DEPARTMENT OF FOOD AND RESOURCE ECONOMICS
UNIVERSITY OF COPENHAGEN

IFRO Working Paper

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2017 / 06

IFRO Working Paper 2017 / 06

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JEL-classification: D61, Q51, Q58

Published: June 2017

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Management of Invasive Species: Should We Prevent Introduction or Mitigate Damages?

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JEL: codes: D61, Q51, Q58.

Keywords: cost-benefit analysis, invasive species, prevention, mitigation

Abstract: In this paper, we conduct a number of cost-benefit analyses to clarify whether the establishment of invasive species should be prevented or the damage of such species should be mitigated after introduction. We use the potential establishment of ragweed in Denmark as an empirical case. The main impact of the establishment of this invasive species is a substantial increase in the number of allergy cases, which we use as a measure of the physical damage. As valuation methods, we use both the cost-of-illness method and the benefit transfer method to quantify the total gross benefits of the two policy actions. Based on the idea of an invasion function, we identify the total and average net benefit under both prevention and mitigation. For both policy actions, the total and average net benefits are significantly positive irrespective of the valuation method used; therefore, both prevention and mitigation are beneficial policy actions. However, the total and average net benefits under mitigation are larger than the benefits under prevention, implying that the former policy action is more beneficial. Despite this result, we conclude that prevention, not mitigation, shall be used because of information externalities, altruistic preferences, possible catastrophic events and ethical considerations.

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1. Introduction

Invasive species, which can be defined as “alien species whose introduction and spread threatens ecosystems, habitats or species with socio-cultural, economic and/or environmental harm and/or harm to human health”[2], are causing major problems around the world. For example, the Office of Technology Assessment (2013) has estimated that the damage costs of 79 invasive species constitute approximately 1.4% of the GDP in the United States, and Gren et al. (2009) find large damage costs of invasive species in selected countries around the world. Given these problems, policy actions may be necessary to avoid the damages caused by invasive species.[3] To investigate whether these actions are beneficial, it is useful to conduct a cost-benefit analysis (CBA).[4]

However, the existing literature conducting CBA of policy actions to combat invasive species lacks research on four major issues. First, the total and average (discounted) net benefits of preventing the establishment of invasive species (prevention) are rarely identified (Beck, 2012 and Naylor, 2000). Second, ex-ante evaluations of policy actions are seldom undertaken (see, e.g., Marbuah et al., 2014). Third, although there is significant uncertainty regarding the physical and economic impact of invasive species,[5] this uncertainty is normally not considered in CBAs (see, e.g., Born et al., 2005). Last, the total and average net benefits under alternative policy actions are seldom compared (see, e.g., Perrings et al., 2002 and Born et al., 2005). Specifically, it is important to compare the outcome under prevention with a policy in which the damages after the establishment of invasive species are mitigated (mitigation).

One potential invasive species in Denmark is ragweed (Ambrosia artemisiifolia), which grows natively 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 (Danish Nature Agency, 2014). The main impact of the establishment of ragweed in Denmark is a substantial increase in the number of pollen allergy cases. If ragweed becomes established in Denmark, it is estimated that the species will generate 100,000 additional pollen allergy cases; however, this number is uncertain (see Astma Allergi Denmark, 2014). Because pollen allergy can be treated, mitigation is a possible policy action. To prevent the establishment of ragweed, a threshold on the content of the species in bird

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[2] See Jaay et al (2003) for this definition.

[3] See, e.g., Marbuah et al. (2005) for a discussion of policy actions to combat invasive species.

[4] See ,e.g., Layard and Glaister (2012) for an introduction to CBA.

[5] See Epanchin-Nill and Hastings (2010) and Sims and Finnoff (2013) for a discussion of the impact of uncertainty on policy actions to address problems with invasive species.

seed is fixed in an EU directive (European Commission, 2011). In 2012 and 2013, the Danish Veterinary and Food Administration held a control campaign against ragweed, demonstrating that the only source for the introduction of the species in Denmark is from imported bird seed. Since there are only a few importers of bird seeds in Denmark, prevention is also a feasible policy action.

In this paper, we use the potential establishment of ragweed in Denmark as an empirical case. We contribute to the existing literature conducting CBAs of policy actions for invasive species in four ways. First, we calculate the total and average net benefits for the prevention of ragweed in Denmark. Second, we conduct an ex-ante evaluation of policy actions to combat invasive species since ragweed has not yet been established in Denmark. Third, we investigate the implications of uncertainty regarding the impact of invasive species by performing a large number of sensitivity analyses. Last, we compare the total and average net benefits under prevention and mitigation. Thus, in total, we make important contributions to the existing research conducting CBAs of policy actions to fight invasive species.

Under both prevention and mitigation, we compare the results when valuing the gross benefits with a cost-of-illness (avoided cost) method and a benefit transfer method. For both policies and valuation methods, we show that the total and average net benefits are significantly positive, implying that both prevention and mitigation are beneficial compared to doing nothing. However, in all the analysed scenarios, the total and average net benefits under mitigation are higher than under prevention, which indicates that the former is the more beneficial policy action. Despite this result, we conclude that the problems arising from the potential establishment of ragweed in Denmark should be addressed using prevention instead of mitigation because of information externalities, altruistic preferences, possible catastrophic events and ethical considerations.

The remainder of the paper is organized as follows. In section 2, theoretical issues are summarized. Section 3 provides an overview of a number of practical assumptions behind the analysis in the paper. Section 4 presents the results of the CBAs, while the policy implications are discussed in section 5. Section 6 concludes the paper.

