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Abstract

The paper considers an industry where the effects of pollution can be off-set by investing in adaptation as a private good. The focus is not on external effects, but on economies of scale that are introduced when the costs of adapting to pollution are independent from the quantity produced. The structure of the resulting oligopolistic market is endogenous in the model, since adaptation expenditures are like fixed costs in production, but the amount of these expenditures is itself a choice variable for the firms. The analysis of externalities usually disregards defensive or adaptation measures, with a few exceptions that indicate considerable complications. The present debate on adaptation to climate change yet shows the importance of understanding defensive measures. Is there a case for governmental action in private adaptation? It is shown that market failure caused by private adaptation leads to production costs above the social optimum, i.e. to under-adapation. When pollution increases, adaptation only increases if demand is inelastic. Only then welfare loss from market failure increases. Total welfare loss from pollution is only convex if demand is inelastic and the influence of pollution on production costs is stronger than the influence of adaptation.

Keywords: self-protection, climate change, oligopoly, welfare, damage
JEL: L-13, Q-52, Q-54

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1. Introduction

Producers that are affected by negative externalities can be expected to invest in activities that reduce the incurred damage. Independtly from whether pollution is controlled at an optimal level or not, e.g. with a Pigou tax, there is no incentive to react with non-optimal investment in damage reduction, since damage reduction is a private good. Such activities, also called defensive, protective measures or averting behaviour in the literature (e.g. Baumol, 1972; Butler and Maher, 1986; McKitrick and Collinge, 2002), are reffered to as adaptation in this paper. This paper investigates whether adaptation is indeed socially optimal when adaptation costs are independent from the quantities produced. It thus aims at contributing to the question about the need of public adaptation policies. If adaptation results in market failure, it is crucial to know whether this leads to adaptation above or below the efficient level.

In particular, adaptation to climate change has got increasing attention in the recent discourse (e.g. Pielke et al., 2007). It is quite clear that even an efficient global regime for climate protection cannot complete stop global warming anymore. It has therefore become crucial to adapt to climate change impacts that are unavoidable. Moreover, international financing of adaptation as part of a global agreement has become a cornerstone of international climate negotiations.

Compared to abatement, adaptation has received little attention from environmental economics yet. Although this was already stated by Butler and Maher (1986), little seems to have changed in this respect. There are some arguments that damage functions are not necessarily convex when adaptation is considered (Butler and Maher, 1986), such that Pigouvian taxes are not efficient (Winrich, 1982; McKitrick and Collinge, 2002). Another obvious market failure is associated with protective measures having the character of a local public good, e.g. against floods or droughts (cf. Fankhauser et al., 1999; Lecocq and Shalizi, 2007). However, in this paper I analyse adaptation being a private good. I also disregard the effects of adaptation on abatement decisions: the amount of pollution and the external effect is taken as exogeneously given. This specific focus already shows a complex spectrum of interesting cases.

The paper considers a situation where production costs increase with pollution, but where this effect can be off-set by adaptation. It is assumed that the cost-reducing effect is independent from the produced quantity. This assumption might be questionable for some adaptations, but it is quite reasonable for others. Protective measures as sea-walls, drainage systems, security or fences may well defend a production unit mostly independent from its production capacity. For the case of climate change, it is likely that many adaptation actions involve fixed or sunk costs (cf. Lecocq and Shalizi, 2007). Some authors argue that the most crucial adaptations are needed in terms of labour and production organisation, and therefore apply to the whole firm (e.g. Berkhout et al., 2006). As a consequence, adaptation costs are like fixed costs for production. However, since firms individually decide on their adaptation expenditures, these fixed costs are endogeneous to the model and determine the market structure.

I deduce from these assumptions how a Cournot oligoploy with free entry/exit deviates from a social planner solution, and how this depends on the amount of pollution. It is shown that adaptation indeed introduces economies of scale with respect to production, such that market failure results. Under profit maximizing adaptation unit production costs are higher than would be efficient – an effect that is termed as under-adaptation. While adaptation on the firm level is below the optimum, it is possible that total adaptation expenditures in the industry are above when demand is elastic. With additional pollution, adaptation expenditures can increase or decrease, depending on whether demand is inelastic or elastic. Under special conditions (that are associated with a non-existent market equilibrium) it may even be the case that there is both more production and adaptation due to pollution. In any case, pollution causes welfare to decrease, i.e. there is a welfare loss. A share of this loss can be attributed to market failure. However, the welfare loss from market failure decreases with pollution if damand is elastic. Total welfare loss from pollution and the welfare loss from market failure only increase convexly with pollution if demand is inelastic and the influence of pollution on production costs is stronger than the influence of adaptation. Otherwise, the welfare loss is concave with respect to pollution.

I first introduce the basic model of the paper in a social planner context, and determine the oligopolistic equilibrium subsequently. Both solutions are compared for a given pollution level by showing that the oligopoly solution can be reduced to a special social planner problem. Finally, it is determined how the different effects change with increasing pollution. A proof of all relevant cases for the effects of pollution in the presence of adaptation and a discussion concludes the paper.

2. The model and optimal adaptation

In this section I consider the adaptation and production decision of a social planner that takes pollution k as given. This might represent the situation for a region that is affected by climate change, but has only marginal influence on global emissions.

