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Voluntary carbon neutral programs. Adoption and firms' strategies

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ABSTRACT

Voluntary Carbon Neutral (CN) programs promote the reduction of Greenhouse Gas emissions of participants. The main objective of this article is to review the literature about firms' behavior in connection to CN programs, paying particular attention to the adoption decision and the firms' strategies to meet the CN requirements. As an additional aim, we analyze the economic rationale behind the firms' decisions by connecting our literature review to a simple model based on the standard microeconomic theory of the firm. We model the firm's decision as a three-stage problem which includes, first, the adoption (or not) of a voluntary CN program, second, the selection of strategies to become CN (if the program is adopted) and third, the usual price and quantity decisions in the output market. The model helps understand some results found in the literature, such as why some activity sectors are more prone than others to adopt the CN certification. It also provides an explanation for the fact that these voluntary programs tend to be adopted by firms that are large, innovative, and more concerned about intergenerational equity and environmental preservation.

1. Introduction

Decarbonization and the fight against climate change have become key objectives in the global policy agenda, in accordance with the 13th United Nations (UN) Sustainable Development Goal (SDG) "Take urgent action to combat climate change and its impacts". The most traditional policy approach to promote sustainable practices, such as reducing GHG emissions, is based on command-and-control regulations, including standards, quotas and alike. These instruments have been criticized for being economically inefficient, administratively complex, inflexible and slow, especially when the regulator faces numerous heterogeneous companies (Higley and Lévêque, 2001; Khanna, 2001).

A second strand uses incentives in the form of taxes, subsidies and tradable permits, which rely on price signals in order to reduce emissions in a more flexible and less costly way. See Pigou (1932), Baumol and Oates (1971) for pioneering works, or André and de Castro (2020a), Verde et al. (2019), García-Alaminos and Rubio (2021) for more recent studies. Despite such advantages, these approaches tend to generate strategic behaviors that may undermine their effectiveness (Alvarez et al., 2019; André and Arguedas, 2018; André and de Castro, 2020b). They also have a compulsory nature and involve some degree of public control and sanctioning.

A more recent trend to induce sustainable behavior involve so-called voluntary approaches, such as environmental programs, certifications, and ecolabels. These initiatives are not mandatory and may involve different stakeholders or groups of stakeholders such as public agencies, non-profit organizations, firms and consumers (DeLeon et al., 2009; Khanna, 2001). This article focuses on voluntary carbon neutral (CN) programs, which are specifically aimed at decarbonizing the economy.

Table 1 presents an inventory of voluntary CN programs implemented throughout the world.[1] These programs differ in terms of their developers and the participant organizations. Regarding the organizers, some programs have been developed by public agencies, but others have been proposed by non-governmental organizations, such as the International Organization for Standardization or the Second Nature and Natural Capital Partners. As for participants, while some programs are focused on public organizations and departments, others are mainly devoted to the private sector. A third group is available both for public

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[1] Apart from these CN initiatives, there are many other policies that pursue GHG emissions reductions without reaching full carbon neutrality. Some of them are surveyed, e.g., in Fu et al. (2014) and Lee et al. (2016).

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Table 1
Features of some Voluntary CN Programs around the world.

Program	Developer	Aim
Argentine CN Program	Chambers of Commerce and Agriculture	Agricultural companies
Climate Active CN Standard of Australia	Department of Industry, Science, Energy and Resources.	Public and private organizations, buildings, events, products, and services
British Columbia's CN Government Program	Ministry for the Environment and Climate Change Strategy	Provincial public sector organizations
CN Colleges and Universities	Second Nature and The American College and University Presidents' Climate Commitment	Colleges and Universities
Carbon Offset Funds	Mayor of London	Public sector
Chilean Carbon Management Program	Ministry of Environment	Public and private organizations.
Climate Neutral Now	UNFCCC	Public and private organizations, people, events
Costa Rican CN Program	Ministry for the Environment and Energy	Public and private organizations.
Ecuadorian CN Environmental Recognition	Ministry of Environment and Water	Public and private organizations.
ISO 14064	International Organization for Standardization	Public and private organizations.
Mexican Carbon Platform	Mexican Stock Exchange	Public and private organizations.
New Zealand CN Government Program	Ministry for the Environment	Public sector entities
Organizational CN Brand Program	Regional Government of Cali, Colombia	Companies
The CN Protocol	Natural Capital Partners.	Companies

and private entities. Other initiatives are not focused on a whole organization, but on specific products or services. This is the case of the Publicly Available Standard 2050 (PAS 2050), the GHG Protocol Product Life Cycle Accounting and Reporting Standard, ISO 14067 and PAS 2060.

