevention

As discussed in the introduction, ragweed would potentially enter Denmark through imported birdseed, and a threshold for the content of ragweed in imported seeds is defined in an EU directive (European Commission, 2011). Based on this threshold, the Danish Veterinary and Food Administration conducted a random control campaign to address the amount of birdseed in imported food in 2012 and 2013 (Danish Veterinary and Food Administration 2012, 2013). We use the total control costs of this authority and the firms involved in the campaign as a measure of the cost under prevention, although other costs may exist. We treat these costs as fixed in the sense that they are independent of the number of pollen allergy cases (or the amount of ragweed potentially established in Denmark). Thus, we assume that whether 1 seed or 1000 seeds are potentially introduced at $t = 1$, the same control costs arise. The fixed control costs of the authority and the firms are estimated as 196 (1000 DKK; Table 2), but these costs can change over time. To address this problem, we introduce upper and lower bounds for the fixed costs on 133 (1000 DKK) and 247 (1000 DKK; Table 2). We also assume that the control costs are covered for every time period from $t = 1$ until the terminal time period because the costs under prevention must be covered even if ragweed is not established in Denmark.

Modern pollen allergy medicine is normally considered very effective in the sense that patients experience almost no harm from the disease provided the treatment is appropriate (see, e.g., Calderon & Brandt, 2008; Bergmann et al., 2014; Larsen et al., 2016). Despite this fact, a problem with our measures for the net benefits of prevention and mitigation is that the harm from treated allergies compared to no allergies is not taken into account. In section 3.10, we will discuss whether the harm from treated allergies shall be incorporated in the net benefits of prevention or mitigation but assume for the moment that the harm is taken into account under prevention. Because the harm is measured along the whole linear invasion function in Figure 2, we need a simplifying assumption. Therefore, we assume that the monetary cost of the harm from treated allergies is a constant and identical share of the net benefits under prevention for all time periods.

Given this assumption, it is possible to use the model from Section 2 to obtain a measure for the net benefit of prevention when including the harm from treated allergies. By using the definition in Equation (3) we obtain that:

$$NB_p' = \sum_{t=1}^{S} \frac{\gamma\left[B_{pt}(q_t) - C_{pt}(q_t)\right]}{(1+r)^t} \tag{4}$$

where $\gamma > 1$ is a constant scaling factor capturing the size of the harm from treated allergies and NB_p' is the net benefit of prevention when including the harm. Because γ is constant and identical for all time periods, this term can be factored outside the summation sign so the net benefit of prevention can be written as:

$$NB_p' = \gamma NB_p \tag{5}$$

where NB_p is the net benefit of prevention without including the harm from treated allergies. In section 3.9.2, we will use a break-even condition to derive a critical level for γ where the net benefits under prevention and mitigation are identical.

Because we assume that γ is a constant and identical share of the net benefits of prevention, we obtain an approximation for the true net benefits when including the harm from treated allergies. One reason for this fact is that the total costs under prevention are fixed and, thereby, independent of the number of allergy cases. With fixed costs the total costs should be unaffected by γ, and this consideration is not taken into account in Equation (5). However, from Table 2, we see that the total fixed cost under prevention is very low so the approximation for the total net benefits of prevention when including the harm indicated by Equation (5) seems reasonable.

3.9 Total gross benefits under mitigation

As mentioned in Section 2, we assume that: (*a*) ragweed immediately enters Denmark; and (*b*) the probability of introduction is equal to one at this point in time. Therefore, the gross benefits under mitigation can be defined as the monetary value of moving from untreated pollen allergies to treated pollen allergies. To value the gross benefit under mitigation, we compare the following two methods: (*a*) the avoided cost method; and (*b*) the benefit transfer method. An overview of the parameter values used in the calculations of the gross benefit under mitigation is provided in Table 3. In the following two subsections, we discuss the main assumptions behind these parameter values.