Production of a consumption good can be delegated to $n \geq 1$ firms with identical unit production costs $c(a_i, k)$, where a_i is the defensive adaptation of a single firm i. The partial derivatives $c_k > 0, c_{kk} > 0, c_a < 0, c_{aa} < 0, c_{ak} < 0$, such that unit costs convexly increase with pollution, and convexly decrease with defensive adaptation. The cost-reducing effect of adaptation increases for higher pollution. The quantity produced by firm i is denoted by x_i. Preferences are expressed by a utility function $U(x)$ with the usual properties, where $x = \sum_{i=1,\ldots,n} x_i$ is total production. Utility is not directly affected by pollution, i.e. pollution only changes production costs. The social planner decides on the number of firms n, production $x_i, i = 1, \ldots, n$ and defensive adaptation $a_i, i = 1, \ldots, n$. Taking constant unit costs of defensive adaptation q, welfare

$$W^S := U(nx_i) - \alpha c(a_i, k) n x_i - q n a_i, \tag{1}$$

needs to be maximized with respect to x_i, a_i, n. The constant paramter α is introduced for use in a later section (to reduce the market solution to a special social planner case). The social optimum corresponds to $\alpha = 1$. Since $\frac{dW^S}{dn} < 0$, the smallest possible number of firms $n^* = 1$ is optimal.

The first order conditions for production and adaptation then yield the equations

$$U'(x_i^*) = \alpha c(a_i^*, k), \tag{2}$$

$$-\alpha c_a(a_i^*, k)\; x_i^* = q, \tag{3}$$

that determine the optimal production x_i^* and defensive adaptation a_i^* for given pollution k. Note that $x_i^* = x^*$ due to $n^* = 1$. The equations state that the marginal benefits of production and of defensive adaptation, respectively, equal the marginal costs. For convenience, $c^* := c(a_i^*, k)$ in the following.

By defining the cost elasticity of adaptation $\epsilon_a = c_a \frac{a}{c} < 0$, Eq. (3) is equivalent to

$$-\alpha \epsilon_a = \frac{q a_i^*}{c^* x_i^*}, \tag{4}$$

such that the fraction of expenditures for defensive adaptation to production costs increases when costs are more elastic with respect to adaptation.

By taking the total differential it can now be determined how the solution depends on pollution k and unit adaptation costs q (see Appendix A for detailed calculations). To simplify expressions, the cost elasticity of adaptation $\epsilon_a < 0$, the cost elasticity of pollution $\epsilon_k = c_k \frac{k}{c} > 0$, and the inverse elasticity of marginal utility $\epsilon_p = (U'' \frac{x}{U'})^{-1}$ are used. Elastic marginal utility corresponds to $-1 < \epsilon_p < 0$. We further introduce the parameter

$$u := \epsilon_a \epsilon_p + \epsilon_a - 1 = \epsilon_a(\epsilon_p + 1) - 1. \tag{5}$$

It has an indeterminate sign and will be crucial in the remainder of this paper. The comparative statics for the social optimum can then be expressed as

$$\frac{dx_i^*}{dq} = -\frac{\epsilon_p}{\alpha u} \frac{a_i^*}{c^*}, \tag{6}$$

$$\frac{da_i^*}{dq} = \frac{a_i^*}{qu}, \tag{7}$$

$$\frac{dx_i^*}{dk} = -\frac{\epsilon_k \epsilon_p}{u} \frac{x_i^*}{k}, \tag{8}$$

$$\frac{da_i^*}{dk} = -\frac{\epsilon_k(1 + \epsilon_p)}{u} \frac{a_i^*}{k}. \tag{9}$$

(Recall that $x_i^* = x^*$.) All these expressions have an ambigous sign that is partially determined by u. Observe that the cost elasticity of pollution ϵ_k has no influence on the effect of adaptation costs. The (technical) parameter α only plays a role for the sensitivity of production to adaptation cost changes. Interestingly, defensive adaptation does not necessarily increase or decrease with adaptation costs. The intuition that higher costs for adaptation make this activity less attractive is only true for $u < 0$. Moreover, also higher pollution does not necessarily increase adaptation. Both depends on u and on the elasticity of marginal utility. Also the effects of adaptation costs and pollution on production are ambigous, but solely depend on u. Observe that u completely determines the sign of three of these expressions. Both pollution and increasing unit adaptation costs move production in the same direction. If pollution causes a reduction of optimal production, an increasing q has the same effect. Changing unit adaptation costs shift production and defensive adaptation in the same direction. If less defensive adaptation is optimal due to increasing costs, production is reduced as well.

Since the sign of u and the elasticity of marginal utility determines these effects, it is worth having an overview of all possible cases. Note that $0 < \epsilon_p + 1$ implies $u < 0$. Hence, there are just three cases (see Table 1). Case (1) applies for elastic marginal utility. For inelastic marginal utility, case (2) is appropriate

	case (1)		case (2)		case(3)	
u	(–)		(–)		(+)	
$\epsilon_p + 1$	(+)		(–)		(–)	
marginal utility	elastic		inelastic		inelastic	
	x^*	a_i^*	x^*	a_i^*	x^*	a_i^*
d/dq	(–)	(–)	(–)	(–)	(+)	(+)
d/dk	(–)	(+)	(–)	(–)	(+)	(+)

Table 1: Cases for the comparative statics in the social optimum.

if additionally, e.g., the costs from pollution are very inelastic with respect to defensive adaptation. Case (3) is in particular relevant if both demand and defensive adaptation are very elastic.

