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Efficiency properties of binary ecolabeling[☆]

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ABSTRACT

We investigate efficiency properties of binary ecolabels in a homogeneous good market with heterogeneous consumers. Faced with the minimum technology standard, firms make endogenous entry, certification, and price/quantity decisions. We consider both perfect and imperfect competition with or without sunk fixed costs. Our findings are as follows. Ecolabeling alone does not achieve the first-best outcome and, to achieve the second best, may need to set the standard less strict than the efficient level. Without sunk fixed costs, ecolabeling can achieve the first-best outcome provided that both the technology standard and the complementary pollution tax are set at efficient levels. With sunk fixed costs, however, differential excise taxes that would restore allocative efficiency induce more entry than optimal, and thus, can be even welfare decreasing relative to no tax outcome. Tightening the technology standard may ameliorate such an adverse effect of the corrective tax system by reducing excessive entry and pollution per output by the certified firms.

1. Introduction

Over the last two decades, ecolabeling has gained popularity not only as a means to resolve information asymmetry in environmental attributes between buyers and sellers of marketed commodities but also as a means to address economic inefficiency arising from externalities. Can ecolabeling be a complement or substitute for conventional policy instruments such as taxes and subsidies? Or does it only offer an imperfect mechanism for consumers to 'vote' for environmental quality, with which efficient outcomes are unattainable?

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Earlier theoretical studies (e.g. Amacher et al., 2004; Arora and Gangopadhyay, 1995; Bansal and Gangopadhyay, 2003; Conrad, 2005; Eriksson, 2004; Lombardini-Riipinen, 2005) have investigated these questions, either explicitly or implicitly, using vertical product differentiation models. In these studies, duopolists compete in price and environmental quality over which consumers have a hierarchical preference ordering. This line of research has generally established three important results. First, firms may overcomply with environmental regulation to attract environmentally aware consumers. Second, ecolabeling allows consumers to internalize their intrinsic tastes for environmental quality but not environmental externalities fully in their purchasing decisions. Third and most importantly, ecolabeling can be a complement to more conventional policy instruments such as taxes and subsides (e.g. Bansal and Gangopadhyay, 2003; Conrad, 2005; Lombardini-Riipinen, 2005).[1]

These studies, however, make two common assumptions that we wish to diverge from. First, these studies assume that consumers have perfect information about environmental quality in which firms compete. An implicit assumption therein seems that ecolabeling results in well-informed, if not perfect, purchasing decisions. Under such an assumption, firms fully compete in environmental quality. However, many ecolabeling programs worldwide award only a *binary* seal of approval to each product. With binary labels, firms do not face full incentives to internalize consumers' environmental tastes. It is unclear *a priori* whether the complementary result still holds with binary labels.

Second, these studies consider duopolists and no endogenous entry. This assumption is reasonable in an industry with significant entry barriers, in which the study of duopolists' behaviors may provide a reasonable approximation to an oligopolistic industry. There is no *a priori* reason to believe that the complementarity result still holds with active entry–exit in markets. It is well known in the international trade and the industrial organization literature (e.g. Pomfret, 1992; Bhaskar and To, 2004) that endogenous entry, even if a few oligopolists enter the market in equilibrium, can result in significantly different analysis and policy implications. Endogenous entry should *not*, of course, be a barrier to efficiency provided that there is no (substantial) entry barrier that fosters oligopolistic competition. With imperfect competition, however, a corrective tax that restores efficiency in the output market may have perverse effects on entry.

This paper investigates the efficiency properties of binary ecolabels in a homogeneous-good market with free entry, following closely the model of Bagnoli and Watts (2003). Consumers have heterogeneous preferences both for environmental product quality, which originates from impure altruism (Andreoni, 1989, 1990), and for aggregate environmental externality, which originates from purely altruistic motives.[2] Consumers internalize the former, but not the latter, in their consumption decisions. On one hand, the binary ecolabel induces consumers to purchase the product of firms that use clean technologies rather than the product of their rivals that do not. On the other hand, firms incur increased costs of production to meet environmental technology criteria for the ecolabel ("environmental standard" henceforth), hoping to attract more consumers and reduce competitive pressure from other firms. Thus, our model pins down the underlying trade-off laid out in Hotelling's seminal paper (Hotelling, 1929). Creation of an ecolabel in the market has an impact on industry composition, splitting the market between those that sell the labeled version and those that do not. Given consumers' heterogeneous tastes for green products, there is an associated equilibrium composition of the industry for each level of environmental standard, as it has differential effects on the costs of production, on one hand, and on consumers' marginal willingness-to-pay for the labeled good, on the other hand.

Under these modeling assumptions, we find the following results. Binary ecolabeling per se cannot achieve the first-best outcome. With a complementary Pigouvian tax, however, full efficiency can be

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[1] Bansal and Gangopadhyay (2003) consider the effects of uniform versus discriminatory ad valorem subsidy/tax policies in a model of duopolists in a homogenous-good market in which firms can choose from a continuum of pollution reduction technologies. Interestingly, they find both uniform and discriminatory subsidy policies reduce pollution while uniform and discriminatory tax policies increase it. Conrad (2005) and Lombardini-Riipinen (2005) independently extend these results in similar models, and find that first-best socially optimal level of environmental quality can be achieved through a mix of policy instruments.

[2] A large literature now exists, which finds the empirical evidence for green consumer behavior (e.g. Bjorner et al., 2004; Blend et al., 1999; Moon et al., 2002; Teisl et al., 2002).

restored. This efficient outcome cannot be achieved without ecolabeling for two reasons. First, without ecolabeling, firms cannot appeal to consumer's preferences for environmentally friendly products, and thus, the Pigouvian tax per se cannot internalize it. Second, ecolabeling can induce efficient investment in environmental technologies by imposing environmental standards. Furthermore, we show that the second-best environmental standard when ecolabeling is used alone must be lower than the first-best standard when used in conjunction with the optimal Pigouvian tax if and only if equilibrium quantity of the labeled product decreases in response to stricter standard. In addition, with free entry without sunk fixed costs, equilibrium outcomes are the same under all market structures: perfect, Bertrand, and Cournot competition. Thus the first-best standard, combined with the optimal tax, can attain full efficiency. These results imply that binary ecolabeling can be a complement, rather than a substitute, for conventional environmental policies.

It turns out that these results do not hold with endogenous entry with sunk fixed costs, however. Environmental technologies are often associated with sunk fixed costs, since at least some part of the costs of environmental technologies are not related to output quantities and the technologies are not directly transferable to other producers. We show that the corrective differential tax that would work in the absence of sunk fixed costs no longer works in the presence of such fixed costs. This second-best corrective tax can restore efficiency in the output market by correcting for both imperfect competition and environmental externality, but induces more entry than optimal, because it subsidies production thereby lowering average cost curves. We show, by construction of a simple numerical example, that such a second-best tax can be welfare decreasing relative to no tax outcome over a range of environmental standards. Importantly, the adverse impact of the corrective taxes can be mitigated by imposing a stringent ecolabeling standard, for it can reduce both excessive entry and pollution per output of the certified firms.

Our paper is most closely related to Ibanez and Grolleau (2008) and Bagnoli and Watts (2003). Ibanez and Grolleau (2008) consider a model of duopolists who play the three-stage game of technology choice, ecocertification, and price competition and find that ecolabeling per se cannot fully internalize environmental externalities to the optimum. Their model setup is similar to the model of Bertrand duopolists competition cited above (Amacher et al., 2004; Arora and Gangopadhyay, 1995; Bansal and Gangopadhyay, 2003; Conrad, 2005; Lombardini-Riipinen, 2005), but is distinct because in their model, the binary nature of ecolabeling is explicit as in ours. Though our results are consistent with their main result, we differ on a number of important accounts. First, unlike theirs, we do not model consumers beliefs explicitly—ours is not a signaling model. Because we assume no errors in certification and auditing so that no firms that violate the standard can obtain an ecolabel. Thus upon labeling, information asymmetry no longer plagues economic efficiency. This point is important, because we obtain the same result as Ibanez and Grolleau that binary ecolabeling per se cannot achieve efficiency even in the absence of information asymmetry and imperfect competition, both of which are essential features of Ibanez and Grolleau. More importantly, we show that in the absence of information asymmetry, the first-best outcome can be achieved by a combination of efficient environmental standard and tax even under imperfect competition. Thus our paper helps to disentangle sources of inefficiency with binary ecolabeling.

On the other hand, Bagnoli and Watts (BW) (2003) consider a homogenous-good market in which firms may engage in social activities (a public good) that are linked to the sales of a private good. Firms choose to sell either the linked version, the non-linked version, or neither. As in ours, binary product type, perfect information, and endogenous entry are all the important features of their model. In fact, we closely follow their modeling strategies. Our model, however, differs substantially from theirs on one important account. In their model, consumption of one unit of the private good is linked to a *fixed* amount of the public good provision. In other words, neither firms nor ecolabeling agency choose technologies endogenously in theirs while in ours, *both* production costs *and* public good provision (in pollution reduction) are a function of production technologies, which are chosen by the firms. This has two important implications for our results. First, unlike with the BW model, our modeling setup allows us to discuss the welfare impacts of remedial regulatory instruments *through their effects on environmental technologies* the firms choose—one of the main questions in ours as well as in the existing literature (Amacher et al., 2004; Arora and Gangopadhyay, 1995; Bansal and Gangopadhyay, 2003; Conrad, 2005; Eriksson, 2004; Lombardini-Riipinen, 2005). In this sense, our paper may be thought of as a bridge between the BW model, which captures the binary nature of ecolabeling, but leaves out endogenous technology choice, on one hand, and more conventional models based on vertical environmental quality differentiation (Amacher et al., 2004; Arora and Gangopadhyay, 1995; Bansal and Gangopadhyay, 2003; Conrad, 2005; Eriksson, 2004; Lombardini-Riipinen, 2005), which leave out the former, but incorporate the latter, on the other hand. Second, another undesirable implication of the BW model is that the overall environmental quality improves unambiguously as the entry into the labeled version increases. However, to the extent that environmental technologies are costly, the environmental standard must be lowered to induce more firms to certify, but the lower standard means higher pollution per output of the certified firms. Indeed, in our model, aggregate equilibrium pollution is not monotonically increasing or decreasing with the number of firms selling the labeled version. This point is critical in understanding one of our main results—that the corrective taxes induce excessive entry into the labeled version, which *may increase pollution and decrease welfare relative to no tax*.