3.9.1 Avoided cost method

As in section 3.7.1, we use the fact that the main impact of ragweed becoming established in Denmark is an increase in the number of pollen allergy cases. Thus, we must find the cost-of-illness of untreated pollen allergies, so the medical costs and staff costs can be disregarded. However, lost working and leisure time still exist with untreated pollen allergies, and Luskin et al. (2004) calculate these values using respondents from the USA. We choose to use these values even though it is not straightforward to apply working and leisure time information from another country to a Danish case. Converted for our case, untreated allergies result in an average lost working time of 51 hours and an average lost leisure time of 245 hours (Table 3). The lost working and leisure time shall, in principle, be adjusted for differences between Denmark and the USA in, for example, working time or the length of the pollen season. However, Lee et al. (2007) indicate that the average working time is nearly identical in Denmark and the USA while Mahhuro et al. (2007) show that the length of the pollen season is also nearly identical. Thus, correcting for differences in working time or the length of the pollen season will not affect the results of the BCAs, but we still introduce upper and lower bounds on the numbers by using average lost working times of 66 hours and 36 hours, respectively, and average lost leisure times of 319 hours and 171 hours, respectively (Table 3). By using the average cost of lost working and leisure time from prevention (Table 2), we can thus calculate the cost-of-illness of untreated pollen allergies. Note three facts in relation to these numbers. First, there is a significant increase in the average number of lost working and leisure hours when compared with treated pollen allergies (Table 2). Second, the gross benefit under mitigation will vary on an adjustment path toward a steady-state equilibrium. Last, by using the average cost of lost working and leisure time (Table 2), we assume constant average and marginal costs for both.

3.9.2 Benefit transfer method

As in section 3.7.2, we use a simple unit root benefit transfer method to find the gross benefit under mitigation. Slavin (2009) estimates the average willingness-to-accept (WTA) for not receiving pollen allergy treatment among randomly selected patients in the USA, and this average WTA value, converted to our case, is 52 (1000 DKK per case; Table 3). As in section 3.9.1, correcting for differences in the length of the pollen season between the USA and Denmark will not affect the results of the BCAs (Mahoro et al., 2007), but because an average WTA from the USA is used, we introduce upper and lower bounds by using WTA values of 52 (1000 DKK per case) and 36 (1000 DKK per case), respectively. Note two facts in relation to this measure. First, there is a large difference between the average WTP for prevention (payment given) and the average WTA for mitigation (compensation required). Although these two values should be nearly identical, it is well known that WTP and WTA measures may differ significantly (see, e.g., Kahneman & Tversky, 1979). Second, the average

WTA values shall be used on the entire adjustment path toward a steady-state equilibrium, as described by the linear invasion function in Figure 2.

3.10 Total cost under mitigation

From our definitions, it follows that the total gross benefit under prevention valued using the cost-of-illness method (section 3.7.1) is identical to the total costs under mitigation. Thus, the cost under mitigation consists of medical costs, staff costs, costs of lost working time, and costs of lost leisure time (Table 2), and we use the same upper and lower bounds as under prevention. In this cost calculation, we notably assume constant marginal and average costs of medicine, staff, lost working time, and lost leisure time. The mitigation costs must be identified for the entire linear invasion function in Figure 2.

Next, let us discuss the implications of taking the harm from treated allergies into account. In section 3.7.2, we assumed that the net benefits under prevention should include the harm from treated allergies. One implication of this assumption is that the net benefits under mitigation should not take this harm into account because we want to avoid double counting. We can use these facts to find a critical level for γ (the harm from treated allergies) where the net benefits of prevention and mitigation are identical. By using Equations (2), (5), and a break-even condition, we reach that:

$$NB_M = NB_p' = \gamma NB_p \tag{6}$$

By sharing all terms in Equation (6) with T and reorganizing we obtain:

$$\gamma = \frac{AB_M}{AB_p} \tag{7}$$

where AB_p is the average net benefit of prevention without including the harm from treated allergies. According to Equation (7), we can find a critical level for the scaling factor measuring the harm from treated allergies as the relation between the average net benefits under mitigation and prevention (without including the harm under treated allergies). In section 4.4, we report a benchmark value and upper/lower bounds for this critical level of γ.

Let us also discuss whether the harm from treated allergies should be incorporated in the net benefits of prevention or mitigation. If the harm is included in the net benefits of prevention, this strategy becomes more beneficial, while mitigation becomes less beneficial if the harm is included in the net benefits of this policy strategy. However, from Equation (6), it clearly does not matter whether the harm from treated allergies is included in the net benefits under prevention and mitigation if the two policy strategies are compared. Furthermore, the net benefits of prevention are measured by using treated allergies as a point of departure while no allergy is used under mitigation. Due to these definitions, it is natural to include the harm from treated allergies in the net benefits under prevention.