Proposition 1. *When the effect of adaptation is independent from the produced quantity, it is socially optimal to produce with one firm, i.e.* $n^* = 1$. *The adaptation and production decision is determined by Eq. (2) and Eq. (3). They depend on pollution and unit adaptation costs as given in Table 1.*

Case (1) roughly corresponds to what could be expected: When there is more pollution, the effort put into adaptation should increase, but cannot fully compensate production loss. The present analysis shows that this is yet just a particular situation. It might as well be that there is less adaptation in the presence of increasing pollution (case 2). Since marginal utility is inelastic in that case, the increasing costs from pollution cause production to decline sharply. Under these shrinking conditions, it is not worth putting too much effort in keeping costs stable. Case (3) also shows a contra-intuitive situation, where production expands due to pollution. The cost-reducing effect of adaptation is so strong that more production becomes efficient. It should be noted that this case does not imply welfare gains from pollution, since the increasing expenditures for defensive adaptation have to be taken into account. I will show below that this case corresponds to a non-existing market equilibrium. In sum, the diversity of cases is caused by the fact that pollution does not only change the optimal level of defensive adaptation, but also the amount of production. Both effects can interfere in different ways and become more complicated in oligopolistic markets.

3. Adaptation in the oligopolistic market

This section determines how a market economy solves the adaptation problem. Since adaptation costs are independent from the amount of production, there are economies of scale such that there is an oligopolistic situation.

It is assumed that there are no barriers to entry and to exit the market. All firms simultanously decide on market participation, on production and on adaptation. The number of participating firms is thus endogenous in this model. The adaptation decision, the production decision and the market structure are interdependent. For analytical reasons I proceed in two steps. First I take the number of firms n as fixed, and determine their production quantity decision $x_i, i = 1, \ldots, n$ and adaptation decision $a_i = 1, \ldots, n$. Second, the equilibrium number of firms is determined from the zero profit condition.

As in the last section, the unit production cost function $c(a_i, k)$ and the unit adaptation costs q are assumed to be identical for all firms. I set the parameter $\alpha = 1$ in the following calculations (it can be skipped for the market solution by reasons that will become clear below). All firms operate on the same market with the inverse demand function $p(x) = U'(x)$. The inverse elasticity of marginal utility ϵ_p is thus equivalent to the elasticity of demand, such that $\epsilon_p < -1$ corresponds to elastic demand. When considering a single firm i, the production of all other firms is denoted by x_{-i}, i.e. $x = x_i + x_{-i}$. Each firm thus faces the problem

$$\max_{x_i, a_i} \pi_i = p(x_i + x_{-i})x_i - c(a_i, k)x_i - qa_i, \tag{10}$$

where π_i represents the profits of the ith firm. By symmetry it can be concluded that $x = nx_i$. The first order condition with respect to x_i is

$$p(nx_i)(1 + \frac{1}{n\epsilon_p}) = c(a_i, k), \tag{11}$$

which is a solution only if

$$1 + \frac{1}{n\epsilon_p} > 0. \tag{12}$$

The latter holds, for example, if demand is elastic ($\epsilon_p + 1 < 0$) and $n \geq 1$. For inelastic demand an interior solution depends on n in a more complex way.

For the adaptation decision, the first order condition yields

$$-c_a(a_i, k)x_i = q. \tag{13}$$

Eq. (11) and Eq. (13) together represent the market solution for a given number n. Is is already obvious that this solution is different from the social optimum (cf. Eq. 2, Eq. 3). It is also clear that the degree of the difference depends on n. Eq. (13) reflects that the costs of defensive adaptation are endogenously selected by the firm. Unit adaptation costs then equal the associated marginal cost reduction. Eq. (11) shows a price mark-up depending on the number of firms. Since adaptation costs are like fixed costs for the production decision (they do not explicitly appear in Eq. 11), increasing adaptation might squeeze competitors out of the market, such that the price mark-up would increase, thereby providing an additional incentive for adaptation. I explore this now.

Without entry/exit barriers, firms enter/leave the market until profits vanish. The number n is thus determined by the zero profit condition $\pi_i = 0$ that is equivalent to

$$p(nx_i) = c(a_i, k) + \frac{nqa_i}{x}, \tag{14}$$

such that the market price is equal to the average costs: the costs of defensive adaptation can be recovered from the quantity that is sold on the market. By substituting Eq. (13) for q in Eq. (14) we obtain

$$p(nx_i) = c(a_i, k) - a_i c_a(a_i, k). \tag{15}$$

Substituting this in Eq. (11) results in the market equilibrium number of firms determined by

$$(1 + \frac{1}{n\epsilon_p}) = \frac{c}{c - a_i c_a}. \tag{16}$$

In practice, n can only be an integer. To simplify the further argument we will disregard this to prevent distractions. Eq. (16) shows that the number of firms depends on the adaptation decision, but in an ambigous way if no additional properties of production costs are known. With increasing pollution the number of firms may change as well. There is a potential for a "squeezing out effect" due to pollution and adaptation. Yet, for the special case of an isoelastic production cost and demand function, the equilibrium number of firms derived from Eq. (16) is

$$n = \frac{1 - \epsilon_a}{\epsilon_a \epsilon_p}, \tag{17}$$

being *independent* from pollution. The number of firms n increases with both ϵ_p and ϵ_a. If (ceteris paribus) demand is less elastic or if defensive adaptation reduces costs more effectively, there are more producers in the market. There is more leeway for cost recovery due to higher price mark-up or less need for adaptation expenditures. Interestingly, n is also independent from the effect of pollution on production costs c_k. These statements have yet to be taken with care, since they correspond to the special case of isoelasticity.

It can now easily be seen that for $u < 0$ the equilibrium number of firms indeed yields a proper market solution: (i) Eq. (17) respects the condition Eq. (12) by elementary calculations; and (ii) $u < 0$ is equivalent to $n > 1$. With reference to Tab. 1 it can be concluded that in the cases (1) and (2) a Cournot equilibrium exists, while in case (3) no equilibrium exists. I therefore concentrate on the cases (1) and (2) in the remainder of the paper.