2. Theoretical considerations

The theoretical considerations in this section begin with the fact that although ragweed has not yet been established in Denmark, the plant will spread rapidly upon entry (see Danish Nature Agency, 2014). Following Beck (2012), we capture the establishment of ragweed with an invasion function that expresses the development in the population of an invasive species over time until an equilibrium is reached (a steady-state equilibrium). To describe the invasion function, let q_{t+1} be the population of ragweed at time $t+1$ while q_t is the population of ragweed at time t. Now we assume the following relation:

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

In (1), $f(q_t)$ is the invasion function, and we assume that a large population of ragweed in a given time period will generate a large population in the next time period ($f'(q_t) > 0$). However, a maximum capacity level for the population of ragweed is assumed to exist, and without policy actions, this level is reached at time T. Formally, T is found by requiring that $q_{t+1} = q_t$, and we label the population of ragweed fulfilling this condition q^* . Expressed in mathematical terminology, q^* is a steady-state equilibrium while $f(q_t)$ indicates an adjustment path towards this equilibrium.[6] In Figure 1 below, one possible invasion function is illustrated.

Figure 1: An example of an invasion function

In Figure 1 we have time on the x-axis whereas the y-axis captures the population of ragweed. Since ragweed has not yet been introduced in Denmark, the population is zero at the initial time period ($t = 0$). Over time, the population of ragweed develops as illustrated with the invasion function, $f(q_t)$, and at $t = T$ we reach a steady-state equilibrium ($q = q^*$) where the population of ragweed is constant over time.

Now let us consider prevention and mitigation as two alternative policy actions to combat the impacts of ragweed in Denmark. In this section, we will describe the total gross benefits, the total costs and the total net benefits of these two policy actions in a general way, whereas we will discuss how these benefits and costs are measured in section 3. First, consider prevention and assume that the total gross benefit under prevention depends on the population of ragweed that would have existed without policy action.[7] We label the total gross benefit under prevention $B_{pt}(q_t)$, where the subscript p captures prevention and t express a given time period. We also need a total cost function

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[6] See Conrad and Clark (1987) for a mathematical treatment of steady-state equilibria and adjustment paths towards these within bio-economic models.

[7] See ,e.g., Marbuah et al. (2005) for a discussion of the gross benefit function under prevention.

under prevention given as $C_{pt}(q_t)$ [8] , and because ragweed has not yet been established in Denmark, the total gross benefit and costs are measured ex-ante. Now the total discounted net benefits under prevention become the following:

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

where r is the discount rate, S is a terminal time period for measuring the benefits and costs, and NB_p is the total (discounted) net benefits under prevention. Note three facts in relation to (2). First, because the total gross benefits and costs are defined for each time period, we consider that the population of ragweed may change over time as described with the invasion function in Figure 1. Second, 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 prevention is the only possible policy action, we shall prevent if $NB_p > 0$ and do nothing provided $NB_p < 0$.[9]

In a similar manner, we may define the total gross benefits under mitigation as $B_{tm}(q_t)$ and the total costs under mitigation as $C_{tm}(q_t)$,[10] where the subscript m covers mitigation. The total discounted net benefits under mitigation are now:

$$NB_m = \frac{\sum_{t=1}^{S} [B_{tm}(q_t) - C_{tm}(q_t)]}{(1+r)^t} \tag{3}$$

We assume that r and S are identical when calculating (2) and (3) to make NB_p and NB_m comparable. If mitigation is the only policy action, this shall be chosen if $NB_m > 0$ whereas nothing should be done provided $NB_m < 0$. If a manager can choose between prevention and mitigation, we shall prevent 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 CBA of two policy actions for addressing the problems with invasive species.

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[8] See, e.g., Marbuah et al. (2005) for a discussion of the cost function under prevention.

[9] See Boadway and Bruce (1984) for a discussion of decision rules in CBAs.

[10] See, e.g., Marbuah et al. (2005) for a discussion of the benefits and costs under mitigation.

In section 3 below, we discuss how the parameters and values necessary to calculate NB_p and NB_m for ragweed in Denmark are determined, whereas section 4 presents the results of the calculations of the total net benefits. However, we also calculate the average, yearly discounted net benefits under prevention and mitigation defined as $AB_p = \frac{NB_P}{S}$ and $AB_M = \frac{NB_M}{S}$. Because S is identical under prevention and mitigation, the decision criteria for the total net benefits mentioned below (2) and (3) also hold when investigating AB_p and AB_M. In sections 3 and 4, we label AB_p and AB_M the average net benefit under prevention and mitigation, respectively.

The two policy actions discussed above represent two extreme cases, which can be characterized as pure prevention and pure mitigation. However, it may be beneficial to use a mixed policy action that includes certain levels of both prevention and mitigation (see Hanley et al., 1997). This is the case if the marginal costs of preventing the establishment of the last unit of ragweed are high and/or the marginal costs of mitigating the damage from the last unit of ragweed are high (see, e.g., Baumol and Oates, 1988). Stated within the model in this section, a mixed strategy may be optimal if the invasion function in Figure 1 can be affected by policy actions.[11] By using the theoretical considerations above, we can identify an optimal mixed strategy by maximizing (2) subject to (1) and (3). However, in this paper, we chose to investigate pure prevention and pure mitigation because extreme policy actions to combat the impacts of invasive species are common in practice.

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 prevention and mitigation for ragweed in Denmark. Tables 1, 2 and 3 provide an overview of the parameters and values used in the calculations.