Our paper is organized as follows. The next section describes institutional background on ecolabeling programs worldwide. Section 3 sets up our model, followed by a brief discussion of the first-best outcome of our economy in Section 4. We then establish efficiency and inefficiency properties of binary ecolabeling in Section 5. In Section 6, we extend our model to the case of sunk fixed costs. The last section discusses implications and limitations of our modeling strategies and concludes the paper.

2. Institutional background on binary ecolabels

This section discusses stylized facts about a criteria selection process for *Type I* ecolabeling programs, which motivates our modeling assumptions.[3] According to the International Organization for Standardization, *Type I* labels compare products in the same category and award labels to those that have desirable environmentally characteristics. An independent third-party organization develops the criteria and administers a certification and auditing process for its *Type I* labels. Thus *Type I* labels differ significantly from *Type II* labels, which are simply environmental claims made about goods and services by their sellers. *Type III* labels are similar to *Type I* labels, except that the former provide a menu of a product's environmental impacts throughout its life cycle while the latter provide a binary seal of approval without providing such information. Nutrition labels on food products are a good example of *Type III* labels. We focus on *Type I* labels, since our interest lies in the role ecolabels play as a voluntary mechanism to address environmental externalities and *Type I* labels are by far the most common among government-based ecolabeling programs around the world today.

Virtually all *Type I* ecolabeling programs follow three important steps in their certification processes. First, they select product categories for which ecolabels are to be developed. Second, they develop specific criteria that products in each product category must meet to obtain an ecolabel. Third, they either administer or monitor the auditing process in which applications for ecolabels are evaluated against the adopted criteria. Once the program office (or an independent certifier) certifies that all criteria are met, the applicants obtain a license to use an ecolabel but only for its approved product. Applicants often pay application fees, which cover the costs of auditing and certification, plus annual fees for use of ecolabels. The second step, criteria selection, is one of the key policy variables of interest in this paper.

Table 1 summarizes criteria selection processes for seven major ecolabeling programs worldwide. All these programs, except Swedish Environmental Choice and U.S. Green Seal, are established through governments' initiatives. Different programs use different product categories and choose different criteria through their own criteria selection processes. Nonetheless, their criteria selection practices show surprising similarities between themselves and, to some degree, to regulatory policy making. In all seven programs, an independent body consisting of a group of experts write draft criteria. Both environmental and industry stakeholders are involved in criteria development either as part of working groups or as outside consultants. Once the proposal for criteria is complete, it is made

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[3] This section is based on these programs' websites as well as various summary documents such as Global Ecolabelling Network (2004), OECD (1997, 2005), and UNEP (2006).

Table 1
Criteria development process for selected ecolabeling programs.

Ecolabeling program	Primary organizing entity	Decision-making authority	Primary drafter of criteria	Env. stakeholder involvement	Industry involvement	External reviews	Life-cycle assessment	Target market share	Duration of criteria
1. EU Flower Label	Multi-national gov.	Regulatory Committee	EC with help of working group [a]	Yes	Yes	Yes	Yes	5–30%	3 years
2. Swedish Environmental Choice	Private non-profit	SSNC Board [b]	SSNC with help of consultants	Yes	Yes	Yes	Yes	10–15%	N.A.
3. Nordic Swan	Multi-national gov.	National Board	Working group of experts	Yes	Yes	Yes	Yes	N.A.	N.A.
4. Canada Environmental Choice	National gov.	Terra Choice Review Committee [c]	Terra Choice	Yes	Yes	Yes	Yes	20%	3 years
5. Germany Blue Angel	National gov.	Fed. Env. Agency Jury Umweltzeichen	Fed. Env. Agency	Yes	Yes	Yes	Yes	N.A.	Maximum of 4 years
6. U.S. Green Seal	Private non-profit	Environmental Standards Board	Working group of experts	Yes	Yes	Yes	Yes	Maximum of 10–20%	3 years
7. Japan Eco-Mark	National gov.	Promotion Committee	Working group of experts	Yes	Yes	Yes	Yes	Small percentage	3–5 years

Source: OECD (1997) and program websites

[a] European Commission (EC).

[b] Swedish Society of Nature Conservation (SSNC).

[c] Canadian Environmental Choice Programme is a government program, yet is delivered by a private company, Terra Choice Environmental Services Inc.

available for the public and other interest groups to review and comment. The final draft criteria are then presented to a decision-making body for approval.

The criteria are set so that ecolabeled products represent only a small portion of the *existing* market. To reflect technological advances, these criteria are revised every three to five years. Lastly, all seven programs use some type of life-cycle assessment—i.e. assessing environmental impacts of production technologies and inputs per unit of production throughout the life cycle of each product. Since full life-cycle assessment is complex and expensive, many of these programs often focus on a limited set of environmental attributes such as recycled content, reduced toxicity, pollution reduction, energy efficiency, and recyclable content. These criteria thus translate into the environmental impacts per unit of ecolabeled products.

3. Model

3.1. Consumers

Our basic setup follows closely Bagnoli and Watt (BW) (2003). The economy consists of a continuum of consumers indexed by $i \in [0, 1]$. Each consumer buys at most one unit of the commodity in question and chooses to buy the ecolabeled version, the non-labeled version, or neither. Consumers are heterogeneous in preferences. Consumer i's utility is given by

$$u(x, j, E; i) = \begin{cases} y - D(i, E) & \text{if } x = 0 \\ y + \sigma(i) - D(i, E) & \text{if } x = 1,\ j = l \\ y + \rho(i) + \sigma(i) - D(i, E) & \text{if } x = 1,\ j = nl \end{cases} \tag{1}$$

where y is the consumer's income, x is one if the consumer buys the commodity and zero otherwise, j equals l if the consumer buys the ecolabeled version and nl if non-labeled, $\sigma(i)$ is the monetary value of the consumption good x, $\rho(i)$ is the monetary value of 'participating' in green consumerism, and $D(i, E)$ is the monetary measure of environmental damages from pollution. Consumers may buy the ecolabeled version of the commodity for a variety of *private* motives. Such motives may include health concerns (e.g. organic foods), savings in electricity bills (e.g. energy-saving computers), and reputation and guilt (e.g. warm-glow green consumerism). Kotchen (2005, 2006) applied Andreoni's (1989, 1990) impure altruism concept in a general model of green consumerism. We follow this interpretation henceforth. Assume that $D_E > 0$ and $D_{EE} \geq 0$.

Each version of the product is associated with environmental characteristics. We assume that there exist summary statistics of the environmental characteristics such that aggregate pollution of the economy can be represented by

$$E = \omega_l Q_l + \omega_{nl} Q_{nl} \tag{2}$$

where Q_j is (equilibrium) quantity consumed of variant j, and ω_j serves a dual purpose of indexing environmental characteristics and pollution (in summary statistic) per unit of each variant. This modeling assumption is not only consistent with previous studies (Bansal and Gangopadhyay, 2003; Conrad, 2005; Eriksson, 2004; Lombardini-Riipinen, 2005) but also with the stylized fact about ecolabeling as discussed in Section 2.[4] In the BW model, ω s are fixed and firms do not choose them endogenously whereas in ours, ω s are variable and the firms choose them endogenously in response to regulatory instruments, which we shall discuss below.

We assume that $\rho(i)$ is a function of ω_l and that $\rho(i, \omega_l) = \gamma - \delta(\omega_l)i$ and $\sigma(i) = a - i$ with $a, \gamma, \delta > 0$ and $\delta' \geq 0$. This assumption implies, first, that a consumer with a smaller index have a larger willingness-to-pay premium for the ecolabeled good, and second, that the willingness-to-pay premium increases with improvements in environmental technologies. Note further that our formulation results in perfect correlation, either positive or negative, between consumers' impure altruism and pure environmental preferences. A consumer with a smaller index also obtains higher utility from pollution

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[4] This assumption does not necessarily limit the generality of our analysis and neither implies nor requires that the product's environmental attributes have a single dimension. In the concluding section, we discuss the condition under which the multiple dimensionality of attributes may result in the loss of generality of our analysis.

reduction if $D_i < 0$. It suffices here to note that our main results do not depend on this correlation. Furthermore, in the BW model, δ is constant, because ω_l is exogenously fixed whereas in ours, we allow consumers' willingness-to-pay premium to increase with improvements in environmental technologies. Lastly, as in Bagnoli and Watts (2003), we restrict the parameters of the model such that $\gamma > \delta$, which ensures that every consumer has some willingness-to-pay premium for the ecolabeled version.