Despite some differences across existing CN programs, the main requirements tend to be the same. First, companies need to make their baseline emissions inventory and compute their carbon footprint (André and Valenciano-Salazar, 2020). An auditing agency must verify the inventory according to established standards, such as ISO 14064-1, the GHG Protocol and the Emissions Trading Directive (Osorio et al., 2022; Scipioni et al., 2012). Second, companies must build strategies to remove, abate and offset their emissions in order to achieve carbon neutrality (Climate Active, 2022; Government of British Columbia, 2020; Valenciano-Salazar et al., 2022; UNFCCC, 2020).

For the sake of concreteness, to some extent our study is inspired by a specific case study, the one in Costa Rica. Despite traditionally being considered a developing country, Costa Rica has adopted a very active role in the fight against climate change (see e.g., UN Environment Programme, 2019). The Costa Rican CN program began in 2012, being the first public CN program in Latin America, and one of the first worldwide.[2] Table 2 summarizes the strategies followed by Costa Rican CN companies to meet the program requirements. According to Climatewatchdata.org, Costa Rican's equivalent carbon emissions (CO_{2e}) in 2010 were about 12.8 million tons, and dropped to 8.48 MtCO_{2e} in 2019.[3]

Table 2
Strategies followed by CN in Costa Rica. 2012–2019.

Strategies	Tons of CO2e	%
Carbon removal	407,000	45.89
Carbon abatement	244,000	27.50
Carbon offset (carbon credits)	236,000	26.61
TOTAL	**887,000**	**100**

Source: MINAE et al., 2019.

The aim of this article is twofold. First, we provide a review of the literature on voluntary CN initiatives from the point of view of firms and their decisions. Specifically, we focus on the adoption decision and the behavior of firms in terms of choosing an *optimal* combination of strategies to meet the CN requirements. Our second aim is to provide an analysis of the economic rationale behind these firms' decisions. We do so by building a simple microeconomic model and connecting it to our literature review. Since we are not aware of any published theoretical model about the adoption of a voluntary CN program, we resort to a simple model based on standard microeconomic theory of the firm and adapt it to accommodate the main features of a CN program.

A CN program can involve a specific product or service (see e.g., Birkenberg and Birner, 2018; Birkenberg et al., 2021; Canavari and Coderoni, 2020; Lombardi et al., 2017; Valenciano-Salazar et al., 2021a), or a whole company (André and Valenciano-Salazar, 2020; Falk and Hagsten, 2020; Osorio et al., 2022; Zeppel and Beaumont, 2013). In the former, firms must demonstrate that GHG emissions generated during the life cycle of the product or service have been adequately dealt with. In the latter, the same criteria affect the GHG emissions of the company as such. To simplify the exposition, our theoretical model represents a single-good company and, thus, both CN versions can be seen as equivalent.[4]

We envision the firms' decisions as a three-stage problem. First, the firm decides whether to adopt a CN program or not. Second, if a firm has adopted the program, it must choose the best strategy or combination of strategies to comply with the CN requirements. Finally, the firm decides its optimal quantity and price to maximize its profit. This sequential structure is illustrated in Fig. 1.

Sections 2 to 4 describe the three stages of the problem following a backward-induction logic, i.e, starting with the last one and finishing with the first one. In each of these sections, we first present the building blocks or our theoretical framework (Subsections 2.1, 3.1 and 4.1) and then summarize the main literature related to each block (2.2, 3.2 and 4.2). In section 5 we discuss some further issues and Section 6 concludes.

2. Third stage: price and quantity

We first address the third stage of the firm's problem, which involves the price and quantity decisions. In Subsection 2.1 we model this problem in formal terms and Subsection 2.2 present a revision of the related literature.

2.1. Modeling the firms' decisions on prices and quantities

Based on the previous literature (see Section 2.2 below) we assume that consumers are willing to pay a premium for a CN-certified product. To capture this idea, assume that a firm, whether it is CN-certified or not,

[2] Although the program has already accumulated some experience and learning, unfortunately, there is not a database about firms' strategies to comply with the CN requirements, which represents an important limitation to study this initiative in empirical terms.