Table 1: General parameters in the total and average net benefits under prevention and mitigation

Table 2: Total and average net benefits under prevention

Table 3: Total and average net benefits under mitigation

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[11] This is not necessarily true for invasive species. For invasive species, it may be impossible or extremely costly to influence the invasion function once a species is established. This situation has been observed for the Spanish slug (*Arion vulgaris*) and the round goby (*Neogobiusmelanostomus*). Both species have recently been established in Denmark, and no efficient strategy for reducing the population has been found (see Ravn, 2015).

For all parameters and values in Tables 1, 2 and 3, a benchmark case and various sensitivity scenarios are identified. However, it is useful to discuss several considerations regarding the chosen parameters, values and functions, which are done in the following subsections.

3.1. Population of ragweed

In a CBA, it is not the population of ragweed that is important but rather the impact that the species has on human beings (see, e.g., Andersen et al., 1979). Because the main impact of ragweed is an increase in the number of pollen allergy cases, we use this as a measure for q_t in this paper.

3.2. Number of pollen allergy cases

We need information regarding the time path of the number of pollen allergy cases. However, since ragweed has not yet been established in Denmark, we only have a measure for a steady-state equilibrium number of pollen allergy cases caused by the potential establishment of ragweed (q^*). $q^*$is estimated to be 100,000[12] , and as shown in Table 1, we use this amount of pollen allergy cases in the benchmark scenario. However, naturally enough, this amount of pollen allergy cases is uncertain and therefore sensitivity analyses have been conducted for 50,000 cases and 150,000 cases (see Table 1).

3.3. Invasion function

We also need information regarding the invasion function that describes the adjustment path of the number of pollen allergy cases towards 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. For simplicity, we, therefore, assume that the invasion function illustrated in Figure 1 is linear until q^* is reached. We have not been conducting sensitivity analyses for the functional form of the invasion function, since a linear specification is the only function with a unique slope that can be determined when we only have information on an initial point ($t = 0$ and no allergy cases) and a terminal point ($t = T$ and 100.000 allergy cases).[13]

3.4. Time until the 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 CBA (particularly for high discount rates)

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[12] See Astma Allergi Denmark (2014).

[13] See, e.g., Varian (1992) for a discussion.

because the size of the time period affects the net benefits from $t = 0$ to $t = T$. Although we have no information on T, we know that the amount of ragweed in Denmark will approach q^*reasonably rapidly.[14] As shown in Table 1, we have therefore chosen to set T equal to 10 time periods (years) in the benchmark case; however, due to the unknown value, we have also conducted two sensitivity analyses by using $T = 5$ and $T = 15$. Note that the value of T only affects the slope of the invasion function in the interval between 0 and T because the time until a steady-state equilibrium is reached is solely used to calculate the increasing portion of the invasion function in Figure 1.

3.5. Terminal time period

Concerning the terminal time period for evaluating the gross benefits and the costs (S), this represents the time horizon of a manager; as for T, we have no information on S. However, S is probably not as important for the results of the CBAs 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 sensitivity analyses for $S = 25$ and $S = 75$ (see Table 1).

3.6. Discount rate

The discount rate captures the weight attached to future gross benefits and costs. In the CBA literature, the choice of a discount rate is a controversial topic (see Freemann, 1993). A high discount rate implies that a high weight is attached to a current time period's total net benefits compared to future time periods. As shown in Table 1, we follow the recommendations of the European Commission (2015) by using $r = 0.03$ in the benchmark case but we conduct sensitivity analyses for $r = 0$, $r = 0.05$ and $r = 0.09$.

3.7. Total gross benefits under prevention

Our measure for the total gross benefits under prevention begins with two observations. First, ragweed has not yet been established in Denmark. Second, the main impact of ragweed is an increase in the number of pollen allergy cases. For these reasons, our measure for the total gross benefits under prevention is defined by considering the effect for one person of moving from no pollen allergy to treated pollen allergy. Based on this definition, we compare the following two methods for valuing the total gross benefits under prevention:

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[14] See Astma Allergi Denmark (2014).

1. The avoided cost method.[15]
2. The benefit transfer method.[16]

Table 2 provides an overview of the numbers used when valuing the gross benefit under prevention with these two methods. In the following two subsections, we discuss the assumptions behind the values in Table 2.

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 this action is adopted. In our case, the avoided costs arise due to the treatment of pollen allergy, and valuing the total gross benefits by the costs of sickness is normally labelled the cost-of-illness method.[17] Petersen et al. (2005) calculate the average costs of a standard treatment for pollen allergy in Denmark, showing 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, treated pollen allergies imply 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 now found by using the loss in marginal productivity; here, the cost is approximated by the average wage to skilled labour of 0.28 (1000 DKK/per hour).[18] The average cost of lost leisure time is approximated by the average income per hour after taxes. With a marginal tax rate of 51.7%[19] , the average cost of lost leisure becomes 0.1432 (1000 DKK/per hour). As shown in Table 2, these values are used in the benchmark case. By using simple multiplication, we reach a measure for the gross benefit under prevention. Note that 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 conduct sensitivity analyses by varying the average medical costs, the average staff costs, the average lost working time and the average lost leisure time as shown in Table 2. We have not undertaken sensitivity analyses with respect to the average cost of lost working and leisure time because these costs have the same impact on the

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[15] See, e.g., Pearse et al. (2006) for a discussion of the avoided cost method.
[16] See, e.g., Johnston et al. (2015) for a discussion of the benefit transfer method.
[17] See, e.g., Tarricone (2006) for a discussion of the cost-of-illness method.
[18] See Statistics Denmark (2015).
[19] See Danish Ministry of Taxation (2014).

results as the average lost working and leisure time due to the use of simple multiplication. Despite the sensitivity analyses, 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 (see Danish Nature Agency, 2014). Therefore, using more advanced preference-based valuation methods such as contingent valuation or hypothetical choice[20] will also generate a very uncertain estimate for the gross benefits under prevention, and therefore we might as well use a simple method such as the cost-of-illness approach. Finally, the data in Table 2 are used on the entire adjustment path towards a steady-state equilibrium. Thus, we calculate the total gross benefits under prevention from the avoided pollen allergy along the entire invasion function in Figure 1.