Consumer i buys the ecolabeled variant if $y+\gamma-\delta i+a-i-D(i,E)-p_l > y-D(i,E)$ (or $\gamma-\delta i+a-i > p_l$) and $y+\gamma-\delta i+a-i-D(i,E)-p_l > y+a-i-D(i,E)-p_{nl}$ (or $\gamma-\delta i > p_l-p_{nl}$). Similarly, consumer i buys the non-labeled if $y+a-i-D(i,\ E)-p_{nl} > y-D(i,\ E)$ (or $a-i > p_{nl}$) and $\gamma-\delta i \le p_l-p_{nl}$. Consumer i buys neither if $a-i \le p_{nl}$ and $\gamma-\delta i+a-i \le p_l$. Note that since there is a continuum of consumers, each consumer ignores the marginal impact of her purchasing decision on overall environmental pollution. There is a marginal consumer, i_l, who is indifferent between buying the labeled and the non-labeled versions, and another marginal consumer, i_{nl}, who is indifferent between buying the non-labeled version and not buying the commodity at all. All consumers with $i \le i_l$ buy one unit of the labeled good; all consumers with $i_l < i \le i_{nl}$ buy the non-labeled good; and all consumers with $i > i_{nl}$ do not buy the good. Thus we can describe the demand system:

$$Q_l = i_l = \frac{\gamma - p_l + p_{nl}}{\delta} \tag{3a}$$

$$Q_{nl} = i_{nl} - i_l = \frac{\delta a - \gamma - (1+\delta)\, p_{nl} + p_l}{\delta} \tag{3b}$$

Inverting the system, we can also obtain the inverse demand system:

$$P_l = (a+\gamma) - Q_{nl} - (1+\delta) Q_l \tag{4a}$$

$$P_{nl} = a - Q_{nl} - Q_l \tag{4b}$$

It is straightforward to derive demand systems in the cases where only one variant is sold in the market. Though we focus our exposition on the case where both variants of the product are sold to economize our space, cases with only one variant are implicit behind all of our analyses and results to follow.

3.2. *Firms*

In our economy, firms have equal access to technologies and make endogenous decisions about entry, environmental/production technologies, and prices/quantities. As a benchmark, we assume constant returns to scale—the marginal cost of production is independent of quantity with no fixed cost. We, however, assume that the marginal cost is convex in environmental quality: $MC(\omega) = c(\omega)$ with $c' < 0$ and $c'' > 0$. These assumptions are consistent with vertical product differentiation models (Amacher et al., 2004; Arora and Gangopadhyay, 1995; Bansal and Gangopadhyay, 2003; Cremer and Thisse, 1994; Eriksson, 2004; Lombardini-Riipinen, 2005). We relax this assumption in Section 6 in which we introduce both quadratic variable costs and fixed costs. We normalize aggregate pollution so that our technology space is confined to $\Omega = [0, 1]$.[5] For notational ease, we also define the marginal cost of production when firms make no abatement investment: $c_x \equiv c(1)$.

We shall consider three alternative market structures in the output market: perfect, Bertrand, and Cournot competition. We assume that firms play a generic three-stage game of entry, technology/certification, and pricing/output (Bagnoli and Watts, 2003; Mazzeo, 2002). Entry occurs until all incumbent firms obtain zero profits. Upon entry, firms choose whether to sell the ecolabel or the non-labeled, simultaneously with technology choice ω. Firms then choose output taking prices as given under perfect competition. If instead we assume imperfect competition, firms then choose either

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[5] The unit of firm is the plant level, so that each firm can have at most one value of ω. Thus in my model, no firm can choose to produce both the ecolabeled and the non-labeled goods. This modeling assumption is consistent with numerous standard models in the industrial organization literature.

prices (Bertrand) or quantities (Cournot). Here our model differs substantially from the BW model—in theirs, environmental technologies and associated (marginal) production costs are fixed, and therefore, neither the regulatory authority nor the firms have any control over the technology level ω of each variant of the product while in ours, they do.

3.3. Certification agency

Another departure from the BW model is that we assume there is an independent third-party organization, which exogenously sets a technology standard $\theta \in \Omega$.[6] For simplicity, we assume the cost of auditing is invariant with θ and normalized to zero. We assume no measurement errors, stochastic investment outcomes, or fraudulent labeling. Hence, all products with $\omega \leq \theta$ will be certified. Under these conditions, it is easy to show that without other corrective policies, firms selling the *l*-version choose exactly θ and firms selling the *nl*-version choose $\omega = 1$ (in the absence of other corrective policies) and that knowing this, consumers perfectly predict the ecolabeled version has $\omega = \theta$ and the non-labeled version has $\omega = 1$. Thus our model setup guarantees a separating equilibrium. This assumption allows us to focus on environmental externalities, isolating the effect of information asymmetry.[7] Lastly, we emphasize here that what we have in mind is that ecolabeling agency establishes a set of guidelines and criteria for production technologies and inputs. These criteria translate, in an abstract manner, into θ, which serves a dual purpose of summarizing the production technologies/inputs and measuring the life-cycle environmental impacts per unit.

4. The first-best outcome

What is the first-best outcome of this economy? As with previous studies (Amacher et al., 2004; Arora and Gangopadhyay, 1995; Bansal and Gangopadhyay, 2003; Cremer and Thisse, 1994; Eriksson, 2004; Lombardini-Riipinen, 2005), we consider the utilitarian welfare function. With quasi-linear preferences, utilities are directly comparable to costs. We can thus derive the total surplus of the economy by integrating utilities over i and subtracting costs:

$$W(i_l, i_{nl}, \omega_l, \omega_{nl}) = y + \gamma i_l - \frac{1}{2}\delta(\omega_l) i_l^2 - c(\omega_l) i_l + a i_{nl} - \frac{1}{2} i_{nl}^2 - c(\omega_{nl})(i_{nl} - i_l) - \int D(i, E) di \tag{5}$$

where aggregate pollution is $E = \omega_l i_l + \omega_{nl}(i_{nl} - i_l)$.

Under our assumptions, W is a concave function of each of the arguments. Taking the first-order condition, we have necessary and sufficient conditions for the interior optimum:

$$i_l : \gamma - c(\omega_l) + c(\omega_{nl}) - \delta(\omega_l) i_l + (\omega_{nl} - \omega_l) \int D_E(i, E) di = 0 \tag{6a}$$

$$i_{nl} : a - c(\omega_{nl}) - i_{nl} - \omega_{nl} \int D_E(i, E) di = 0 \tag{6b}$$

$$\omega_l : -c'(\omega_l) = \int D_E(i, E) di + \frac{1}{2} \delta'(\omega_l) i_l \tag{6c}$$

$$\omega_{nl} : -c'(\omega_{nl}) = \int D_E(i, E) di \tag{6d}$$

Conditions (6a) and (6b) are the familiar 'textbook' formula for social optimum with environmental externality, which says that the optimal level of output quantity is that which equates the marginal social benefit with the marginal cost of output. Conventional wisdom would argue that the optimal level of *abatement* is that which equates the marginal social benefit with the marginal cost of

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[6] One could, of course, consider a model with endogenous competition for environmental standard, just like a model of tax competition in the literature. Our model should be considered as one end of the spectrum in which both the standard and the complementary policies are exogenous whereas both would be endogenous in the other end of the spectrum.

[7] In the concluding section, we discuss the implication of imperfect monitoring and certification for our analysis and results.

abatement, for which output decisions are implicit. In our setup, however, both output and environmental product quality levels are explicitly determined jointly. Conditions (6c) and (6d) say that the optimal environmental product quality must equate the marginal social benefit with the marginal cost. Note that optimality requires that two variants of the commodity with different environmental technologies be sold even though firms have *a priori* equal access to the same technology set. This result is consistent with analogous studies (e.g. Cremer and Thisse, 1994; Lombardini-Riipinen, 2005), and more generally with the idea that consumers have preferences for product variety (see Dixit and Stiglitz, 1977). Lastly, if firms face fixed costs, there will be another pair of familiar break-even conditions that determine optimal numbers of firms in the economy. In Bagnoli and Watts (2003), the first-best optimum refers only to (6a) and (6b) (and additional entry conditions in the case of fixed costs), since technology levels ω_l and ω_{nl} are exogenously fixed.

5. Efficiency and inefficiency properties of ecolabeling equilibrium

Can binary ecolabeling achieve the first-best efficient outcome, either by itself or in conjunction with other policy instruments? To address this question, we first establish that without fixed costs, equilibrium outcome is the same regardless of market structures. We shall focus on the case in which the model parameters are such that both variants of the product are sold in equilibrium under perfect competition.

Under the competitive environment, firms maximize profits taking prices given and thus prices equal marginal costs for both variants. With constant marginal costs and no fixed costs, all firms obtain zero profits upon entry. Given the exogenous standard θ and increasing costs, firms choose to just meet this standard. Firms choosing to sell the non-labeled version would choose the business-as-usual level of technology $\omega_{nl}=1$. Note that firms cannot internalize consumers' taste parameter δ in technology choice, since they take prices as given. Since profits are equalized across two variants, firms are indifferent between selling the ecolabeled variant and selling the non-labeled variant. The market clears in equilibrium. Note that without fixed costs, the number of firms selling each version of the product is irrelevant under perfect competition. Because prices equal minimum average costs in equilibrium, without fixed costs, we have $p_l=c(\theta)$ and $p_{nl}=c_x$.

With Bertrand competition, without taxes, each firm selling the labeled version must choose $\omega_l=\theta$, for otherwise it will lose price competition in the output market. Similarly, each firm selling the non-labeled version must choose $\omega_{nl}=1$. Thus potential entrants observe the marginal costs $c_l=c(\theta)>c_x=c_{nl}$ at the time of entry decisions. If there is only one firm selling either version, then that single firm can set a monopoly price for that version. Since the monopoly price is higher than the marginal cost, the monopolist obtains a non-zero profit. With free entry, a potential entrant will enter the market and choose to sell the version for which there is a higher non-negative profit. If there are two or more firms selling each variant, firms selling the same version undercut each other's price until prices equal marginal costs. Thus in equilibrium, prices equal marginal costs regardless of the number of firms in each product variant. Therefore, Bertrand equilibrium prices and quantities are identical to those of competitive equilibrium.