4 Results

In this section, we present the results of BCAs under mitigation and prevention. In sections 4.1 and 4.2, we present the results for the benchmark case and the upper/lower bounds for all parameter values, respectively. Section 4.3 contains the results when using a logistic invasion function while we discuss the critical level for the harm from treated allergies in section 4.4.

4.1 Benchmark case

Table 4 shows the main results of the BCAs under prevention and mitigation in the benchmark case.

We find that the total gross benefit under mitigation valued by both the cost-of-illness and benefit transfer methods is larger than that under prevention (Table 4). The explanation for this result is a large increase in the average number of lost working and leisure hours and the average WTP/WTA when moving from prevention to mitigation. However, the total costs under mitigation are also larger than under prevention (Table 4). In fact, as noted in section 3.10, the total costs under mitigation (with both valuation methods) are identical to the total gross benefits under prevention measured by the cost-of-illness method, whereas the total costs under prevention are equal to the fixed control costs (section 3.8). Furthermore, the total and average net benefits under both prevention and mitigation are significantly

Table 4 The benchmark case.

	Prevention		Mitigation	
Measure	**Cost-of-illness**	**Benefit transfer**	**Cost-of-illness**	**Benefit transfer**
Total gross benefit (1000 DKK)	49,440,718	10,829,794	110,965,591	117,322,771
Total cost (1000 DKK)	5078	5078	49,440,718	49,440,718
Total net benefit (1000 DKK)	49,435,639	10,824,716	61,524,873	67,882,053
Average net benefit (1000 DKK)	988,712	216,494	1,230,497	1,357,641
Prevention/mitigation (%)	80	16	–	–

positive, leading to the result that one of the policy actions shall be adopted (Table 4). However, the total and average net benefits under mitigation are larger than under prevention as valued with both the cost-of-illness and benefit transfer methods. We also find that if the cost-of-illness method is used, the total and average net benefits under prevention in relation to mitigation constitute 80 %, whereas the total and average net benefits under prevention in relation to mitigation only constitute 16 % if a benefit transfer method is used (Table 4). To summarize these results, the benchmark case indicates that mitigation may be preferred over prevention.

4.2 Upper and lower bounds

However, a natural question is whether this result is robust to changes in the parameter values used for calculating the total and average net benefits under the two policy actions. To investigate this issue, we present the results for the upper and lower bounds of all parameter values below. The results for the general parameter values (apart from the discount rate) are shown in Table 5.

When considering the results for the adjustment time, T, we note that an increase in T will decrease the average net benefits measured with both valuation methods under both policy actions (Table 5). The explanation for this result is that an increase in T implies that it takes a longer time to reach a steady-state equilibrium. Thus, the total net benefits in the first time periods decrease, implying a reduction in the average net benefits. However, the average net benefits under prevention in relation to mitigation (with both valuation methods) constitute approximately the same share for all values of T. This result occurs because the adjustment time affects the average net benefit under prevention and mitigation identically.

Furthermore, the average net benefits under mitigation and prevention valued with both methods increase with the number of pollen allergy cases in the steady-state equilibrium (Table 5) because an increase in q^* implies that the total gross benefits increase under both policy actions. Under mitigation, the increase in the total gross benefit is counteracted by an increase in the total costs. However, the increase in the total gross benefits due to an increase in q^* is so large that it outweighs the increase in the total cost, leading to an increase in the average net benefits under mitigation. Indeed, the average net benefit under prevention in relation to mitigation is virtually unaffected by the increase in q^* despite the increase in the total costs under mitigation (Table 5).

Finally, we consider the results of the BCAs when varying the time horizon, S. Here, we see that the average net benefits under both prevention and mitigation

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Table 5 Upper and lower bounds for the general parameter values.