3.7.2. Benefit transfer method

A theoretically correct preference-based measure for 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 pollen allergy as respondents, Petersen et al.(2010) find that the average WTP for a treatment is 4.8 (1000 DKK/per case). One possibility is to conduct a benefit transfer by using this average WTP value in our case. We chose to conduct a simple unit root benefit transfer[21] where the average WTP value from Petersen et al. (2010) is transferred directly to our case. However, the average WTP found by Petersen et al. (2010) is uncertain; therefore, as shown in Table 2, we conduct sensitivity analyses by using WTP values on 3.4 (1000 DKK/per case) and 0.2 (1000 DKK/per case).

One problem with the simple unit root benefit transfer method is that dissimilarities between the transfer 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.[22] However, significant uncertainty regarding the invasion function may justify using a simple benefit transfer method (see section 3.7.1). Notably, the average WTP values in Table 2 are used on the entire adjustment path towards the steady-state equilibrium described by the invasion function (see Figure 1).

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[20] See, e.g., Pearce et al. (2006) for a discussion of the contingent valuation method and the hypothetical choice method.

[21] See, e.g., Johnston et al. (2015) for a discussion of unit root benefit transfer.

[22] See, e.g., Johnston et al. (2015) for a discussion of these problems.

3.8. Total cost under prevention

As discussed in section 1, ragweed will potentially enter Denmark through imports of bird seed. Therefore, a threshold exists for the content of ragweed in imported seeds in an EU directive (see EU Commission, 2011). Based on this threshold, the Danish Veterinary and Food Administration conducted a random control campaign to address the amount of bird seed in imported food in 2012 and 2013 (see Danish Veterinary and Food Administration 2012 and 2013). We use the total control costs of this authority and the firms during the campaign as a measure for the cost under prevention, although other costs may exist. We treat these control 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 introduced at $t = 0$, the population will converge towards the steady-state equilibrium (q^*) as described by the invasion function in Figure 1. As shown in Table 2, the fixed control costs by the authority and the firms are estimated to 196 (1000 DKK). However, the fixed control costs can change over time. To address this problem, we vary the fixed costs as shown in Table 2. We also assume that the control costs are to be paid for every time period from $t = 0$ until the terminal time period since the costs under prevention must be covered even if ragweed is not established in Denmark.

3.9. Total gross benefits under mitigation

The point of departure for the valuation of the gross benefit under mitigation is that this policy action requires that ragweed must have been established in Denmark. Therefore, the gross benefits under mitigation for one person must be found by comparing untreated pollen allergy with treated pollen allergy. To value the gross benefit under mitigation, we compare the following two methods:

1. The avoided cost method
2. The benefit transfer method

An overview of the values used in the calculations of the gross benefit under mitigation is provided in Table 3. In the two subsections below, we discuss the main assumptions behind these values.

3.9.1. Avoided cost method

As in section 3.7.1, we use the fact that the main impact if ragweed is established in Denmark is an increase in the number of pollen allergy cases. Thus, we must find the cost-of-illness of untreated pollen allergy; therefore, the medical costs and staff costs can be disregarded. However, lost working and leisure time still exist with untreated pollen allergy Luskin et al. (2004) calculate the average lost working and leisure time of untreated allergy by using respondents from the United States. Even though it is not straightforward to use values from another country in a Danish case, we choose to do so. Converting our case of untreated allergy imply an average lost working time of 51 hours and an average lost leisure time of 245 hours (see Table 3).[23] However, as shown in Table 3, we conduct sensitivity analyses by using average lost working time of 36 hours and 66 hours and average lost leisure time of 171 hours and 319 hours. By using the average cost of lost working and leisure time from Table 2, we now calculate the cost-of-illness of untreated pollen allergy. Note three facts in relation to these numbers. First, there is a significant increase in the average number of lost working and leisure time hours when compared with treated pollen allergy (Table 2). Second, the gross benefit under prevention will vary on an adjustment path towards a steady-state equilibrium. Last, by using the average cost of lost working and leisure time from Table 2, we assume constant average and marginal costs of lost working time and leisure time.

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) of not receiving pollen allergy treatment among randomly selected patients in the United States. From Table 3, we see that this average WTA value, converted to our case, is 52 (1000 DKK/per case).[24] However, because an average WTA from the United States is used, we conduct sensitivity analyses by using WTA values on 36 (1000 DKK/per case) and 52 (1000 DKK/per case). Note two facts in relation to this measure. First, there is a large difference between the average WTP value in Table 2 (payment given) and the average WTA value in Table 3 (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 and Tversky, 1979). Second, the average WTA values shall be used on the entire adjustment path towards a steady-state equilibrium, as illustrated in Figure 1.

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[23] Arguably, the lost working and leisure time shall be adjusted for differences between Denmark and the United States in, for example, working time or the length of the pollen season. However, Lee et al. (2007) suggest that the average working time is nearly identical in Denmark and the United States while Mahuro et al. (2007) show that the length of the pollen season is nearly identical. Thus, correcting for differences in working time or the length of the pollen season will not affect the results of the CBAs.