When n is determined by Eq. (17), the marginal condition for the production decision Eq. (11) simplifies to $p(nx_i) = (1 - \epsilon_a)c(a_i, k)$. The solution can therefore be summarized as follows:

Proposition 2. *Assume that demand and unit production costs are isoelastic. If* $u = \epsilon_a(\epsilon_p + 1) - 1 < 0$, *then there exists a Cournot equilibrium* $x_i^+, a_i^+, n^+ = \frac{1-\epsilon_a}{\epsilon_a \epsilon_p}$ *that is determined by*

$$p(n^+ x_i^+) = (1 - \epsilon_a)\, c(a_i^+, k), \tag{18}$$

$$-c_a(a_i^+, k)\, x_i^+ = q. \tag{19}$$

Here and in the following, the superscript $\cdot^+$ denotes the market solution, and $c^+ := c(a_i^+, k)$. As in Eq. (4) for the social planner case, the ratio of expenditures for defensive adaptation costs to production costs is described by the equation

$$-\epsilon_a = \frac{q a_i^+}{c^+ x_i^+}. \tag{20}$$

4. Over- and underadaptation in the Cournot equilibrium

The inefficiency of the oligopolistic solution is obvious. The interesting question is yet *how* both solutions differ. How do both solutions change with respect to adaptation costs and pollution? Does the market spend too much or too little for defensive adaptation? Does market failure cause under- or over-adaptation?

I define *under-adaptation* as unit production costs above the efficient level, i.e. $c^* < c^+$, and *over-adaptation* by $c^+ < c^*$. When there is more than one firm in the oligopoly, there may be too little defensive adaptation, since the benefits of adaptation only contribute to the profits of the firm that undertakes it. On the other hand, since the adaptation decision is linked to economies of scale, and therefore to the number of competitors, there might be an incentive for overspending in defensive adaptation. Finally, increasing revenues from mark-up pricing in oligopoly may finance more adaptation. At the current stage of the argument it is unclear which of these effects is dominant, and ambiguous results may be expected. The following paragraphs solve these questions step by step.

I first ease the comparison of the market solution and the social planner by using the parameter α from the social planner solution Eq. (2), Eq. (3). By setting $\alpha = (1-\epsilon_a) > 1$, and by replacing q with $\tilde{q} = \alpha q n$, it is straightforward to compute that the optimal solution of this modified equation system is *formally* equivalent to the oligopoly solution Eq. (18), Eq. (19). This means that the oligopoly solution is identical to that of a social planner that accounts for productions costs that are multiplied by the factor $(1 - \epsilon_a) > 1$ and adaptation costs multiplied by the factor $n(1-\epsilon_a) > 1$. Since $1 < \alpha$ and $q < \tilde{q}$ the replaced paramters can be interpreted as a situation with less effective adaptation and more pollution. The oligopoly market behaves like a counterfactual social optimum with less favourable environmental conditions.

Next turn to the comparative statics of the Cournot equilibrium. This is straigt-forward due to the reduction to a modified social planner solution above. Since $\frac{d\tilde{q}}{dq} = n(1 - \epsilon_a)$, Eq. (6)-Eq. (9) yield

$$\frac{dx_i^+}{dq} = -\frac{\epsilon_p}{(1-\epsilon_a)u}\frac{a_i^+}{c^+}, \tag{21}$$

$$\frac{da_i^+}{dq} = \frac{a_i^+}{qu}, \tag{22}$$

$$\frac{dx_i^+}{dk} = -\frac{\epsilon_k\epsilon_p}{u}\frac{x_i^+}{k}, \tag{23}$$

$$\frac{da_i^+}{dk} = -\frac{\epsilon_k(1+\epsilon_p)}{u}\frac{a_i^+}{k}. \tag{24}$$

These expressions have the same signs as in the social optimum. The cases (1), (2) from Tab. 1 therefore apply to the market solutions as well. Yet the sensitivity of the market solution to changes in unit adaptation costs and pollution makes a difference in terms of degree.

Now compare the social optimum with the market solution. Since $u < 0$, production decreases for higher pollution and higher adaptation costs due to Eq. (21), Eq. (22). As we have seen above, the oligopolistic solution is identical to a social optimum with higher k and q. Since also $n > 1$, for both cases

$$x_i^+ < x_i^* = x^* \tag{25}$$

Comparing the adaptation decision is less obvious, but it can be shown (in Appendix B) that due to the convexitiy properties of production costs and demand function

$$x_i^+ < x^* \Leftrightarrow a_i^+ < a_i^* \tag{26}$$

for both cases (1) and (2). The main conclusion of Eq. (25) and Eq. (26) can thus be summarized as follows.

Proposition 3. *If demand and unit production costs are isoelastic and $u < 0$, there is under-adaptation in the Cournot equilibrium and it is produced less than would be socially optimal.*

It should be noted that it remains open whether the total amount of adaptation $n^+a_i^+$ is above or below $n^*a_i^*$. It holds that $n^+a_i^+ > n^*a_i^*$ if and only if $(n^+)^{(\epsilon_a+\epsilon_p)\epsilon_p^{-1}} > (1-\epsilon_a)$. Although there is under-adaptation in the market, total adaptation expenditures of all firms might be too high.