With Cournot competition, firms compete in quantities taking the inverse demand (4) as given. As long as prices are higher than marginal costs, each firm makes a positive profit and entry continues. Clearly, as N_l and N_{nl} increase, prices converge to marginal costs. Thus again Cournot equilibrium prices and quantities are identical to those of competitive equilibrium. These logics are well explained in Bagnoli and Watts (2003).

Result 1. *With free entry without fixed costs, ecolabeling equilibrium is the same under perfect, Bertrand, and Cournot competition.*

Though not explicitly stated, this result is implicit in Bagnoli and Watts (2003). It must be clear from the above arguments that the overall size of entry and the entry into each variant become important for the welfare analysis of the market outcome *only in the presence of fixed costs*. We thus defer our discussion on the sorting behavior of firms into each variant and its welfare effects until

Section 6. Furthermore, since the market equilibrium is the same regardless of the market structures in the absence of fixed costs, we shall discuss the competitive equilibrium and compare it with the first-best outcome.

Using demand system (3), we can describe the equilibrium in terms of marginal consumers:

$$i_l^* = \frac{\gamma - c(\theta) + c_x}{\delta(\theta)} \tag{7a}$$

$$i_{nl}^* = a - c_x \tag{7b}$$

On the other hand, solving Eqs. (6a) and (6b), we see that the first-best optimum requires:

$$i_l^s = \frac{\gamma - c(\omega_l^s) + c(\omega_{nl}^s) + (\omega_{nl}^s - \omega_l^s)\int D_E(i, E^s)di}{\delta(\omega_l^s)} \tag{8a}$$

$$i_{nl}^s = a - c(\omega_{nl}^s) - \omega_{nl}^s \int D_E(i, E^s)di \tag{8b}$$

Comparing (7) with (8) it follows that $i_l^s \neq i_l^*$ and $i_{nl}^s \neq i_{nl}^*$ even if ecolabeling agency chooses the standard optimally at $\theta = \omega_l^s$. Moreover, Bagnoli and Watts (2003) argue (in their Propositions 2 and 3) that both Cournot and Bertrand competition lead to too little provision of a public good. An equivalent result in our setup would be $i_l^* < i_l^s$. However, comparing (7a) and (8a), we see that whether this inequality holds or not depends critically on the values of θ relative to ω_l^s and ω_{nl}^s. The difference occurs because all of these variables are endogenous in ours, but not in theirs.[8] Endogenous technology choice is not only consistent with the existing literature and the stylized fact about ecolabeling, but also important in understanding our main results in Section 6.

Result 2. *With free entry without fixed costs, binary ecolabeling per se cannot achieve the first-best outcome in all three market structures.* i_l^* *may be larger or smaller than* i_l^s, *depending on the values of* θ, ω_l^s, *and* ω_{nl}^s.

This result also somewhat parallels Ibanez and Grolleau (2008). However, in their model, duopolists compete in a signaling model. Thus both information asymmetry and imperfect competition obscure the result. Our result shows that even in the absence of asymmetric information and imperfect information, binary ecolabeling per se can never achieve the first-best outcome.

Even so, ecolabeling agency can influence the equilibrium outcome substantially by choosing a level of θ. What level of θ can and should the agency choose as the second best? We know from (6c) and (6d) that optimal environmental technology is that which equates marginal benefits and costs and that marginal benefits depend on equilibrium quantities. In the efficient outcome, both Q_l and Q_{nl} are chosen optimally. In the market equilibrium, however, output quantities depend on the level of standard chosen by the agency as shown in (7). Thus the second-best θ^{SB} must differ from the first-best level θ^s. Substituting (7) into (5) and differentiating it with respect to θ, we obtain the second-best condition:

$$-c'(\theta) = \left[1 - (1-\theta)\frac{i_l'(\theta)}{i_l(\theta)}\right] \int D_E(i, E)di \tag{9}$$

where the term in the bracket is less than 1 if and only if $i_l'(\theta) > 0$. Comparing (6c) and (9) and recalling $c' < 0$ and $c'' > 0$, we see $\theta^s < \theta^{SB}$ if and only if $i_l'(\theta) > 0$. Given the equilibrium quantity (7a), $i_l'(\theta) > 0$ if and

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[8] Indeed, in their setup, these important technology variables are exogenously set as if $\omega_l^s = \theta$ and $\omega_{nl}^s = 1$. To see why the inequality $i_l^* < i_l^s$ may not hold, suppose for simplicity $\delta > 0$ is constant. Substituting (7a) and (8a) and manipulating, we see that for the inequality to hold, the following must be true:

$$[c(\omega_l^s) - c(\omega_{nl}^s)] - [c(\theta) - c_x] < (\omega_{nl}^s - \omega_l^s)\int D_E(i, E^s)di$$

which says that the difference in the marginal cost differentials of the *l*-version over the *nl*-version between the first-best and the ecolabeling outcomes is smaller than the (per-unit) marginal damage differential.

only if

$$\frac{-c'(\theta)}{\gamma - c(\theta) + c_x} > \frac{\delta'(\theta)}{\delta(\theta)} \tag{10}$$

which says roughly the cost effect of θ dominates the demand effect. This establishes:

Result 3. *With free entry without fixed costs, the second-best standard is less strict than the first-best optimal standard for the ecolabeled product if and only if inequality (10) holds.*

Intuitively, this result occurs because of another trade-off ecolabeling agency must take into account. The stricter the standard, the more costly it is for firms to produce the ecolabeled version. The stricter the standard, the more the consumer might be willing to pay for the ecolabeled good. If the former effect is stronger than the latter, equilibrium quantity of the labeled version will be reduced. If the equilibrium quantity falls with the stricter standard, this becomes an additional cost of tightening the standard.

We now answer our second question: Can binary ecolabeling achieve the efficient outcome in conjunction with complementary policy instruments? The answer is yes. It turns out that we only need to impose an efficient pollution tax. To see this, let t be a tax per unit of pollution. Competitive firms facing this tax would choose quantity and technology such that $p_j = c(\omega_j) + t\omega_j$ and $-c'(\omega_j) = t$ for $j = l, nl$. Substituting these into (3) and manipulating, we have

$$i_l : \gamma - c(\omega_l) + c(\omega_{nl}) - \delta(\omega_l) i_l + (\omega_{nl} - \omega_l)t = 0 \tag{11a}$$

$$i_{nl} : a - c(\omega_{nl}) - i_{nl} - \omega_{nl} t = 0 \tag{11b}$$

$$\omega_l : -c'(\omega_l) = t \tag{11c}$$

$$\omega_{nl} : -c'(\omega_{nl}) = t \tag{11d}$$

Letting $t = \int D_E(i, E^s)di$ (i.e. marginal environmental damages), equation system (11) is identical to (6) except for (6c) and (11c). Since firms are identical *a priori*, unless there is a means to internalize consumer's demand for environmental technology, they will end up choosing the same technology. In this regard, ecolabeling agency can play two important roles. First, it offers information to consumers about environmental technologies firms use so that they can internalize their preferences for environmentally friendly products. Without this, two product varieties cannot be offered. Second, it can (and should) bring the environmental technology of the firms selling the labeled version to the efficient level by setting $\theta = \omega_l^s$.

Result 4. *With free entry without fixed costs, ecolabeling can achieve the first-best outcome in all three market structures provided that the regulator imposes an efficient pollution tax $t^s = \int D_E(i, E^s)di$ and the ecolabeling standard is set according to (6c).*

This result also explains why we need ecolabeling in the first place. If the goal is simply to correct for environmental externalities, we have better instruments, such as taxes and permit trading. However, efficient pollution taxes cannot fully internalize consumers' personal tastes $\rho(i)$ for environmentally friendly products. Ecolabeling can provide a means for consumers to vote for their own preferences by correcting asymmetric information.[9]

We made one important assumption in deriving this result—no sunk fixed costs of production. It turns out that this assumption is critical. We shall see that even when entry is "free", equilibrium outcomes exhibit substantial variation due to market structures.

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[9] In this connection, one may wonder why ecolabeling has to be binary. The economics literature seems relatively limited as to whether other modes of environmental labeling results in better welfare outcomes. We will discuss this point further in the concluding section.

Before turning to the case of endogenous entry with sunk fixed costs, it is useful to discuss corrective taxes that could be used to restore efficiency when the industry consists of a fixed number of firms due to substantial entry barriers. For ease of exposition, we shall consider the case of duopolists as in Conrad (2005), Cremer and Thisse (1994), Ibanez and Grolleau (2008), and Lombardini-Riipinen (2005). It has been established (Barnett, 1980; Katsoulacos and Xepapadeas, 1995) that with a fixed number of firms and no endogenous quality choice, efficient pollution taxes should be less than marginal environmental damages. Cremer and Thisse (1994) have shown that when quality choice is endogenous and no environmental externality exists, there is no *ad valorem* tax, either uniform or differential, that would achieve the first-best outcome in both qualities and prices (Cremer and Thisse, 1994, Proposition 2). Intuitively, this occurs because taxes need to correct for imperfect competition in *both* output/price *and* quality competition, but differential taxes can only correct one of them. In our case, corrective taxes need to correct for three market inefficiencies: environmental externality, imperfect competition in output/price, and imperfect competition in quality choice. We can show, however, combined with the environmental standard that sets the minimum quality standard, corrective differential taxes set lower than marginal environmental damages can restore full efficiency. Specifically, the corrective tax is a differentiated quantity or excise tax system such that:

$$t_j(\omega_j) = \tau_j + \omega_j t \tag{12}$$

where

$$\tau_j = Q_j^s \frac{dP_j}{dQ_j} \quad \text{and}\; t = \int D_E(i, E^s)di$$

This is essentially the (lump-sum) quantity tax system frequently discussed in public finance, except it is differentiated between the two variants for degree of imperfect competition and marginal environmental damages. Or put differently, one can think of this as a combination of excise tax τ_j and pollution tax t. This tax system can correct for imperfect competition and environmental externality in output/price, but not in technology/quality choice. However, the latter inefficiency can be addressed directly by enforcing the optimal technology standard. We focus on asymmetric Nash equilibrium (i.e. duopolists choose to sell different versions of the product) and summarize the result below. The proof is in Appendix A.