[24] As in section 3.9.1, correcting for differences in the length of the pollen season between the United States and Denmark will not affect the results of the CBAs (see Mahoro et al., 2007).

3.10. Total cost under mitigation

From our definitions, it follows that the total gross benefit under prevention valued with the cost-of-illness method (see section 7.7.1) 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, as calculated using the data in Table 2. Furthermore, we also conduct the same sensitivity analyses as described in Table 2. Notably, in this cost calculation, we assume constant marginal and average costs of medicine, staff, lost working time and lost leisure time. The costs of mitigation must be identified for the entire invasion function in Figure 1.

4. Results

In this section, we present the results of CBAs under mitigation and prevention. In section 4.1 and section 4.2, the results of the benchmark case and the results of the sensitivity analyses are discussed, respectively.

4.1. Benchmark case

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

Table 4: Results for the benchmark case

In Table 4 we see that the total gross benefit under mitigation valued by both the cost-of-illness method and the benefit transfer method is larger than under prevention. 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, as shown in Table 4, the total costs under mitigation are also larger than under prevention. 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 (see section 3.8).

Table 4 also shows that the total net benefits under both prevention and mitigation are significantly positive leading to the result that one of the policy actions shall be adopted. However, the total net benefits under mitigation are larger than under prevention, valued with both the cost-of-illness method and the benefit transfer method. This result can also be seen from the average net benefits under prevention and mitigation. Table 4 also shows that if the cost-of-illness method is used, the average net benefits under prevention in relation to mitigation constitute 80%, whereas the average net benefits under prevention in relation to mitigation only constitute 16% if a benefit transfer method is used. To summarize the results in Table 4, the CBAs indicate that mitigation may be preferred over prevention.

4.2. Sensitivity analyses

However, a natural question is whether this result is robust to changes in the parameters and values used for calculating the total and average net benefits under the two policy actions. To investigate this issue, we conduct a number of sensitivity analyses. The results of varying the general parameters in the net benefit functions (apart from the discount rate) are shown in Table 5.

Table 5: Sensitivity analyses for general parameters

When considering the results for the adjustment time T in Table 5, we note that an increase in T will decrease the average net benefits measured with both valuation methods under both policy actions. The explanation for this result is that an increase in T implies that it takes longer time before a steady-state equilibrium is reached. Therefore, the total net benefits in the first time periods decrease, implying that the average net benefits are reduced. 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 in an identical way.

Table 5 also shows that the average net benefits under mitigation and prevention valued with both methods are increasing in the number of pollen allergy cases in the steady-state equilibrium, q^*. The explanation for this result is that 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, as shown in Table 5, 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.

Finally, consider the results for the regulator´s time horizon, S, in Table 5. Here, we see that the average net benefits under both prevention and mitigation (measured with both valuation methods) decrease when *S* increases. This result occurs because an increase in the regulator´s time horizon has two effects on the average net benefits. First, an increase in *S* implies that an increasing number of future total net benefits are considered, but due to discounting, these obtain a low weight when the total net benefits are calculated. Second, an increase in *S* increases the number of time periods over which the average net benefits are defined. When these two effects are combined, it is clear that an increase in *S* will 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 in relation to mitigation (measured by both methods) is virtually unaffected by a change in *S* (see Table 5).

Table 6 depicts the sensitivity analyses with respect to the discount rate *r*.

Table 6: Sensitivity analyses for the discount rate

In Table 6 we see that an increase in *r* implies a lower average net benefit under mitigation and prevention with both valuation methods. This result occurs because an increase in the discount rate implies that a lower weight is attached to the future total net benefits, which 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 conclusion that an increase in *r* has a significant impact on the results of a CBA. However, from Table 6 we also see that the average net benefits under prevention in relation to mitigation are virtually unaffected by a change in *r*. This result occurs because a change in the discount rate affects the average net benefits under prevention and mitigation valued with both methods in an identical way. Thus, when comparing two or more policy actions, *r* does not necessarily affect the ranking of the actions.

Table 7 presents the results of the sensitivity analyses with respect to the cost-of-illness values.

Table 7: Sensitivity analyses for the average cost-of-illness values

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

Table 7 also shows that an increase in the average lost working and leisure hours will increase the average net benefits under both prevention and mitigation valued by the cost-of-illness method. Under prevention, an increase in the average lost working and leisure hours will increase the total avoided costs. Under mitigation, two counteracting effects exist when cost-of-illness is used as the valuation method. First, an increase in the average lost working and leisure hours will increase the total costs under mitigation. Second, an increase in the average lost working and leisure hours will increase the total gross benefit under mitigation valued with the cost-of-illness method. Because the latter effect dominates the former, an increase in average lost leisure and working hours will increase the average net benefits. 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 in relation 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 allergy (see section 3.9.1). If the gross benefit under mitigation is measured with 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 in relation to mitigation valued with the benefit transfer method is very low.

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

Table 8: Sensitivity analyses for the control costs and the average benefit transfer values

Table 8 shows 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. 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 in relation to mitigation, and this conclusion holds even though the fixed control costs shall be covered already from the initial time period.

In Table 8 we also observe that an increase in the average WTP under prevention implies a large increase in the average net benefits of this policy but leaves the other net benefit values unchanged. Furthermore, an increase in the average WTP prevention generates a significant increase in the average net benefit under prevention in relation to mitigation. Finally, from Table 8 we observe that 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. Indeed, an increase in the average WTA of mitigation implies a significant decrease in the average net benefit under prevention in relation to mitigation.