Parameter	Scenario	Measure	Prevention		Mitigation	
			Cost-of-illness	**Benefit transfer**	**Cost-of-illness**	**Benefit transfer**
	Benchmark	Average net benefit (1000 DKK)	988,712	216,494	1,230,497	1,357,641
		Prevention/mitigation (%)	80	16	–	–
Adjustment time, T (number of years)	Lower bound ($T = 5$)	Average net benefit (1000 DKK)	1,086,231	237,855	1,351,851	1,491,533
		Prevention/mitigation (%)	80	16	–	–
	Upper bound ($T = 20$)	Average net benefit (1000 DKK)	819,552	179,440	1,019,991	1,125,384
		Prevention/mitigation (%)	80	16	–	–
Allergy cases, $q*$ (number of cases)	Lower bound ($q* = 50{,}000$)	Average net benefit (1000 DKK)	494,306	101,896	615,249	678,821
		Prevention/mitigation (%)	80	15	–	–
	Upper bound ($q* = 150{,}000$)	Average net benefit (1000 DKK)	1,431,200	324,792	1,845,460	2,036,461
		Prevention/mitigation (%)	78	16	–	–
Time horizon, S (number of years)	Lower bound ($S = 25$)	Average net benefit (1000 DKK)	1,248,514	273,372	1,553,846	1,714,401
		Prevention/mitigation (%)	81	16	–	–
	Upper bound ($S = 75$)	Average net benefit (1000 DKK)	775,186	169,741	944,751	1,064,436
		Prevention/mitigation (%)	82	16	–	–

Table 6 Upper and lower bounds for the discount rate.

			Prevention		Mitigation	
Parameter	**Scenario**	**Measure**	**Cost-of-illness**	**Benefit transfer**	**Cost-of-illness**	**Benefit transfer**
	Benchmark	Average net benefit (1000 DKK)	988,712	216,494	1,230,497	1,357,641
		Prevention/mitigation (%)	80	16	–	–
Discount rate, r	Lower bound ($r = 0$)	Average net benefit (1000 DKK)	2,037,734	446,206	2,536,032	2,798,072
		Prevention/mitigation (%)	80	16	–	–
	Upper bound ($r = 5$)	Average net benefit (1000 DKK)	669,697	146,637	833,478	919,594
		Prevention/mitigation (%)	80	16	–	–
	Upper bound ($r = 9$)	Average net benefit (1000 DKK)	364,704	79,851	453,900	500,806
		Prevention/mitigation (%)	80	16	–	–

(measured with both valuation methods) decrease with an increase in S (Table 5). This result arises because an increase in the time horizon has two effects on the average net benefits: (a) an increase in S implies that an increasing number of future total net benefits are considered, but due to discounting, these are given a low weight when the total net benefits are calculated; and (b) an increase in S increases the number of time periods over which the average net benefits are defined. When these two effects are combined, an increase in S will clearly lead to a decrease in the average net benefits. However, the two effects will influence the average net benefit under mitigation and prevention in an identical way, so the average net benefit under prevention relative to mitigation (measured by both methods) is virtually unaffected by a change in S (Table 5).

Table 6 depicts the results for the lower and two upper bounds for the discount rate, r.

We obtain that an increase in r implies a lower average net benefit under mitigation and prevention with both valuation methods (Table 6). This result occurs because an increase in the discount rate implies that a lower weight is attached to the future total net benefits and this will generate a lower average net benefit. In fact, the decrease in the average net benefits is large even with a small increase in r, thus confirming the result that an increase in r has a significant impact on the results of a BCA. However, we also find that the average net benefits under prevention in relation to mitigation are almost unaffected by a change in r (Table 6) because a change in the discount rate affects the average net benefits under prevention and mitigation as valued with both methods identically. Thus, when comparing two or more policy actions, r does not necessarily affect the ranking of these actions.

Table 7 presents the results for the upper and lower bounds with respect to the cost-of-illness values.

We find that an increase in the average medical costs will increase the average net benefits under prevention as valued with the cost-of-illness method (Table 7). This result is a natural implication of the fact that an increase in average medical costs will increase the avoided costs under prevention. Furthermore, an increase in the average medical costs will decrease the average net benefits under mitigation valued by both methods (Table 7) because the total gross benefit under mitigation is unaffected by a change in the average medical costs (valued with both the cost-of-illness and benefit transfer methods). However, the gross benefit under prevention measured by the cost-of-illness method is identical to the cost under mitigation, so the average net benefit under mitigation decreases. However, although an increase in the average medical costs will increase the average benefit under prevention in relation to mitigation, this change is minor (Table 7). A change in the average staff costs will generate results in the same direction as the average medical costs, but the size of the effect is lower because the former costs are lower than the latter.

Table 7 Upper and lower bounds for the cost-of-illness values.