Result 5. *Consider duopolists with either Bertrand or Cournot competition in the model of* Section 3. *Suppose an asymmetric Nash equilibrium occurs. The corrective tax* (12) *can achieve the first-best outcome provided that the ecolabeling standard is set according to* (6c).

6. Equilibrium with sunk fixed costs

Pollution control technologies are often associated with large fixed costs, and at least part of the fixed costs are sunk. For example, an electric power company may install scrubber technologies at one of its plants. Capital and other costs they incurred are not directly related to the amount of electricity produced. Moreover, pollution control technologies are fit to each plant's needs, and cannot be readily transferable to other plants should the management decide to close the plant. There are numerous other examples of environmental technologies involving sunk fixed costs. The question then is, do sunk fixed costs present a substantial difference for analysis and ecolabeling policy?

Even when entry is "free", sunk fixed costs constitute barriers to entry (Baumol and Willig, 1981). With sunk costs as entry barriers, incumbent firms in the output market can exercise market power, which can result in *both* markup pricing *and* zero profits. It is natural to expect then that the optimal tax need to be adjusted to account for imperfect competition in the market. We shall show that while a corrective pollution tax can restore efficiency in the output market, it induces more than the optimal number of firms into the market. Thus the corrective tax is the second-best in general.

To investigate this question, we consider the following cost structures:

$$C(\omega, q) = \frac{1}{2}c(\omega)q^2 + k(\omega) \tag{13}$$

where the first term captures non-sunk variable costs and $k(\omega)$ captures sunk fixed costs. Note that we assume variable costs are strictly convex in quantity. This assumption is made to preclude strictly increasing returns to scale, and is necessary for existence of competitive equilibrium.

In this modified economy, the first-best optimality conditions closely parallel those of (6) and are thus omitted. Additionally, there is a pair of zero-profit conditions that determine optimal entry:

$$N_j : c(\omega_j)q_j = \frac{(1/2)c(\omega_j)q_j^2 + k(\omega_j)}{q_j} \quad \text{for } j = l, nl \tag{14}$$

where $q_l = i_l/N_l$ and $q_{nl} = (i_{nl} - i_l)/N_{nl}$. The condition simply states that marginal costs equal average costs. One advantage of the quadratic cost assumption is that we can solve (14) to obtain optimal per-firm quantities: $q_j^s = \sqrt{2k(\omega_j)/c(\omega_j)}$. In other words, environmental technology ω implicitly determines minimum efficiency scale for each product variant.

We shall focus our subsequent analysis on Cournot competition. Though a similar analysis applies to Bertrand competition, our arguments become more involved than necessary, not only because there will generally be multiple pure-strategy Bertrand–Nash equilibria but also because the equilibrium outcome may or may not be characterized by the first-order conditions depending on entry.[10]

6.1. Subgame perfect Nash equilibrium of three-stage game

Unlike in Section 5, the size of entry into each variant of the product becomes analytically important, because all outcome variables of our interest such as emissions total economic surplus critically depend on it. Yet, there are several ways in which the equilibrium of the "entry" and "product-choice" substages may be defined and solved (Mazzeo, 2002). In this subsection, we thus formally define the equilibrium of our three-stage game, show its existence and uniqueness, and provide our solution algorithm.

Our equilibrium definition follows closely that of Mazzeo (2002), except that in ours, deviation profits are directly compared against equilibrium profits. The first-stage "entry" game is immaterial, and simply enables us to consider equilibrium configurations for a fixed number of market participants. Upon commitment to entry, firms then select product types simultaneously (instead of sequentially), anticipating the Cournot–Nash equilibrium profits in the outcome stage. Firms sort themselves into the two product types in such a way that in equilibrium, firms have no incentive to deviate from the product types they selected. Formally, we define:

The subgame perfect Nash equilibrium of the three-stage game is $\{N^*, N_j^*, \pi_j^*, \omega_j^*, P_j^*, Q_j^*\}_{j=l,nl}$ *with* $N^* = N_l^* + N_{nl}^*$ *such that (i)* N^* *is the maximum of* $(N_l^* + N_{nl}^*)$ *for which* $\pi_l^*(N_l^*, N_{nl}^*) \geq 0$ *and* $\pi_{nl}^*(N_l^*, N_{nl}^*) \geq 0$; (ii)

$$\begin{aligned} &\pi_l^*(N_l^*, N^* - N_l^*) \geq \pi_{nl}^*(N_l^* - 1, N^* - N_l^* + 1), \\ &\pi_{nl}^*(N_l^*, N^* - N_l^*) \geq \pi_l^*(N_l^* + 1, N^* - N_l^* - 1), \end{aligned} \tag{15}$$

with $\omega_l^* = \min(\theta, \arg\min\{\pi_l^*(\omega_l) | \omega_l \in [0,1]\})$ *and* $\omega_{nl}^* = \arg\min\{\pi_{nl}^*(\omega_{nl}) | \omega_{nl} \in [0,1]\}$; *and (iii) given* (N_l^*, N_{nl}^*), π_j^* *is the Cournot–Nash equilibrium profit per firm for variant* j, q_j^* *is the Cournot–Nash equilibrium quantity per firm for variant j,* p_j^* *and* Q_j^* *are given by* $P_j^* = P_j(Q_j^*, Q_{-j}^*)$ *and* $Q_j^* = N_j^* q_j^*$.

Because the third-stage Cournot–Nash equilibrium exists and is unique for a given number of firms under our current setup, to guarantee the existence and uniqueness of the equilibrium of the three-stage game, we need to show that the equilibrium of the first two substages exists and is unique. Following Mazzeo (2002), we can establish the following:

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[10] Full description of pure-strategy Bertrand equilibrium are available upon request.

Result 6. *Suppose that an additional entrant always decreases per-firm profits and that the decrease is larger if the entrant is of the same type. Then an equilibrium for the first two substage game exists, and is unique if the equilibrium requires strict inequalities in (15).*

The proof is in Appendix B. Depending on the model parameters, these assumptions may not be satisfied, but our numerical examples below satisfy them. Importantly, the logic used for the proof is also used as the solution algorithm for the subgame perfect Nash equilibrium of our numerical example below. First, for every pair (N_l, N_{nl}), we compute the (unique) Cournot–Nash equilibrium profits (or the monopoly profits if $(N_l, N_{nl})=(0, 1)$ or $(1, 0)$) and discard the pairs with negative profits. Second, for each remaining pair, we compute deviation profits and discard the pairs that violate (15). We then take the maximum of $N=N_l+N_{nl}$ when there are multiple remaining pairs. The unique pair that remains is the subgame perfect Nash equilibrium of this game.

6.2. Inefficiency of corrective taxes

Upon entry and variety/technology choice, firms compete in quantities in the output market. Given a corrective excise tax t_j, each firm selling variety j would choose quantity to maximize $[P_j(Q_j, Q_{-j}) - t_j]q_j - (1/2)c(\omega_j)q_j^2 - k(\omega_j)$. Given our inverse demand (4) , this objective function is concave in own quantity.[11] Rearranging the first-order condition, we have

$$P_j(n_j^* q_j^*, n_{-j}^* q_{-j}^*) = c(\omega_j^*)q_j^* + t_j - q_j^* \frac{dP_j}{dQ_j} \tag{16}$$

One the other hand, the first-best optimality requires

$$P_j(N_j^s q_j^s, N_{-j}^s q_{-j}^s) = c(\omega_j^s)q_j^s + \omega_j^s \int D_E(i, E^s)di \tag{17}$$

Provided that solutions to (16) and (17) are unique and that entry and technology choice had been made optimally (i.e. $N_j^* = N_j^s$ and $\omega_j^* = \omega_j^s$), Nash-equilibrium per-firm output q_j^* would be at optimum if we set t_j such that

$$t_j = q_j^s \frac{dP_j}{dQ_j} + \omega_j^s \int D_E(i, E^s)di \tag{18}$$

Under the corrective tax, firms produce aggregate outputs at competitive levels and prices equal marginal social costs (i.e. adjustments for externalities). Since both q_j^s and ω_j^s differ between the two versions, tax rates must also be differentiated. Furthermore, because $dP_l/dQ_l=-(1+\delta)<0$ and $dP_{nl}/dQ_{nl}=-1<0$, the corrective tax is less than the Pigouvian tax rate as in Barnett (1980) and Katsoulacos and Xepapadeas (1995).

Now let us take a look at the zero-profit condition: $[P_j(Q_j, Q_{-j}) - t_j]q_j - (1/2)c(\omega_j)q_j^2 - k(\omega_j) = 0$. Substituting (16) for P_j into the zero-profit condition and rearranging terms, it is clear that:

$$MC_j = AC_j + q_j^s \frac{dP_j}{dQ_j} \tag{19}$$

Condition (19) differs from (14) by $q_j^s dP_j/dQ_j < 0$. Because the last term in (19) lowers the average cost curve, it encourages more firms into the market.