To draw an overall conclusion from the CBAs in Tables 5, 6, 7 and 8, mitigation is preferred over prevention in all the investigated scenarios. Therefore, the basic result from section 4.1 is robust to changes in the parameters and values. Furthermore, varying the parameter and values generates a very small change in the average net benefits under prevention in relation to mitigation measured by both the cost-of-illness method and the benefit transfer method.

5. Policy implications

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 possible establishment of ragweed in Denmark. We now discuss this policy conclusion and at least two additional arguments in favour of mitigation can be mentioned. First, even if we invest substantial resources in prevention, there is a positive probability for the event to occur. An (implicit) assumption behind the results in section 4 is that we can prevent the establishment of ragweed with certainty. Including a positive probability for the introduction even under prevention will make mitigation more beneficial.

Second, we assume that the establishment of an invasive species only has a negative impact on utility and welfare (see section 1). However, the establishment of ragweed (and other invasive species) in Denmark may influence both utility and welfare positively in the long run (see Finnoff et al., 2005). Considering this effect will make mitigation more even beneficial.

However, at least four arguments can be summarized for reconsidering whether mitigation is the most desirable policy action. First, it is well-known in health economics that people underestimate the value of preventive actions (see, e.g., Mant et al., 2007 and O´Connell, 2009). This argument can be linked to the observation that many people underestimate small probabilities of uncertain events occurring, leading to an information externality (see, e.g., Hauert and Duebeli, 2004 and Hertvig et al., 2004). Within our model, this argument implies that the average WTP of prevention is underestimated, leading to a higher total and average net benefit under this policy action measured with the benefit transfer method. Thus, when correcting the information externality, prevention becomes a relatively more beneficial policy action.

Second, it is well-known that people may have altruistic preferences regarding the health of other people. Thus, people who are not affected by allergy symptoms may prefer that others do not become ill (see, e.g., Olson et al., 2004 and Jacobsen et al., 2005). Such preferences are not included in the cost-of-illness or benefit transfer calculations under both prevention and mitigation. Including altruistic preferences tends to make prevention relatively more desirable compared to mitigation.

Third, there is significant uncertainty regarding the future impacts if ragweed is established in Denmark; as with all other invasive species, there is a positive probability of a catastrophic event (see, e.g., Horan et al., 2002). In our case, the catastrophic event arises if the population of ragweed in Denmark becomes out of control, leading to a dramatic increase in the number of allergy cases. When considering catastrophic events, it is obvious that prevention becomes more beneficial because the probability of avoiding this event is higher with this policy action than with mitigation.

Fourth, it can be discussed whether mitigation is an ethical acceptable policy action at all. Mitigating the damages from the establishment of ragweed when prevention is a feasible policy action is the same as arguing that making people sick and then curing them yields a higher net benefit than not making people sick at all. Of course, the ethical aspect of this argument can be discussed (see, e.g., Farley, 2016).

Thus, in our opinion, information externality, altruistic preferences, possible catastrophic events and ethical considerations lead to the conclusion that prevention should be adopted instead of mitigation. This conclusion holds even though our CBAs show that the total and average net benefits under mitigation are larger than under prevention.

6. Conclusion

This paper contributes to the existing research on invasive species by performing an ex-ante comparison of the net benefits under prevention and mitigation. We use the potential establishment of ragweed in Denmark as an empirical case. The main impact if ragweed enters the country is a significant increase in the number of pollen allergy cases. Since ragweed has not yet been established in Denmark, we use an invasion function to describe the development in the population of ragweed over time, and this function is considered in the CBAs.

To measure the total gross benefit under prevention and mitigation, we use both a cost-of-illness method and a benefit transfer method. Although there are numerous theoretical and empirical problems with using these two methods, the application is justified by a large uncertainty regarding the impacts if ragweed is established in Denmark. For the two policy actions measured with both valuation methods, the total and average net benefits are significantly positive and this result is robust to changes in the parameters and the values of the CBAs. Thus, either prevention or mitigation should be used to combat the establishment of ragweed in Denmark. Furthermore, the total and average net benefits under mitigation are larger than under prevention, a result that is also robust to changes in the parameter values. Despite this result, we conclude that prevention should be used instead of mitigation due to information externalities, altruistic preferences, possible catastrophic events and ethical considerations.

There are at least three major limitations to the analysis in the paper. First, uncertainty regarding the impact of ragweed is addressed by conducting a large number of sensitivity analyses. An alternative approach is to develop a bio-economic model that incorporates the probabilities for the various possible impacts. Second, we do not investigate whether a mixed policy action is beneficial. From a theoretical point of view, an extreme solution to externality problems such as pure prevention and pure mitigation are often non-optimal. Last, management of invasive species is subject to international political obligations both within the United Nations and the European Union (see, e.g., UN, 2014). These international obligations should be included as restrictions on policy actions in a model for invasive species. Important areas for future research therefore include the development of bio-economic models on invasive species that consider uncertainty, mixed strategies and international conventions.