Parameter	Scenario	Measure	Prevention		Mitigation	
			Cost-of-illness	**Benefit transfer**	**Cost-of-illness**	**Benefit transfer**
	Benchmark	Average net benefit (1000 DKK)	988,712	216,494	1,230,497	1,357,641
		Prevention/mitigation (%)	80	16	–	–
Average medical cost (1000 DKK per case)	Lower bound (1.30)	Average net benefit (1000 DKK)	957,144	Unchanged	1,262,066	1,389,210
		Prevention/mitigation (%)	76	16	–	–
	Upper bound (2.69)	Average net benefit (1000 DKK)	1,020,237	Unchanged	1,198,974	1,326,117
		Prevention/mitigation (%)	85	16	–	–
Average staff cost (1000 DKK per case)	Lower bound (0.44)	Average net benefit (1000 DKK)	980,184	Unchanged	1,239,026	1,366,710
		Prevention/mitigation (%)	79	16	–	–
	Upper bound (0.83)	Average net benefit (1000 DKK)	997,241	Unchanged	1,221,969	1,349,113
		Prevention/mitigation (%)	82	16	–	–
Average working time (hours per case)	Lower bounds (14 and 36)	Average net benefit (1000 DKK)	913,717	Unchanged	1,118,003	1,432,637
		Prevention/mitigation (%)	82	15	–	–
	Upper bounds (26 and 66)	Average net benefit (1000 DKK)	1,063,709	Unchanged	1,342,992	1,282,645
		Prevention/mitigation (%)	79	16	–	–
Average leisure time (hours per case)	Lower bounds (67 and 171)	Average net benefit (1000 DKK)	801,321	Unchanged	941,010	1,545,033
		Prevention/mitigation (%)	85	14	–	–
	Upper bounds (125 and 319)	Average net benefit (1000 DKK)	1,176,104	Unchanged	1,522,570	1,170,250
		Prevention/mitigation(%)	77	18	–	–

An increase in the average lost working and leisure hours will also increase the average net benefits under both prevention and mitigation valued by the cost-of-illness method (Table 7). Under prevention, an increase in the average lost working and leisure hours will increase the total avoided costs. However, under mitigation, two counteracting effects exist when cost-of-illness is used as the valuation method: (*a*) an increase in the average lost working and leisure hours will increase the total costs under mitigation; and (*b*) an increase in the average lost working and leisure hours will increase the total gross benefit under mitigation as valued with the cost-of-illness method. Because (*b*) dominates (*a*), an increase in average lost leisure and working hours will increase the average net benefits under mitigation. In fact, the latter effect is so strong that an increase in the lost average working and leisure hours will decrease the average net benefits under prevention relative to mitigation. This result can be explained by a significant increase in the average lost leisure and working hours when moving from treated to untreated pollen allergies (section 3.9.1). If the gross benefit under mitigation is measured by benefit transfer, the only effect of increasing the average lost working and leisure hours is to increase the total costs, leading to a decrease in the average net benefits. However, this effect is so small that the change in the average net benefits under prevention is very low relative to mitigation, as valued with the benefit transfer method.

Table 8 shows the results of varying the fixed control costs and average benefit transfer values.

We find that an increase in the fixed control costs will decrease the average net benefits under prevention (valued with both methods) but will leave the average net benefits under mitigation unchanged (Table 8). However, a change in the fixed control costs only implies a very small change in the average net benefits under prevention. This result can also be seen from an approximately identical average net benefit under prevention compared to mitigation, and this conclusion holds even though the fixed control costs shall already be covered from the initial time period.

An increase in the average WTP under prevention also implies a large increase in the average net benefits of this policy but leaves the other net benefit values unchanged (Table 8). Furthermore, an increase in the average WTP under prevention generates a significant increase in the average net benefit under this policy action in relation to mitigation. Finally, an increase in the average WTA under mitigation will lead to a significant increase in the average net benefit with this policy action and leave the other average net benefits unchanged (Table 8). Indeed, an increase in the average WTA of mitigation implies a significant decrease in the average net benefit under prevention relative to mitigation.

To draw an overall conclusion from the BCAs for the upper and lower bounds of all parameter values, mitigation is preferred over prevention in all the investigated

Table 8 Upper and lower bounds for the control costs and the benefit transfer values.