5. Welfare effects of pollution

When pollution increases it can be expected that welfare decreases. Until now it yet remains unclear *how* the welfare loss from the externality changes. This is determined in this section. Welfare in the social planner case is given by $W^S = U(x^*) - c^*x^* - n^*qa_i^*$, and in the Cournot oligopoly by

$$W^M = U(n^+x_i^+) - n^+c^+x^+ - n^+qa_i^+.$$

Both W^S and W^M depend on the amount of pollution k. With welfare in the absence of pollution denoted by $\bar{W}^S$ and $\bar{W}^M$, respectively, the (total) welfare loss from pollution is defined as $\bar{W}^S - W^S$ for the social planner, and $\bar{W}^M - W^M$ in the oligopolistic market. The marginal welfare loss from pollution is thus $-\frac{dW^S}{dk}$ and $-\frac{dW^H}{dk}$. For a given amount of pollution, the difference $\Delta = W^S - W^M$, called welfare loss from market failure, compares welfare between the optimal solution and the market equilibrium. It measures the degree of market failure and is always positive since the Cournot solution is not efficient. The welfare loss from market failure may also change with k.

To simplify calculations, I concentrate on isoelastic demand and production costs. It is assumed that case (1) or (2) (with an existing market solution) applies. Already under these conditions a spectrum of different crucial cases appear. The results of the preceeding sections already show that the produced quantity decreases with pollution – both in the market and the optimal solution (cf. Tab. 1). Expenditures for defensive adaptation costs might increase or decrease depending on the case.

It is straightforward to determine that the welfare loss increases with pollution,

$$-\frac{dW^S}{dk} = x^* c_k^* = \epsilon_k \frac{c^* x^*}{k} > 0, \tag{27}$$

by using Eq. (2) and Eq. (3). In the market solution

$$-\frac{dW^M}{dk} = \epsilon_a c^+ n^+ \frac{\partial x_i^+}{\partial_k} + n^+ x_i^+ c_k^+ = \epsilon_k \frac{\epsilon_a - 1}{u} \frac{c^+ n^+ x_i^+}{k} > 0, \tag{28}$$

due to Eq. (18), Eq. (19) and the comparative statics Eq. (23). The marginal welfare loss includes the effects from (i) increased production costs, (ii) expenditures for defensive adaptation, and (iii) changes in market structure. In the market solution, welfare decreases with pollution as well, but at a different rate. Note that $\frac{\epsilon_a - 1}{u} > 1$, such that the market solution is more sensitive to pollution in a situation with comparable adaptation and production levels.

By using the comparative statics Eq. (8), Eq. (9), and Eq. (23), Eq. (24), respectively, the second derivates are

$$-\frac{d^2 W^S}{dk^2} = -\epsilon_k \left(\frac{\epsilon_k(\epsilon_p + 1)}{u} + 1\right) \frac{c^* x^*}{k^2}, \tag{29}$$

$$-\frac{d^2 W^M}{dk^2} = -\epsilon_k \frac{\epsilon_a - 1}{u} \left(\frac{\epsilon_k(\epsilon_p + 1)}{u} + 1\right) \frac{c^+ n^+ x_i^+}{k^2}. \tag{30}$$

Again, both expressions formally only differ by the factor $\frac{\epsilon_a - 1}{u}$. More importantly, they have an indeterminate sign. The welfare loss from pollution is convex both in the market and optimal solution if and only if

$$\frac{\epsilon_k(\epsilon_p + 1)}{u} + 1 < 0. \tag{31}$$

Finally, turn to the welfare loss from market failure Δ. By employing the above Eq. (27) and Eq. (28),

$$\frac{\partial \Delta}{\partial k} = -\frac{\epsilon_p}{k}\left(c^* x^* + \frac{1 - \epsilon_a}{u} c^+ n^+ x_i^+\right) \tag{32}$$

$$= \frac{\epsilon_k}{\epsilon_a} \frac{q}{k}\left(n^* a_i^* - \frac{\epsilon_a - 1}{u} n^+ a_i^+\right). \tag{33}$$

The second equality is due to Eq. (4) and Eq. (20). This expression has an indeterminate sign, depending on a relation of the production costs or on the expenditures for defensive adaptation, respectively. A special case applies when the total adaptation expenditures are higher in the oligopoly than in the social optimum. Since $\frac{\epsilon_a - 1}{u} > 1$, Eq. (33) shows that for $na_i^+ > n^* a_i^*$ higher pollution increases welfare loss from market failure. Otherwise, the effect remains ambiguous. Recall from the last section that both is possible.

6. The complete effects of increasing pollution

The above analysis shows that the three cases introduced in Tab. 1 are crucial when consequences of the interdependency of adaptation and market structure are considered. Only cases (1) and (2) lead to a Cournot equilibrium, where the parameter u is negative. In these cases production always decreases for higher levels of pollution, while adaptation may increase or decrease depending on whether demand is inelastic or elastic. The comparison of the social optimum with the oligopolistic market shows that production is always lower in the market, and that rising unit production cost from pollution are not set to the efficient level by adaptation. The loss from this market failure may yet decrease or increase with pollution, depending on the sign of Eq. (33). This condition contains the paramter u, but this does not determine the effect completely. Finally, condition Eq. (31) shows that the welfare loss may be convex or concave in the amount of pollution. This is, again, not completely determined by the sign of u and the demand elasticity. Combinatorically, there may thus be potentially eight cases, of which, however, only three cases can occur.

Proposition 4. *If a Cournot equilibrium exists, and if both demand and unit production costs are isoelastic, increasing pollution has the following effects: (i) production x^+ decreases, (ii) welfare decreases, (iii) there is under-adaptation, (iv) defensive adaptation a_i^+, welfare loss from market failure Δ, and total welfare loss change according to one of the cases given in Tab. 2.*

A complete proof is given in Appendix C.