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Figure 1: An example of an invasion function

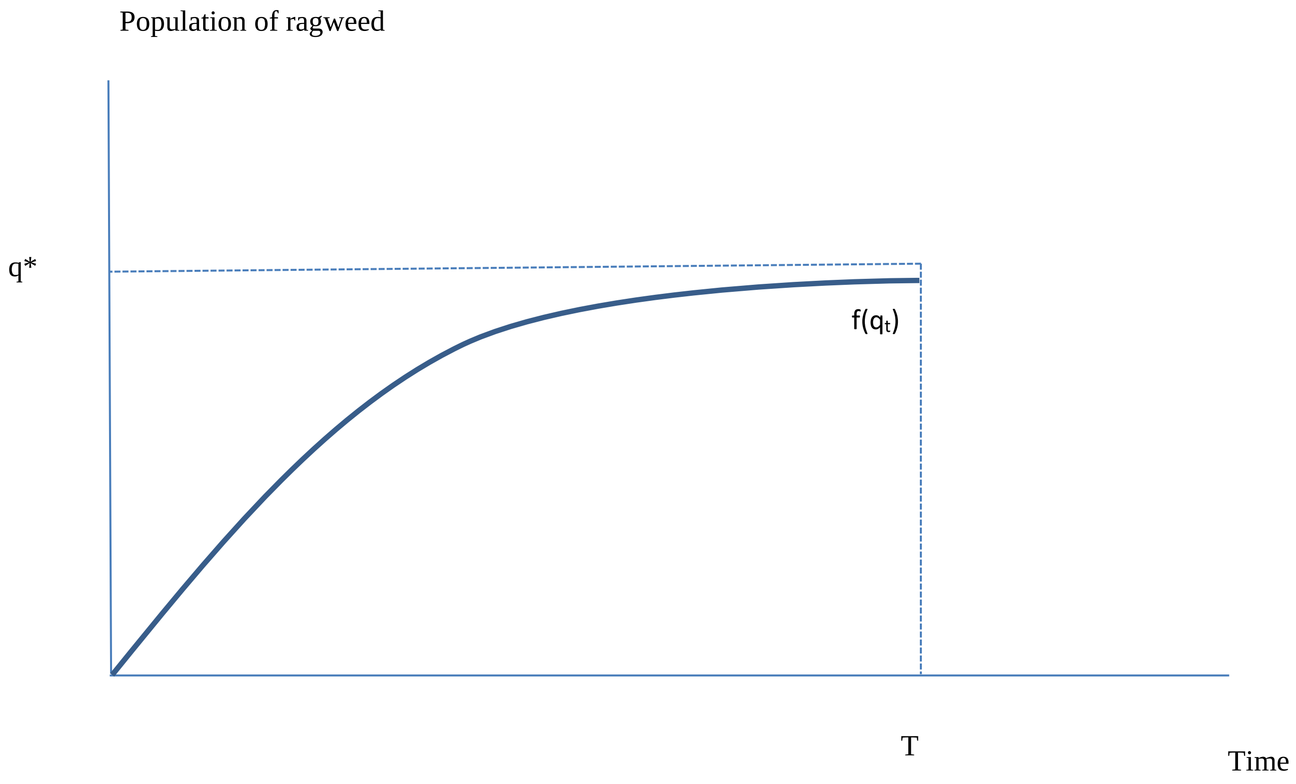

Table 1: General parameters in the total and average net benefits under prevention and mitigation

Parameter	Situation	Parameter value
Allergy cases in steady-state, q* (number)	Benchmark case	100,000
	Sensitivity analyses	50,000 and 150,000
Adjustment time before steady-state is reached, T(years)	Benchmark case	10
	Sensitivity analyses	5 and 15
Regulators’ time horizon, S (years)	Benchmark case	50
	Sensitivity analyses	25 and 75
Discount rate, r (%)	Benchmark case	0.03
	Sensitivity analyses	0, 0.05 and 0.09

Table 2: Total and average net benefits under prevention

Category	Value	Situation	Number
Total gross benefit measured by the cost-of-illness method	Average avoided medical costs (1000 DKK per allergy case)	Benchmark	1,99
		Sensitivity analyses	1,30 and 2,69
	Average avoided staff cost (1000 DKK per allergy case)	Benchmark	0,631
		Sensitivity analyses	0,44 and 0,82
	Average lost working time (hours per allergy case)	Benchmark	20
		Sensitivity analyses	14 and 26
	Average lost leisure time (hours per allergy case)	Benchmark	96
		Sensitivity analyses	67 and 125
	Average cost of lost working time (1000 DKK per hour)	Benchmark	0,28
		Sensitivity analyses	Same as for lost working time
	Average costs of lost leisure time (1000 DKK per hour)	Benchmark	0,143
		Sensitivity analyses	Same as for lost leisure time
Total gross benefit measured by the benefit transfer method	Average WTP (1000 DKK per allergy case)	Benchmark	4,8
		Sensitivity analyses	3,4 and 6,2
Total costs under prevention	Fixed control costs (1000 DKK)	Benchmark	196
		Sensitivity analyses	133 and 247

Table 3: Total and average net benefits under mitigation

Category	Value	Situation	Number
Total gross benefit measured by the cost-of-illness method	Average lost working time (hours per allergy case)	Benchmark	51
		Sensitivity analyses	36 and 66
	Average lost leisure time (hours per allergy case)	Benchmark	245
		Sensitivity analyses	171 and 319
Total gross benefit measured by the benefit transfer method	Average WTA (1000 DKK per allergy case)	Benchmark	52
		Sensitivity analyses	36 and 68
Total costs of allergy	Total costs of treatment (1000 DKK)	Benchmark	Same as prevention and avoided costs
		Sensitivity analyses	Same as prevention and avoided costs

Table 4: Results for the benchmark case

	Prevention		Mitigation	
	Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer
Total gross benefit (1000 DKK)	49440718	10829794	110965591	117322771
Total costs (1000 DKK)	5078	5078	49440718	49440718
Total net benefits (1000 DKK)	49435639	10824716	61524873	67882053
Average net benefits (1000 DKK).	988712	216494	1230497	1357641
Average net benefits under prevention in relation to average net benefit under mitigation (%)	80%	16%	------	-------