Result 7. *Under Cournot competition with sunk fixed costs of entry, the corrective tax given by (18) can achieve allocative efficiency in the output market, but induces more entry than optimal, and thus, cannot achieve the first-best outcome.*

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[11] Imposition of this tax alters individual firms' best-response in a non-marginal manner. Thus allocative equivalence between the first-best and the Nash equilibrium under the corrective tax requires the strict concavity of the objective function (Guesnerie and Laffont, 1978).

6.3. Numerical example

Industry stakeholders often have some influence on ecolabeling criteria selection. Furthermore, ecolabeling agencies often use somewhat arbitrary market-share criterion, as discussed in Section 2. Thus the environmental standard may not be set at the first-best level. A series of questions are in order in this context. How does the equilibrium respond to a change in the ecolabeling standard, with or without the corrective tax? How must we adjust the complementary corrective tax in the presence of such an arbitrary standard?

It is tempting to adjust the tax according to the formula (18). However, our analysis above suggests a trade-off we must face in setting corrective taxes. To restore allocative efficiency in the output market, we must adjust the pollution tax by the amount $q_j^s(dP_j/dQ_j)$. If this amount is large enough, we might *subsidize* firms. Suppose q_l^s is large enough and is larger for stricter standards, then there will be more firms selling *l*-version than optimal. And vice versa. With more firms than optimal, the society incurs more costs. The net effect of corrective taxes can be negative. It then seems important to ask whether the corrective taxes would be necessarily welfare increasing.

To address these questions, we construct a simple numerical example. Let $D(i, E)=b(1-i)E$. Then we have $\int D(i, E)di=(1/2)b[(\omega_{nl}-\omega_l)i_l-\omega_{nl}i_{nl}]$ and $\int D_E di=(1/2)b$. Using the minimum efficiency scale formula for q_l^s and (18), we have:

$$t_l(\theta) = -(1+\delta(\theta))\sqrt{\frac{2k(\theta)}{c(\theta)}}+\frac{1}{2}b\theta \tag{20}$$

The first term can be decreasing or increasing in θ even if $\delta(\theta)$ is constant, which implies that the corrective tax can be higher or lower than the first-best level for $\theta>\theta^s$.

Let $\delta(\theta)=1+d\theta$, $c_j(\omega)=c_0+c_1(1-\omega_j)^2$, and $k(\omega_j)=k_0+k_1(1-\omega_j)^2$. Let $a=2$, $b=2$, $\gamma=1$, $d=.1$. We consider two sets of cost parameters: (1) $c_0=1$, $c_1=5$, $k_0=.1$, $k_1=.5$; and (2) $c_0=1$, $c_1=1$, $k_0=.1$, $k_1=.5$. Demand parameters are chosen with the restriction $\gamma>\delta$ as discussed in Section 3. Cost parameters are chosen such that, given the demand parameters, both Cournot and first-best outcomes exist and that (20) is increasing in θ. Using the algorithm described in Section 6.1, we compute the subgame perfect Nash equilibrium of the three-stage game with and without the corrective tax.[12] The results are presented in Fig. 1.

Case 1 ($c_0=1$, $c_1=5$, $k_0=.1$, $k_1=.5$).

Fig. 1.1-a. depicts the second-best tax $t_l^c(\theta)$ for the Cournot case and the efficient excise tax $t_l^{pc}(\theta)=\theta t$ for the competitive case for the *l*-version. $t_l^c(\theta)$ is negative over the effective range ($\theta<.77$), implying that it subsidies the ecolabeled-good production. Though not depicted, with these parameters, $\omega_{nl}^s\approx.77$ and $t_{nl}^c(\omega_{nl}^s)\approx.32$. Fig. 1.1-b. illustrates the significant effects on entry of both the environmental standard and the corrective taxes. As the standard gets tightened (i.e. smaller θ), the cost of producing the *l*-version becomes expensive, and thus, less firms choose to sell that version (i.e. N_l smaller) and more firms sell the *nl*-version (i.e. $N-N_l$ larger). At a given level of θ, the corrective taxes induce more firms into the *l*-version while less firms into the *nl*-version. In this case, the overall market entry is less with than without the taxes—the equilibrium entry is between three and five depending on the value of θ with the taxes, but is five for any value of θ without the taxes. Fig. 1.1-c. and 1.1-d. shows the impacts on emissions E and welfare W, respectively, of the standard and the (second-best) tax system. As a benchmark, the first-best outcomes are depicted as E^s and W^s evaluated at solution $(i_l^s, i_{nl}^s, N_l^s, N_{nl}^s)$ for each value of θ. The first-best outcome occurs at the peak of W^s, which occurs at $\theta^s=.41$. In the absence of imperfect competition, this outcome can be achieved by a combination of the ecolabeling standard θ^s and an efficient pollution tax $t=\int D_E(i, E^s)di$. The welfare outcome of Cournot equilibrium is labeled as W^c with or without tax. It is important to note here that total industry emissions do not decrease monotonically with the number of firms selling the *l*-version, either with or without tax. There are two important trade-offs here—one is that the number of firms induced to the *l*-version increases as the environmental standard gets less stringent, but the

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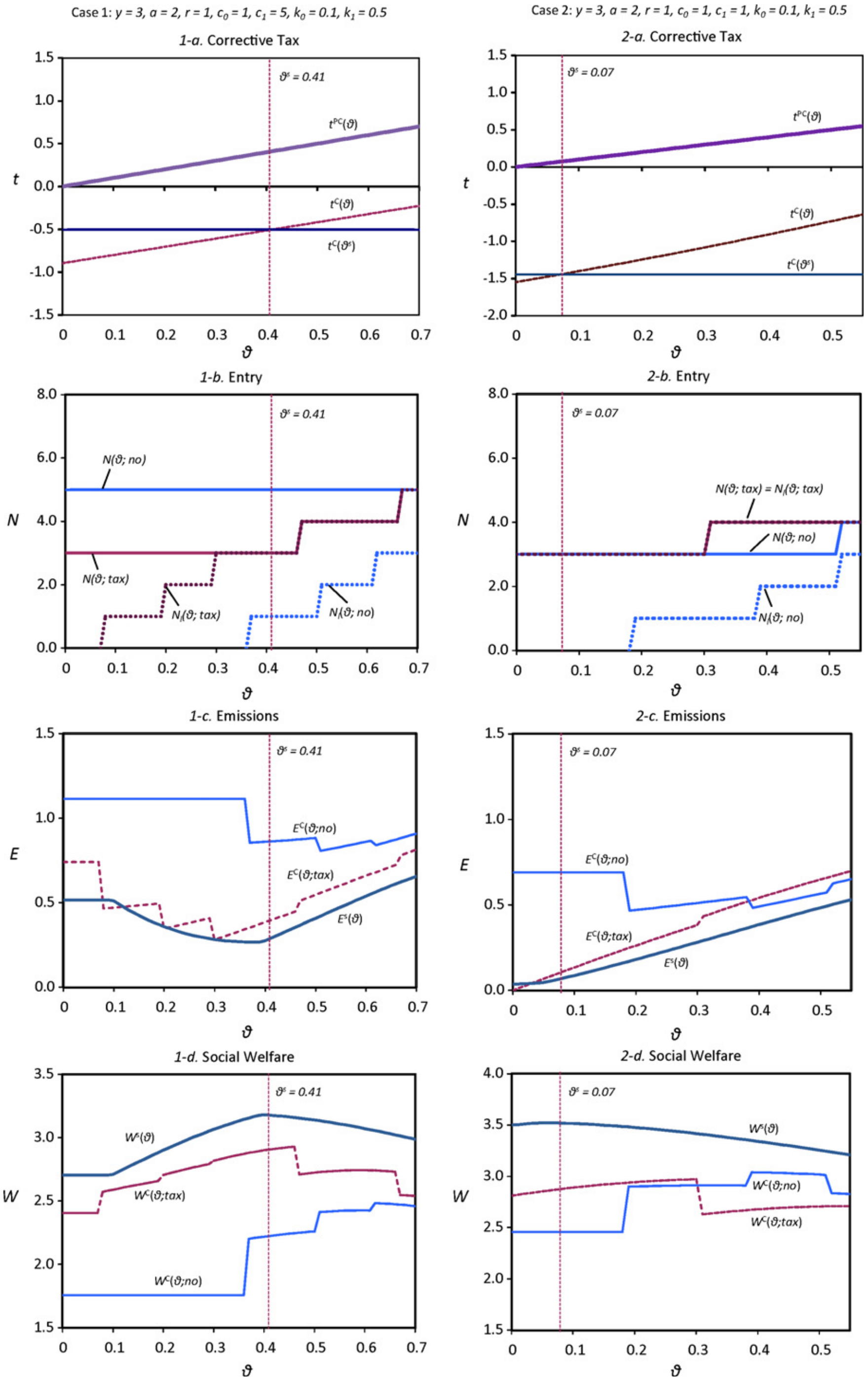
[12] Computation of Cournot equilibrium is done using Gauss 10.0.



Case 1: $y = 3$, $a = 2$, $r = 1$, $c_0 = 1$, $c_1 = 5$, $k_0 = 0.1$, $k_1 = 0.5$

Case 2: $y = 3$, $a = 2$, $r = 1$, $c_0 = 1$, $c_1 = 1$, $k_0 = 0.1$, $k_1 = 0.5$

1-a. Corrective Tax

2-a. Corrective Tax

1-b. Entry

2-b. Entry

1-c. Emissions

2-c. Emissions

1-d. Social Welfare

2-d. Social Welfare

Fig. 1. Inefficiency of corrective tax under Cournot competition with endogenous entry.

emissions per unit of output gets higher, precisely because of the lax standard; another is that the effective subsidy increases as the environmental standard gets more strict, but it induces more entry in the *l*-version, increasing the total emissions and the total costs. In this case, the overall effect of the corrective taxes on welfare is positive, since the negative effect of encouraging excessive entry is more than offset by the positive effect of restoring allocative efficiency in the output market. However, this tax system still fails to restore the full efficiency due to the excessive entry (i.e. $W^s(\theta^s) > W^c(\theta; tax)$ over the effective range of θ).