The cases (1a) and (1b) further refine the former case (1) in Tab. 1. Recall that case (3) in Tab. 1 is not considered here since for $u > 0$ no Cournot equilibrium exists. It holds in all cases that

$$\frac{dc^+}{dk} = -\frac{\epsilon_k}{u}\frac{c^+}{k} > 0,$$

due to Eq. (24), i.e. even if defensive adaptation increases with pollution, the unit production costs are still rising.

case	(1a)	(1b)	(2)
description	inelastic demand	inelastic demand	elastic demand
	& $\epsilon_k > \frac{1}{\epsilon_p+1} - \epsilon_a$	& $\epsilon_k < \frac{1}{\epsilon_p+1} - \epsilon_a$	
adaptation	increasing	increasing	decreasing
loss from market failure	convex inc.	concave inc.	convex dec.
total welfare loss	convex inc.	concave inc.	concave inc.

Table 2: All cases for the effects of increasing pollution.

The differences due to the demand elasticity were already discussed in Sec. 2. When demand is elastic (case 2), rising production costs lead to strongly decreasing demand, such that there are less incentives to spend for defensive adaptation. Due to pollution, the market is shrinking at a rate that requires a reduction of adaptation. Decreasing adaptation reduces economies of scale such that the cause of market imperfection is less dominant, leading to less welfare loss in the oligopoly compared to the social planner. Although there is a rising total welfare loss from pollution, the share of this loss that is attributed to market failure is getting smaller. In case (2), pollution partially "cures" market failure. This effect is strong enough to make total welfare loss a concave function in k.

In the cases (1a) and (1b) the inelastic demand makes it profitable to increase adaptation (as intuition would suggest for all cases), since prices strongly increase due to reduced production. This gives revenues to cover adaptation costs. Since this effect increases with pollution, welfare loss from market failure increases. In case (1b) the elasticity of production costs to pollution ϵ_k is lower than the joint effect of defensive adaptation $-\epsilon_a$ and the market adjustments $(\epsilon_p + 1)^{-1}$. The welfare loss from market failure is thus only a concave function in k. Only if pollution increases production costs with an elasticity that cannot be off-set by defensive adaptation and adjustments of the market (case 1a), the welfare loss is a convex function in k. In the presence of such a strong externality, the loss from market failure convexly increases as well. In both cases (1a) and (1b), considering the adaptation decisions implies increasing market failure from pollution. Yet only in case (1a) this effect may become excessive.

7. Discussion

The above shows that there is a welfare loss when adaptation is left to the market. What is then, precisely, the underlying market failure? The problems arise due to the oligopolistic market structure, but how does the possibility of adaptation cause this? Since the number of firms is bounded, there is an option for mark-up pricing. The higher revenues can be used to finance more adaptation, with the side effect that competitors that do not expand their adaptation expenditures suffer from higher production costs and may be driven out of the market. This would, in turn, increase mark-up prices and thus set incentives for over-adaptation. On the other hand, with more than one firm in the market, there is an incentive for under-adaptation since only the individual firm benefits from private adaptation, although other firms could do so as well. The analysis revealed which of these effects dominate. The crucial point here is the assumption that the effects of adaptation are independent from the quantity produced, being the core reason for the oligopoly to emerge.

For the case of constant pollution, this argument of endogenous market structure boils down to the special case analyzed by Dasgupta and Stiglitz (1980). In their interpretation, defensive adaptation has an analogue in process innovation, where the innovation costs are like fixed costs, and benefits of innovation are private. That gives a competitive advantage, increases economies of scale, but leads to duplication of the innovation compared to the social planner. The interpretation as defensive adaptation or as innovation is not only a formal analogy. It is likely that many adaptations to pollution require new technologies or organisational innovations. For the case of climate change that is already claimed in some literature (e.g. Berkhout et al., 2006). We therefore have an analogy and a fresh new view on adaptation. The present paper extends this analysis by considering pollution as an influence on the cost reductions achievable by innovation. Since the marginal effect of adaptation increases with higher pollution, this would mean in the analogy that an external effect improves the benefits of research and development. In this sense, the results of the paper can be applied to any case where an externality (be it from pollution or something else) improves the outcome of activities to reduce production costs.

In environmental economics and the integrated assessment of climate change, the damage function that assigns a negative external effect to the level of pollution is a core category. The analysis of this paper indicates that, however, two types of damage functions need to be distinguished. The first, that may be called the “basic damage function”, describes damages under the assumption that the victims of an externality do not undertake any effort to reduce that damage. The second, that may be called “optimized damage function”, assumes that — given a portfolio of adaptations — the victims select the optimal option to avoid negative consequences. In the same vein, Tulkens and van Steenberghe (2009) distinguish between “suffered damage costs” and the “optimally adapted damage cost function", and Fankhauser (1996) between "adaptation costs" and "residual damage costs". Even though the basic damage function might be convex, the optimized damage function can become concave. Of course, there might be other damage functions between the basic and the optimized damage function, when, e.g., institutional constraints or bounded rationality are considered. In this paper, the basic damage function is the increase of unit production costs from pollution. The optimized damage function for a firm determines the profit loss if the firm selects the optimal level of defensive adaptation and adjusts its output. In the aggregate of all producers and consumers in a given market, the total welfare loss from pollution represents a further example for an optimized damage function. It should be carefully noted that this entails two interrelated types of adaptation: *defensive adaptation* to reduce increasing production costs from pollution, and *market adaptation* by adjusting quantities or prices.

8. Conclusions

This paper aims at contributing to the question about the need of adaptation policies in the presence of adaptation costs that are independent from the quantity of production. It is shown that this leads to economies of scale that are associated with market failure. It is therefore crucial to know whether this leads to over- or under-adaptation. The paper further determines how the welfare loss from pollution increases, and how pollution determines the welfare loss from market failure.