Table 5: Sensitivity analyses for general parameters

Parameter	Value	Measure	Prevention		Mitigation	
			Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer
Benchmark case		Average net benefits (1000 DKK)	988712	216494	1230497	1357641
		Prevention shared by mitigation (%)	80	16	------	------
Adjustment time, T = 10 in benchmark case (years)	T = 5	Average net benefits (1000 DKK)	1086231	237855	1351851	1491533
		Prevention shared by mitigation (%)	80	16	-------	-------
	T = 20	Average net benefits (1000 DKK)	819552	179440	1019991	1125384
		Prevention shared by mitigation (%)	80	16	-------	-------
Number of allergy cases, q* = 100,000 in benchmark case (numbers)	q* = 50,000	Average net benefits (1000 DKK)	494306	101896	615249	678821
		Prevention shared by mitigation (%)	80	15	------	-------
	q* = 150,000	Average net benefits (1000 DKK)	1431200	324792	1845460	2036461
		Prevention shared by mitigation (%)	78	16	------	-------
Regulator time horizon, S = 75 in benchmark case (years)	S = 25	Average net benefits (1000 DKK)	1248514	273372	1553846	1714401
		Prevention shared by mitigation (%)	81	16	-------	-------
	S = 75	Average net benefits (1000 DKK)	775186	169741	944751	1064436
		Prevention shared by mitigation (%)	82	16	------	-------

Table 6: Sensitivity analyses for the discount rate

Parameter	Value	Measure	Prevention		Mitigation	
			Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer
Benchmark case		Average net benefits (1000 DKK)	988712	216494	1230497	1357641
		Prevention shared by mitigation (%)	80	16	-------	---------
The discount rate, r = 0.03 in the benchmark case (%)	r = 0	Average net benefits (1000 DKK)	2037734	446206	2536032	2798072
		Prevention shared by mitigation (%)	80	16	-------	-------
	r = 0.05	Average net benefits (1000 DKK)	669697	146637	833478	919594
		Prevention shared by mitigation (%)	80	16	--------	-------
	r = 0.0 9	Average net benefits (1000 DKK)	364704	79851	453900	500806
		Prevention shared by mitigation (%)	80	16	--------	------

Table 7: Sensitivity analyses for average cost-of-illness values

Parameter	Value	Measure	Prevention		Mitigation	
			Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer
Benchmark case		Average net benefits (1000 DKK)	988712	216494	1230497	1357641
		Prevention shared by mitigation (%)	80	16	-------	------
Average medical costs, 1.99 in benchmark case (1000 DKK)	1.30	Average net benefits (1000 DKK)	957144	unchanged	1262066	1389210
		Prevention shared by mitigation (%)	76	16	-------	------
	2.69	Average net benefits (1000 DKK)	1020237	unchanged	1198974	1326117
		Prevention shared by mitigation (%)	85	16	-------	-------
Average staff costs, 0.63 in benchmark case (1000 DKK)	0.44	Average net benefits (1000 DKK)	980184	unchanged	1239026	1366710
		Prevention shared by mitigation (%)	79	16	-------	-------
	0.83	Average net benefits (1000 DKK)	997241	unchanged	1221969	1349113
		Prevention shared by mitigation (%)	82	16	--------	------
Average lost working hours, 20 and 51 in benchmark case (hours)	14 and 36	Average net benefits (1000 DKK)	913717	unchanged	1118003	1432637
		Prevention shared by mitigation (%)	82	15	------	------
	26 and 66	Average net benefits (1000 DKK)	1063709	unchanged	1342992	1282645
		Prevention shared by mitigation (%)	79	16	------	------
Average lost leisure hours, 96 and 245 in benchmark case (hours)	67 and 171	Average net benefits (1000 DKK)	801321	unchanged	941010	1545033
		Prevention shared by mitigation (%)	85	14	------	------
	125 and 319	Average net benefits (1000 DKK)	1176104	unchanged	1522570	1170250
		Prevention shared by mitigation (%)	77	18	------	------

Table 8: Sensitivity analyses for control costs and average benefit transfer values

Parameter	Value	Measure	Prevention		Mitigation	
			Cost-of-illness	Benefit transfer	Cost-of-illness	Benefit transfer
Benchmark case		Average net benefits (1000 DKK)	988712	216494	1230497	1357641
		Prevention shared by mitigation (%)	80	16	--------	-------
Fixes control costs, 196 in benchmark case (1000 DKK)	133	Average net benefits (1000 DKK)	988743	216424	unchanged	unchanged
		Prevention shared by mitigation (%)	80	16	-------	------
	247	Average net benefits (1000 DKK)	988682	216564	unchanged	unchanged
		Prevention shared by mitigation (%)	80	16	-------	------
Average WTP under prevention, 4.8 in benchmark case (1000 DKK)	3.4	Average net benefits (1000 DKK)	unchanged	153321	unchanged	unchanged
		Prevention shared by mitigation (%)	unchanged	11	--------	-------
	6.2	Average net benefits (1000 DKK)	unchanged	279668	unchanged	unchanged
		Prevention shared by mitigation (%)	unchanged	20	-------	------
Average WTA under mitigation, 52 in benchmark case (1000 DKK)	36	Average net benefits (1000 DKK)	unchanged	unchanged	unchanged	635655
		Prevention shared by mitigation (%)	unchanged	34	-------	------
	52	Average net benefits (1000 DKK)	unchanged	unchanged	unchanged	2626110
		Prevention shared by mitigation (%)	unchanged	8	------	------