Case 2 ($c_0 = 1,\ c_1 = 1,\ k_0 = .1,\ k_1 = .5$).

With these parameters, the marginal effect of better environmental technology on the cost of production is relatively small, which justifies a stringent ecolabeling standard. The first-best outcome occurs at $\theta^s = .05$. As depicted in Fig. 1.2-b., three firms are induced to sell the *l*-version of the product even at relatively low values of θ, with or without tax. Indeed, with the second-best tax system, *all* entering firms choose to sell the *l*-version. Moreover, the overall market entry is higher with than without the taxes for some range of θ ($N^c(\theta; tax) > N^c(\theta; notax)$). It is interesting to see the effect of this excessive entry on emissions and welfare. First, despite the fact that more firms are sellers of the *l*-version with than without tax, the total emissions are higher with than without tax, at least for some range of θ (Fig. 1.2-c). This happens because, on this range, the environmental standard is low and the overall entry is higher with than without tax. Second, as demonstrated in Fig. 1.2-d., the welfare might be lower with than without the corrective taxes. In order for the corrective taxes to be welfare improving, the negative effect of the excessive entry (in terms of increases in production costs and emissions) must be more than offset by the positive effect of correcting for non-competitive pricing and negative externalities in the output market. Tightening the environmental standard has two ameliorating effects in this regard—one by reducing entry by increasing the (marginal) costs of production and another by reducing negative externalities by reducing emissions per output (of the *l*-version). Note that in the BW model (Bagnoli and Watts, 2003), technology variables are fixed, and therefore, at the very best, the welfare consequence of the corrective tax system can be discussed in comparison with either the no-tax or the first-best outcome only for some arbitrary technology levels. Roughly speaking, such a comparison would be a *vertical* comparison in Fig. 1.2-d. for some arbitrary θ. However, as demonstrated here, such a comparison is misleading in two ways. First, there must be first-best technology levels for both types of the product as discussed in Section 4 (and in the previous literature). Second, the relative efficiency of no-tax, tax, and first-best outcomes depends crucially on the level of the technology standard imposed by the complementary ecolabeling.

Result 8. *Consider Cournot competition with sunk fixed costs of entry. Then for* $\theta \neq \theta^s$, *the second-best corrective tax* $t_l(\theta)$ *given by (20) may be higher or lower than* $t_l(\theta^s)$ *and may not even be welfare increasing relative to no tax. To ameliorate the negative effect of excessive entry, the ecolabeling authority must set a stringent technology standard.*

7. Discussion

We have investigated the efficiency properties of binary ecolabeling in a homogeneous good market. We find that optimal ecolabeling standard depends crucially on existence of complementary taxes, sunk fixed costs, and market structures. We emphasize here that none of our main results can be obtained without endogenizing firms' technology choice—we differ substantially from Bagnoli and Watts (2003) on this account. Furthermore, our results have broad implications for ecolabeling criteria selection practices. Many ecolabeling programs worldwide have a wide product coverage, ranging from office supplies to personal cares and even to electronics. Germany's Blue Angel, for instance, has awarded ecolabels to more than 10,000 products in 80 product categories to date. These product markets vary in terms of complementary taxes, sunk fixed costs, and market structures.

To delineate important sources of inefficiency, however, we have made several restrictive assumptions. In this concluding section, we shall discuss which of these assumptions are likely to have important implications for analysis and ecolabeling policy.

7.1. Imperfect certification

We have assumed perfect auditing and monitoring so that no errors occur in certification. If instead certification is imperfect, some firms that do not fully meet the standard may be certified while others that meet the standard may be rejected. If mis-certification is sufficiently prevalent, consumers may form subjective beliefs about the environmental quality of the product upon observing whether it is labeled or not. Mason (2006) has considered the equilibrium outcome of imperfect certification. Since Mason's model setup is substantially different from ours, his result is not directly comparable to ours. For example, his model assumes perfectly elastic demand, no endogenous entry, and binary technology space (i.e. either "green" or "brown"), each of which has substantial implications for our analysis. Nonetheless, we conjecture that his general conclusion is still likely to hold—increased accuracy of certification increases the number of firms that sell the labeled version that actually meet the standard, under some plausible conditions, one of which might be to assume that the probability of passing the certification test is a function of the firm's environmental technology, the environmental standard, and accuracy of certification.

7.2. Multiple quality dimensions

As discussed in Section 2, many ecolabeling programs use multiple attribute criteria. We incorporated this stylized fact by assuming the existence of a composite measure or summary statistic of environmental externalities. Our representation is not only by far the common assumption, either explicit or implicit, in previous studies (e.g. Conrad, 2005; Cremer and Thisse, 1994; Ibanez and Grolleau, 2008; Lombardini-Riipinen, 2005; Mason, 2006) but also a stylized description of the criteria development process for some ecolabeling programs. For example, the Nordic Swan use 'matrices' of attributes that are weighted to generate an average score. Multiple attributes per se thus do not necessarily limit the generality of our results. However, product differentiation in multiple attributes can affect sellers' incentives to disclose information on attributes in an important way by creating another dimension of competition (e.g. Sun, 2011)—it may be a *match* between the consumer's preference and the attributes that matters. For example, some consumers may care about carbon emissions more than water pollution and they may prefer the product that offers attributes that are *closer* to their tastes. With such consumer preferences, firms compete in both *vertical* and *horizontal* qualities (Tirole, 1994). In the model of a monopolist with asymmetric information about both vertical and horizontal qualities, Sun (p. 4, 2011) finds that "sellers are more likely to participate in quality surveys with one aggregate vertical measure than those with multiple measures." Her finding implies in our context that firms are less likely to certify in the labeling scheme that discloses multiple attributes than that discloses an average or aggregate environmental attribute. Thus there is a trade-off between the ecolabel's informativeness and its participation rate. The overall efficiency loss due to this effect is left for our future research.

7.3. Heterogenous firms

We study a model of firms that have equal access to production and environmental technologies, but choose heterogenous technologies in market equilibrium. The model is *more* general than models in which firms are endowed exogenously with heterogenous technologies, but is *less* so than models in which firms face heterogenous shocks in access to technologies. The question then is, do some of our results change in a model with firms with heterogenous access to technologies? In such a model, each firm would make technology and certification choices upon observing its idiosyncratic productivity type given the exogenous environmental standard. In general, there are multiple market equilibria that may or may not be welfare equivalent. However, it seems reasonable to expect that under certain conditions, firms with lower costs would use environmentally friendly technologies while those with higher costs refrain from doing so. It seems plausible to conjecture then that in the absence of sunk costs, the optimal combination of the standard and the pollution tax can still implement the first-best outcome under such conditions. These discussions seem to suggest that the major obstacles in achieving social optimum through ecolabels are the existence of sunk fixed costs, as identified in Section 6, and the trade-off between informativeness and participation in the design of ecolabels. Our paper shows the binary feature of ecolabels per se does not present a threat to efficiency. What matters for efficiency is how the informativeness of a variety of labeling formats (e.g. binary, multiple, continuous) affect consumers' perceptions and preferences, and thereby, firms' incentives to participate in certification. Future research should focus on this aspect.

Appendix A. Proof of Result 5

Since there is no endogenous entry, the generic game reduces to the two-stage game of technology choice and price/output. With Bertrand competition, duopolists choose prices in the output market. In the second stage, the firm selling j version chooses price P_j given t_j to maximize $[P_j - c(\omega_j) - t_j(\omega_j)]Q_j(P_j, P_{-j})$ where Q_j is the aggregate demand given by (3). The first-order conditions are

$$\frac{\partial Q_j}{\partial P_j}[P_j - c(\omega_j) - t_j(\omega_j)] + Q_j = 0 \tag{A.1}$$

With linear demand (3), the firm's profit is globally concave in P_j and satisfies conditions for existence and uniqueness of Bertrand–Nash equilibrium (Shapiro, 1989; Singh and Vives, 1984). Substituting (12) into (A.1) and solving for P_j, we see

$$P_j(Q_j^*, Q_j^*) = c(\omega_j) + \omega_j \int D_E(i, E^s)di - \frac{\partial P_j}{\partial Q_j}\left[Q_j^* - Q_j^s\right] \quad \text{for } j = l, nl \tag{A.2}$$

where $dP_l/dQ_l = -(1 + \delta(\omega_l^s))$ and $dP_{nl}/dQ_{nl} = -1$. Note that (Q_l^s, Q_{nl}^s) is the solution to the system

$$P_j(Q_j^s, Q_j^s) = c(\omega_j^s) + \omega_j^s \int D_E(i, E^s)di \quad \text{for } j = l, nl \tag{A.3}$$

That is, the price must equal the marginal social cost. Since (Q_l^s, Q_{nl}^s) is a unique solution to (A.3) and the Bertrand–Nash equilibrium is the unique solution of (A.2), $(Q_l^s, Q_{nl}^s) = (Q_l^*, Q_{nl}^*)$ provided that $\omega_j^* = \omega_j^s$ (which we shall show next). Now let's consider the first-stage technology choice. By assumption, the firm chooses to sell the ecolabeled version if the opponent chooses the labeled and vice versa. The firm choosing to sell the ecolabeled version chooses $\omega_l = \theta = \omega_l^s$, provided that ecolabeling agency sets the standard according to (6c). On the other hand, the firm selling the non-labeled version chooses ω_{nl}, fully recognizing its optimal choice $P_{nl}(\omega_{nl}, \omega_l)$ in the second-stage price competition while taking as given its opponent's technology choice ω_l and price P_l. Thus differentiating the profits with respect to ω_{nl}, the first-order condition is:

$$\left[\frac{\partial P_{nl}}{\partial \omega_{nl}} - c'(\omega_{nl}) - t'_{nl}(\omega_{nl})\right]Q_{nl} + [P_{nl} - c(\omega_{nl}) - t_{nl}(\omega_{nl})]\left[\frac{\partial Q_{nl}}{\partial \omega_{nl}} + \frac{\partial Q_{nl}}{\partial P_{nl}}\frac{\partial P_{nl}}{\partial \omega_{nl}}\right] = 0 \tag{A.4}$$