			Prevention		Mitigation	
Parameter	**Scenario**	**Measure**	**Cost-of-illness**	**Benefit transfer**	**Cost-of-illness**	**Benefit transfer**
	Benchmark	Average net benefit (1000 DKK)	988,712	216,494	1,230,497	1,357,641
		Prevention/mitigation (%)	80	16	–	–
Fixed control cost (1000 DKK)	Lower bound (133)	Average net benefit (1000 DKK)	988,743	216,424	Unchanged	Unchanged
		Prevention/mitigation (%)	80	16	–	–
	Upper bound (247)	Average net benefit (1000 DKK)	988,682	216,564	Unchanged	Unchanged
		Prevention/mitigation (%)	80	16	–	–
Average WTP prevention (1000 DKK per case)	Lower bound (3.4)	Average net benefit (1000 DKK)	Unchanged	153,321	Unchanged	Unchanged
		Prevention/mitigation (%)	Unchanged	11	–	–
	Upper bound (6.2)	Average net benefit (1000 DKK)	Unchanged	279,668	Unchanged	Unchanged
		Prevention/mitigation (%)	Unchanged	20	–	–
Average WTA mitigation (1000 DKK per case)	Lower bound (36)	Average net benefit (1000 DKK)	Unchanged	Unchanged	Unchanged	635,655
		Prevention/mitigation (%)	Unchanged	34	–	–
	Upper bound (52)	Average net benefit (1000 DKK)	Unchanged	Unchanged	Unchanged	2,626,110
		Prevention/mitigation (%)	Unchanged	8	–	–

Table 9 The benchmark case with a logistic growth function.

	Linear invasion function				Logistic invasion function			
	Prevention		Mitigation		Prevention		Mitigation	
Measure	Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer
Total gross benefit (1000 DKK)	49,440,718	10,829,794	110,965,591	117,322,771	48,116,826	10,539,801	107,994,225	114,181,117
Total cost (1000 DKK)	5078	5078	49,440,718	49,440,718	Unchanged	Unchanged	48,116,826	48,116,826
Total net benefit (1000 DKK)	49,435,639	10,824,716	61,524,873	67,882,053	46,823,297	10,534,714	61,165,841	66,643,51
Average net benefit (1000 DKK)	988,712	216,494	1,230,497	1,357,641	936,466	210,694	1,223,317	1,321,817
Prevention/mitigation (%)	80	16	–	–	77	14	–	–

scenarios. Therefore, the basic result from section 4.1 is robust to changes in the parameters and values. Furthermore, varying the parameter values generates a very small change in the average net benefits under prevention in relation to mitigation as measured by both the cost-of-illness and benefit transfer methods.

4.3 Logistic growth function

As mentioned in section 3.4, we have also investigated the implications of using a logistic invasion function (Figure 3) instead of the linear specification (Figure 2). The results are presented in Table 9.

When using a logistic specification instead of a linear function, the gross benefits under prevention and mitigation valued with both cost-of-illness and benefit transfer decrease (Table 9). This result arises because the number of pollen allergy cases for $T < 5$ is lower with a logistic invasion function, and due to discounting, this implies that the gross benefits decrease. Under prevention, the total costs are assumed to be fixed and, thereby, independent of the specification of the invasion function. However, the total costs under mitigation are identical to the total gross benefit under prevention measured by the cost-of-illness approach so these costs are also decreased. It is obvious that the total and average net benefits under prevention decrease when using a logistic invasion function since the gross benefit decreases while the total costs are fixed. However, under mitigation, the total and average net benefits also decrease, indicating that the choice of invasion function matters more for the gross benefit under mitigation than for the total costs. However, since the total cost under prevention is unaffected by adopting a logistic invasion function while the total costs under mitigation decrease, the latter policy strategy becomes relatively more beneficial (Table 9). However, the change in the total and average net benefits when adopting a logistic specification is so small that we can conclude that the choice of functional form for the invasion function does not influence our main results. The explanation for this result is that the functional form of the invasion function only affects the number of allergy cases for $T < 10$.

4.4 Harm from treated allergies

We have also investigated the implications if the harm from treated allergies is included in the net benefit of prevention. From section 3.10, this can be accomplished by identifying a critical level for the scaling factor, which secures that the total and average net benefits under mitigation and prevention (without including the harm) are identical. The critical level of the scaling factor is given by Equation (7), and

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Table 10 Upper and lower bounds for the scaling factor for the harm from treated allergies.