It is investigated how the Cournot equilibrium changes in comparison to a social planner solution. The analysis is based on the assumption that pollution negatively affects unit production costs, but that this effect can be off-set with defensive adaptation. Adaptation is a private good that improves production costs for the whole firm. If the amount of adaptation would be exogeneously set, the associated expenditures were fixed costs. These fixed costs are at the root of the resulting oligopolistic equilibrium, where it is assumed that there are no entry or exit barriers. Firms simultaneously decide on market participation, production and adaptation. The situation becomes complicated since the adaptation decisions determine economies of scale and thus the number of firms – the market structure is therefore endogenous. This, in turn, determines the adaptation and production decision. The core results are shown for isoelastic demand and unit production cost functions. This simplification already yields a spectrum of crucial cases that may serve as a starting point for further analyses.

The results are as follows. Due to the oligopolistic structure, the market equilibrium deviates from the social optimum. Since there are no fixed costs except adaptation expenditures in the model, the market failure is caused by adaptation. As a consequence, there is always under-adaptation to pollution in the sense that unit production costs are above the efficient level. While it might be intuitive that defensive adaptation increases with higher pollution, this is only true if demand is inelastic. Otherwise, market adaptation is so strong such that less adaptation expenditures can be recovered from revenues. This cost recovery is a crucial issue for the market solution, while in the social optimum there is also a case (corresponding to an inexistent market solution) where both defensive adaptation and production increase with emissions. In the cases where a market equilibrium exists, demand elasticity determines whether the market shrinks — making it profitable to spend less for defensive adaptation —, or whether defensive adaptation expands. In both these cases production decreases with pollution. Although welfare is generally reduced by pollution, there are different effects depending on further conditions. When demand is elastic, the total welfare loss from pollution is a concave function of the amount of pollution. For inelastic demand, it is concave or convex depending on a further condition that compares the direct effect of pollution on production costs with the indirect effects of defensive adaptation and market adjustments. If the direct effect is weaker, the function is concave as well. It is only convex if demand is inelastic and the direct effect is comparatively strong. These three cases illustrate that the standard assumption of a convex damage function in environmental economics is just a special case. With elastic demand the standard convexity properties break down. This is in line with the thoughts presented by Starrett (1972); Winrich (1982) and others. More importantly, it can be seen that the welfare loss from market failure is reduced by pollution if demand is elastic. Pollution then “cures” market failure. This is linked to the result that defensive adaptation decreases in this case. On the other hand, the welfare loss from market failure increases for inelastic demand. This relationsship is even convex in the case where the total welfare loss is a convex function of pollution as well.

Independently from which of the cases analysed in this paper actually applies to a concrete market, the results indicate that existing institutions for market regulation of oligopolies need to be adjusted to rising pollution levels. It may even be the case that new market failures arise in sectors that have low fixed costs, but are now increasingly under pressure to adapt. For the special case of adaptation to climate change it follows from the model in this paper that there is no requirement for specific regulations targeted at efficient adaptation. It is, instead, required to mainstream the effects of climate change into existing market regulation.

Appendix A. Comparative statics of social planner

The social planner solution is determined by Eq. (2),Eq. (3), here stated again as

$$U'(x^*) = \alpha c(a^*, k), \tag{A.1}$$

$$-\alpha c_a(a^*, k)\, x^* = q, \tag{A.2}$$

since $x_i^* = x^*, a_i^* = a^*$. The total differential is

$$U'' dx = \alpha(c_a da + c_k dk), \tag{A.3}$$

$$-\frac{1}{\alpha} dq = c_a dx + x c_{aa} da + x c_{ak} dk. \tag{A.4}$$

It follows from Eq. (A.3) that

$$\frac{dx}{da} = \frac{\alpha c_a}{U''} + \frac{\alpha c_k}{U''}\frac{dk}{da}, \tag{A.5}$$

$$\frac{dx}{dk} = \frac{\alpha c_a}{U''}\frac{da}{dk} + \frac{\alpha c_k}{U''}. \tag{A.6}$$

First consider the case where the unit cost of adaptation q changes *ceteris paribus*, i.e. $dk = 0$. It then follows from substituting Eq. (A.5) into Eq. (A.4) that

$$\frac{dx}{dq} = -\frac{c_a}{\alpha c_a^2 + x U'' c_{aa}}, \tag{A.7}$$

Eq. (A.7) together with Eq. (A.5) yields

$$\frac{da}{dq} = \frac{dx/dq}{dx/da} = -\frac{1}{\alpha}\frac{U''}{\alpha c_a^2 + x U'' c_{aa}}. \tag{A.8}$$

I now turn to the effect of *ceteris paribus* changing pollution, i.e. $dq = 0$. It follows from Eq. (A.4) that

$$\frac{dx}{dk} = -\frac{x c_{aa}}{c_a}\frac{da}{dk} - \frac{x c_{ak}}{c_a},$$

and equating with Eq. (A.6) yields

$$\frac{da}{dk} = -\frac{x U'' c_{ak} + \alpha c_a c_k}{x U'' c_{aa} + \alpha c_a^2}, \tag{A.9}$$

and by analogue calculations

$$\frac{dx}{dk} = \frac{\alpha x(c_k c_{aa} - c_a c_{ak})}{xU'' c_{aa} + \alpha c_a^2}. \tag{A.10}$$

These expressions are now simplified using elasticities. Due to Eq. (2)

$$xU'' = \frac{U'}{\epsilon_p} = \frac{\alpha c}{\epsilon_p}. \tag{A.11}$$

The (identical) denominator in Eq. (A.7)–Eq. (A.10) is thus equal to

$$\alpha \frac{c^2}{a^2} \frac{\epsilon_a}{\epsilon_p} (\epsilon_a \epsilon_p + \epsilon_a - 1).$$