Note that the firm fully anticipates its optimal pricing strategy will follow (A.1). Thus substituting (A.1), (A.4) reduces to

$$[-c'(\omega_{nl}) - t'_{nl}(\omega_{nl})]Q_{nl} + [P_{nl} - c(\omega_{nl}) - t_{nl}(\omega_{nl})]\frac{dQ_{nl}}{d\omega_{nl}} = 0 \tag{A.5}$$

Furthermore, substituting (A.2), (12), and $t'_{nl} = \int D_E(i, E^s)di$ and cancelling terms, (A.5) becomes:

$$-c'(\omega_{nl}) = \int D_E(i, E^s)di + \frac{\partial P_{nl}}{\partial \omega_{nl}} \tag{A.6}$$

where it is clear that $\partial P_{nl}/\partial \omega_{nl} = 0$ from (4). Comparing this to (6c), it follows that the firm selling the *nl* version chooses $\omega_{nl} = \omega_{nl}^s < \theta = \omega_l^s$.

An analogous proof applies to Cournot competition. In the output stage, each firm selling j version chooses quantity Q_j given t_j, maximizing its profits $[P_j(Q_j, Q_{-j}; \omega_j, \omega_{-j}) - c(\omega_j) - t_j(\omega_j)]Q_j$. The first-order conditions are

$$P_j + Q_j \frac{\partial P_j}{\partial Q_j} - c(\omega_j) - t_j(\omega_j) = 0 \tag{A.7}$$

Using the same argument as above, it is clear that $(Q_l^s, Q_{nl}^s) = (Q_l^*, Q_{nl}^*)$ provided that $\omega_j^* = \omega_j^s$. Now in the technology choice stage, the firm choosing to sell the non-labeled version chooses ω_{nl}, fully recognizing its optimal choice $Q_{nl}(\omega_{nl}, \omega_l)$ in the output stage while taking as given its opponent's technology choice ω_l and output choice Q_l. Thus differentiating the profits with respect to ω_{nl}, the first-order condition is:

$$\left[\frac{\partial P_{nl}}{\partial \omega_{nl}} - c'(\omega_{nl}) - t'_{nl}(\omega_{nl})\right] Q_{nl} + \left[P_{nl} + Q_{nl}\frac{\partial P_{nl}}{\partial Q_{nl}} - c(\omega_{nl}) - t_{nl}(\omega_{nl})\right]\frac{dQ_{nl}}{d\omega_{nl}} = 0 \tag{A.8}$$

Fully anticipating its optimal quantity choice given by (A.7), (A.8) simplifies to

$$\left[\frac{\partial P_l}{\partial \omega_l} - c'(\omega_j) - t'_j(\omega_j)\right] Q_l = 0 \tag{A.9}$$

From (4), $\partial P_{nl}/\partial \omega_{nl} = 0$ and from (12), $t'_{nl} = \int D_E(i, E^s)di$. Substituting these into (A.9) and rewriting, we obtain:

$$-c'(\omega_l) = \int D_E(i, E^s)di \tag{A.10}$$

Thus the firm chooses $\omega_{nl} = \omega_{nl}^s$.

Lastly, it remains to show that the firm selling the ecolabeled version does not choose $\omega_l = \theta = \omega_l^s$ if θ is not enforced. Following the same steps as above, we can show that the firm selling the ecolabeled variant will choose ω_l such that

$$-c'(\omega_l) = \int D_E(i, E^s)di + \frac{\partial P_l}{\partial \omega_l} \tag{A.11}$$

in either Bertrand or Cournot competition. Note that $\partial P_l/\partial \omega_l = \delta'(\omega_l)Q_l$ whereas we have $(1/2)\delta'(\omega_l)i_l$ in (6c). This difference occurs due to the difference in benefit valuation between the social planner and the duopolist.

Appendix B. Proof of Result 6

We offer here our version of the proof, which is almost identical to, but not the same as, Mazzeo (2002), since our equilibrium definition differs slightly from his. We omit the asterisks for notational simplicity. Note that the first assumption implies that $\pi_j(N_l, N_{nl}) > \pi_j(N_l+1, N_{nl})$ and $\pi_j(N_l, N_{nl}) > \pi_j(N_l, N_{nl}+1)$ for $j = l, nl$; and the second assumption implies $\pi_l(N_l-1, N-N_l) - \pi_l(N_l, N-N_l) > \pi_l(N_l-1, N-N_l) - \pi_l(N_l-1, N-N_l+1)$ and $\pi_{nl}(N_l-1, N-N_l) - \pi_{nl}(N_l, N-N_l) < \pi_{nl}(N_l-1, N-N_l) - \pi_{nl}(N_l-1, N-N_l+1)$, which imply, respectively, $\pi_l(N_l, N-N_l) < \pi_l(N_l-1, N-N_l+1)$ and $\pi_{nl}(N_l, N-N_l) > \pi_{nl}(N_l-1, 1, N-N_l+1)$. *To prove existence, suppose that N firms have entered the market in the entry stage. Thus, by definition we must have some pairs* (N_l, N_{nl}) *such that* $N = N_l + N_{nl}$ *and* $\pi_l(N_l, N_{nl}) > 0$ *and* $\pi_{nl}(N_l, N_{nl}) > 0$. *Such configurations are candidates for possible equilibria. If* (N_l, N_{nl}) *satisfies (15), then it is an equilibrium. Suppose that one of the conditions in (15) is violated: i.e.*

$$\pi_l(N_l, N - N_l) < \pi_{nl}(N_l - 1, N - N_l + 1), \tag{B.1}$$

or

$$\pi_{nl}(N_l, N - N_l) < \pi_l(N_l + 1, N - N_l - 1). \tag{B.2}$$

Note that (B.1) and (B.2) cannot hold simultaneously. Suppose not. Then it follows from (B.1) and the second assumption that $\pi_l(N_l+1, N-N_l) < \pi_{nl}(N_l, N-N_l+1)$. Similarly, from (15) and the second condition, $\pi_{nl}(N_l, N-N_l+1) < \pi_l(N_l+1, N-N_l)$. A contradiction. Therefore, at least one of the conditions

(15) is always satisfied for *any* pair. Suppose that (B.2) holds. Then $\pi_l(N_{nl}+1,\ N-N_l-1)>0$ because $\pi_{nl}(N_l,\ N-N_l)>0$ and $\pi_{nl}(N_{nl}+1,\ N-N_l-1)>0$ because $\pi_{nl}(N_l,\ N-N_l)>0$ and the second assumption. Thus $(N_{nl}+1,\ N-N_l-1)$ is an equilibrium unless $\pi_{nl}(N_l+1,\ N-N_l-)<\pi_l(N_l+2,\ N-N_l-2)$. If this inequality holds, then $(N_l+2, N-N_l-2)$ is a potential equilibrium. We continue this process until $(N, 0)$ or we find an equilibrium. Suppose we have not found an equilibrium until $(N, 0)$. Because there is only the ecolabeled type, $\pi_l(N, 0)>\pi_{nl}(N-1, 1)$ would guarantee an equilibrium. This inequality must hold at this point, for otherwise we would have $\pi_l(N,\ 0)\leq\pi_{nl}(N-1,\ 1)$ in which case $(N-1,\ 1)$ must have been an equilibrium.

To see uniqueness, suppose that $(N_l,\ N_{nl})$ is an equilibrium configuration. Applying strict inequalities in (15), it implies that

$$\pi_l(N_l, N_{nl}) > \pi_{nl}(N_l - 1, N_{nl} + 1), \tag{B.3}$$

and

$$\pi_{nl}(N_l, N_{nl}) > \pi_l(N_l + 1, N_{nl} - 1). \tag{B.4}$$

Suppose by contradiction that $(N_l-1, N_{nl}+1)$ or $(N_l+1, N_{nl}-1)$ is also an equilibrium. If $(N_l-1, N_{nl}+1)$ is an equilibrium, it must follow that $\pi_{nl}(N_l-1,\ N_{nl}+1)>\pi_l(N_l,\ N_{nl})$, which is a contradiction to (B.3). Similarly, $(N_l+1, N_{nl}-1)$ is ruled out by (B.4). Let us consider yet another possibility $(N_l-2, N_{nl}+2)$ or $(N_l+2, N_{nl}-2)$. Suppose that $(N_l-2, N_{nl}+2)$ is an equilibrium, implying that $\pi_{nl}(N_l-2, N_{nl}+2)>\pi_l(N_l-,\ N_{nl}+1)$. Applying the second assumption to (B.3), however, we must have $\pi_l(N_l-1,\ N_{nl}+1)>\pi_l(N_l,\ N_{nl})>\pi_{nl}(N_l-1,\ N_{nl}+1)>\pi_{nl}(N_l-2,\ N_{nl}+2)$. A contradiction. Similarly, $(N_l+2,\ N_{nl}-2)$ is ruled out by (B.4). Continuing this process up to $(N, 0)$ and $(0, N)$, we see that (N_l, N_{nl}) is the unique equilibrium. It is clear from the above argument that if strict inequalities are not required, uniqueness does not hold.

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