Measure	Upper bound	Benchmark	Lower bound
Cost-of-illness	1.32	1.25	1.18
Benefit transfer	12.50	6.25	2.94

because of Equation (7), we can calculate the factor as the inverse of the numbers in the prevention/mitigation row in Tables 4–9. This finding implies that we can identify the scaling factor for the benchmark case and all upper/lower bounds for the parameter values in Tables 1–3. The results are reported in Table 10.

When cost-of-illness is used to measure the gross benefit under prevention (without including the harm) and mitigation, the harm from treated allergies must constitute between 18 and 32 % of the average net benefit of prevention (without including the harm) if the two policy strategies shall be equally beneficial (Table 10). The upper and lower bounds for the scaling factor with the cost-of-illness method occur when varying the average medical costs. The size of and variation in the scaling factor is much larger when the benefit transfer method is used, and the explanation for this result is that mitigation becomes relatively more beneficial when applying this method (Table 10). When using benefit transfer, the upper and lower bounds for the scaling factor are reached when investigating the implications of varying WTA under mitigation. However, as mentioned in section 3.8, modern allergy treatments are very effective so even a critical level of the scaling factor at 1.18 seems high. Therefore, mitigation is likely to be preferred over prevention even if the harm from treated allergies is taken into account.

5 Policy implications

In the CBAs we found that mitigation is preferred over prevention in the sense that the former policy action leads to a significantly higher net benefit from addressing the potential establishment of ragweed in Denmark. We now discuss this policy conclusion and at least three additional arguments favor mitigation. First, we have assumed that: (*a*) the probability of the immediate introduction of ragweed if migration is chosen is one; and (*b*) the probability of preventing the introduction of ragweed if prevention is chosen is one. Naturally, both of these assumptions are extreme, and the probabilities of both events are probably less than one for ragweed in Denmark. If the probabilities are less than one, mitigation becomes a more beneficial strategy, and this should be considered when choosing a policy strategy to address the potential problem with the introduction of ragweed.

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Second, we have also assumed that prevention cannot affect the invasion function for ragweed in Denmark, implying that we cannot: (*a*) postpone the time for the introduction of ragweed; or (*b*) change the invasion function for ragweed such that it becomes flatter before a steady-state equilibrium is reached (the equilibrium occurs at a later point in time). When relaxing these two assumptions, mitigation becomes a more beneficial strategy, and assumptions (*a*) and (*b*) are probably not satisfied for ragweed in Denmark. Thus, from a practical policy perspective, it is important to consider how the invasion function for ragweed is affected by prevention.

Last, we assume that the establishment of ragweed in Denmark only has a negative effect on the utility and welfare (Section 1). However, the establishment of ragweed (and other invasive species) in Denmark may positively influence both utility and welfare (Finnoff et al., 2005), and considering this effect makes mitigation even more beneficial.

However, at least four arguments can be mentioned for reconsidering whether mitigation is the most desirable policy action for ragweed in Denmark. First, it is well known in health economics that people underestimate the value of preventive actions (see, e.g., Mant et al., 2007; O'Connell, 2009), and this argument can be linked to the observation that many people underestimate small probabilities of uncertain events, leading to an information externality (see, e.g., Havert & Doebeli, 2004; Hertwig et al., 2004). For ragweed in Denmark, this argument implies that the average WTP of prevention is underestimated, leading to higher total and average net benefits under this policy action as measured with the benefit transfer method. Thus, when correcting for the information externality, prevention becomes a relatively more beneficial policy action for ragweed in Denmark.

Second, it is also well known that people may have altruistic preferences regarding the health of other people, implying that they may prefer that other people do not become ill (see, e.g., Olson et al., 2004; Jacobsson et al., 2005). Here, we can distinguish between two cases: (*a*) people may have a specific altruistic preference for the health of other people to whom they are closely related (such as family members and work colleagues); and (*b*) people may have a general altruistic preference for the health of other people to whom they are not closely related. Both kinds of altruistic preferences are not included in the cost-of-illness and benefit transfer calculations under both prevention and mitigation for ragweed in Denmark, and taking such preferences into account tends to make prevention relatively more desirable.

Third, there is significant uncertainty regarding the future impacts if ragweed were to become established in Denmark since a positive probability of a catastrophic event exists (see, e.g., Horan et al., 2002). For ragweed in Denmark, a catastrophic event would arise if the species population becomes out of control, leading to a dramatic increase in the number of allergy cases. In an economic model, one way to capture a catastrophic event is through huge mitigation costs. As an example, when the Spanish slug and the round goby became established in Denmark, extremely high mitigation costs were observed (Ravn, 2015). Prevention obviously becomes more beneficial for ragweed in Denmark if there is a positive probability of a very large mitigation cost (a catastrophic event).