This can now be applied to all four equations. Define $u := (\epsilon_a \epsilon_p + \epsilon_a - 1)$. Eq. (A.7) boils down to

$$\frac{dx}{dq} = -\frac{\epsilon_p}{\alpha u} \frac{a}{c}. \tag{A.12}$$

With Eq. (A.11) and Eq. (4),

$$\frac{da}{dq} = \frac{a}{qu} \tag{A.13}$$

is obtained. With the cost elasticity of pollution $\epsilon_k = c_k \frac{k}{c} > 0$, the numerator of Eq. (A.10)

$$\alpha x(c_k c_{aa} - c_a c_{ak}) = -\alpha \epsilon_a \epsilon_k \frac{c^2 x}{a^2 k} > 0,$$

and

$$\frac{dx}{dk} = -\frac{\epsilon_k \epsilon_p}{u} \frac{x}{k}. \tag{A.14}$$

By Eq. (A.11), the numerator of Eq. (A.9) equals

$$\alpha \epsilon_a \epsilon_k \frac{1 + \epsilon_p}{\epsilon_p} \frac{c^2}{ak},$$

yielding

$$\frac{da}{dk} = -\frac{\epsilon_k (1 + \epsilon_p)}{u} \frac{a}{k}. \tag{A.15}$$

Appendix B. Comparison of market and social optimum

This section shows that $x_i^+ < x_i^* \Leftrightarrow a_i^+ < a_i^*$.

The inequality $x_i^+ < x_i^*$ implies that

$$-\frac{q}{x_i^+} < -\frac{q}{x_i^*}.$$

Consequently, due to Eq. (19) and Eq. (3), $c_a(a_i^+, k) < c_a(a_i^*, k)$, such that the convexity of c implies $a_i^+ < a_i^*$, being the first direction of the proposition.

Now assume that $a_i^+ < a_i^*$, such that the monotonicity of c results in

$$c(a_i^+, k) > c(a_i^*, k) > 0.$$

Thus also $(1 - \epsilon_a)c(a_i^+, k) > c(a_i^*, k)$, since the first term is greater than one. Then Eq. (18) and Eq. (2) imply $p(n^+ x_i^+) > p(n^* x_i^*)$. Since $n^+ > 1 = n^*$, the monotonicity of p implies that $x_i^+ < x_i^*$.

Appendix C. Proof of the complete effects of increasing pollution

This appendix provides the proof of Prop. 4.

(i) The production of a single firm x_i^+ decreases with k due to the comparative statics Eq. (23). Since the number of firms is independent from k due to Eq. (17), total production x^+ decreases as well.

(ii) Welfare decreases with pollution by Eq. (28).

(iii) Under-adaptation for all cases is already stated in Prop. 3.

(iv) Adaptation: The difference between case (2) on the one hand, and case (1a), (1b) is obvious by comparing with Tab. 1. Recall that Eq. (21)-Eq. (24) show that the comparative statics for the oligopoly solution have the same signs. Thus, adapation is increasing with pollution in case (1a), (1b), while in case (2) the opposite holds.

(iv) Total welfare loss: Recall that the welfare loss is convex if Eq. (31) holds. In case (2) this is impossible since $\epsilon_p + 1 < 0$, and $u < 0$ by assumption. In the cases (1a) and (1b) with $0 < \epsilon_p + 1$, Eq. (31) is simply equivalent to the condition $\epsilon_k < \frac{1}{\epsilon_p+1} - \epsilon_a$.

(iv) Welfare loss from market failure: By defining

$$v := (a^* - \frac{\epsilon_a - 1}{u} n a_i^+), \tag{C.1}$$

$$\beta := \frac{\epsilon_k}{\epsilon_a} q < 0, \tag{C.2}$$

Eq. (33) can be written as

$$\frac{\partial \Delta}{\partial k} = \beta \frac{v}{k}. \tag{C.3}$$

Now use the elasticities and the comparative statics Eq. (9), Eq. (24) to determine

$$\frac{dv}{dk} = -\frac{\epsilon_k(\epsilon_p + 1)}{u}(a^* - \frac{\epsilon_a - 1}{u} n a_i^+) = \mu \frac{v}{k}, \tag{C.4}$$

with

$$\mu := -\frac{\epsilon_k(\epsilon_p + 1)}{u}. \tag{C.5}$$

Since $u < 0$, μ has the same sign as $(\epsilon_p + 1)$. Eq. (C.4) represents a differential equation for v with respect to k that is solved by

$$v = v_0 k^\mu, \tag{C.6}$$

where v_0 is a constant that needs to be chosen properly. The welfare loss from market failure $\Delta(k) > 0$ in the presence of pollution k can then be determined by integrating Eq. (C.3) with respect to k as

$$\Delta(k) = \int_0^k \beta \frac{v_0 \kappa^\mu}{\kappa} d\kappa = \frac{\beta}{\mu} v_0 k^\mu. \tag{C.7}$$

In case (2), μ is negative, such that Eq. (C.7) shows that Δ is convexly decreasing in k as stated in Tab. 2. In case (1b), the condition $\epsilon_k < \frac{1}{\epsilon_p+1} - \epsilon_a$ is equivalent to $0 < \mu < 1$, making Δ an increasing but concave function in k. By the same argument $1 < \mu$ in case (1a), yielding a convex function.

It has thus been shown that all the properties given in Tab. 2 hold under the conditions given in the first row and the assumption that there is an interior solution of the oligopoly market.

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