Fourth, it can be discussed whether mitigation is an ethically acceptable policy action for ragweed in Denmark. Mitigating the damages from the establishment of ragweed when prevention is a feasible policy action is the same as arguing that giving people allergies and then curing them yields a higher net benefit than not giving people allergies. Of course, the ethical aspect of this argument has to be considered (see, e.g., Farley, 2006).

In our opinion, information externalities, altruistic preferences, possible catastrophic events, and ethical considerations may lead to the conclusion that prevention should be adopted instead of mitigation for ragweed in Denmark given that both policy strategies lead to significant and positive total and average net benefits.

6 Conclusion

In this article, we perform an ex ante comparison of the net benefits under pure prevention and pure mitigation for combating the potential establishment of ragweed in Denmark. If ragweed enters the country, the main impact would be a significant increase in the number of pollen allergy cases. Because ragweed has not yet been established in Denmark, we use an invasion function to describe the development of the ragweed population over time, and this function is incorporated in the BCAs. We mainly assume a linear invasion function until a steady-state equilibrium for the number of allergy cases is reached, but to test the robustness of our results, we also apply a logistic invasion function.

To measure the total gross benefit under prevention and mitigation for ragweed in Denmark, we use both the cost-of-illness and benefit transfer methods. Although there are numerous theoretical and empirical problems with these two methods, their application may be justified by a large uncertainty regarding the impacts if ragweed were to become established in Denmark. For the two policy actions measured with both valuation methods, the total and average net benefits of not having ragweed in Denmark are significantly positive, and this result is robust to changes in the parameter values of the BCAs. Thus, either prevention or mitigation should be used to combat the establishment of ragweed in Denmark. However, the total and average net benefits under mitigation are larger than under prevention for ragweed in Denmark, a result that is also robust to changes in the parameter values (represented by upper and lower bounds) and specification of the invasion function. Thus, mitigation seems to be more beneficial than prevention for ragweed in Denmark. However, a problem with our measures for the net benefits under prevention or mitigation is that we have not considered the harm from treated allergies compared to no allergies. To address this issue, we calculate critical levels for the harm from treated allergies where the net benefit under prevention and mitigation is identical. These critical levels are so high that it is reasonable to believe that mitigation is still more beneficial than prevention even if we take the harm from treated allergies into account. Despite these results, we argue that prevention, not mitigation, is a proper policy strategy for ragweed in Denmark because of information externalities, altruistic preferences, possible catastrophic events and ethical considerations.

An obvious question is whether our results for ragweed in Denmark hold for other invasive species. Naturally, enough, ragweed has a number of special characteristics compared to other species, which make generalization of our results problematic. These factors include the following: (*a*) preventing the introduction of ragweed in Denmark is feasible, and the costs of prevention are easy to measure; (*b*) the gross benefit of mitigation measured with both the cost-of-illness and benefit transfer methods is very large compared to the gross benefit of prevention; and (*c*) the physical impacts of ragweed in Denmark can be quantified with a one-dimensional measure represented by the number of pollen allergy cases. However, despite these characteristics, it is tempting to draw three general conclusions for invasive species management from the results in our article: (*a*) since the total and average net benefit of both policy strategies is large, establishment of many invasive species in a geographical area is very costly; (*b*) because we obtain a major difference between the total and average net benefits under prevention and mitigation in all possible scenarios, mitigation is more beneficial than prevention for many invasive species; and (*c*) despite the conclusion under (*b*), policy makers shall try to prevent the establishment of invasive species in a geographical area due to information externalities, altruistic preferences, possible catastrophic events and ethical considerations.

There are at least two major limitations to the analysis in this article. First, uncertainty regarding the impact of ragweed is only addressed by constructing upper and lower bounds for the included parameter values, and second, we do not investigate whether a mixed policy strategy is beneficial. Both of these limitations can be addressed through a stochastic programming model where: (*a*) the ragweed population depends on the effort applied to mitigation and prevention; and (*b*) the probability of invasion depends on the prevention effort. Conducting a BCA for ragweed management in Denmark using such a model constitutes an important area for future research.

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