[3] https://www.climatewatchdata.org/ghg-emissions?end_year=2019&regions=CRI&start_year=1990.

[4] In accordance with this simplification, although we refer below to "a CN product", our conceptual framework can also be read in terms of "a product produced by a CN firm".

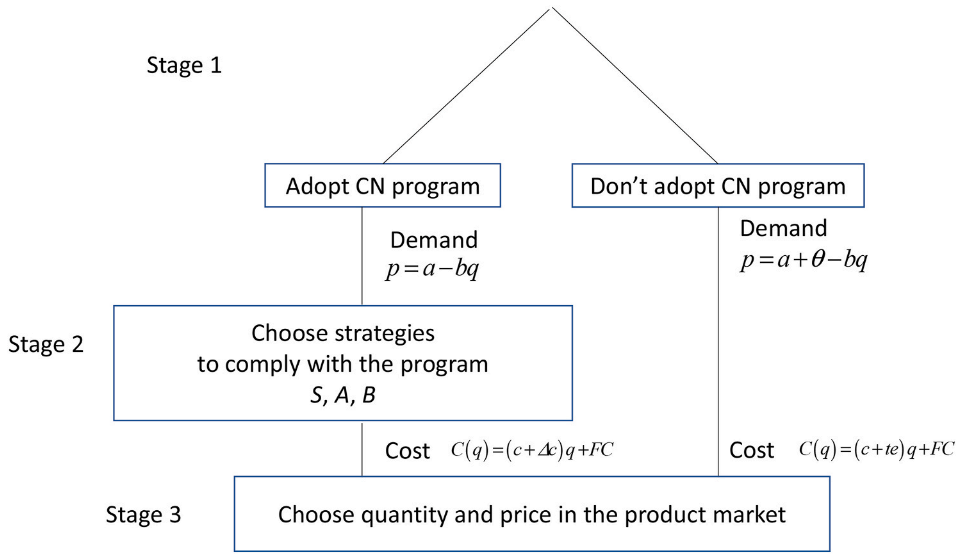

Fig. 1. Timing of the firm's problem.

faces the inverse demand curve

$$p = \widehat{a} - bq, \text{with } \widehat{a} = a + \varphi\theta, \tag{1}$$

where p is the price, q is the quantity produced and sold in the market, $\widehat{a}$ is the intercept (the maximum price compatible with a positive demand) and b is the slope (the sensitivity of the consumers' willingness to pay, WTP, given the supplied amount or, equivalently, the inverse of the sensitivity of demand to the price). Moreover, φ is a dichotomous variable that takes the value 1 if the firm adopts the CN program and 0 otherwise, and θ is the price premium that consumers are willing to pay for a CN product. Thus, a non-certified firm faces the demand $p = a - bq$ and a certified firm faces the demand $p = a + \theta - bq$, which is shifted upwards by the price premium θ.

In Section 3 we explain in more detail how the cost of a CN firm is determined. For the time being, denote the cost function of a generic firm as $C(q) = \widehat{c}\, q + \varphi\, FC$, where FC is a fixed adoption cost to be paid only if the program is adopted (otherwise, $\varphi = 0$ and the fixed term drops) and $\widehat{c} = c + \varphi\, \Delta c$ is the marginal cost, where c is the unit cost of a non-certified firm and Δc is the difference between a certified and a non-certified firm. Denote the unit cost of a certified firm as $c^{CN} = c + \Delta c$. In Subsection 2.2. we show that the empirical results about the impact of adopting a CN program on costs are mixed. In other words, it is not obvious if Δc should be positive or negative; therefore, we don't exclude any of these possibilities. The sign of Δc may be sector-specific, country-specific or even firm-specific.

Assume that CN firms do not emit any carbon, but one unit of output produced by a non-certified firm generates α units of carbon emissions and the firm is subject (or is anticipated to be subject) to a carbon tax or carbon price of t monetary units per unit of carbon. To fix ideas, we will refer to this as "carbon tax", but the formulation is compatible with other policy approaches. The carbon payment of a firm is given by $T = (1 - \varphi)t\alpha q$, which vanishes for a CN firm (when $\varphi = 1$).

As is usual in microeconomic theory, we assume that the firm aims at maximizing its profit. Using the inverse demand function to eliminate the price, profit can be written as

$$\widehat{\pi} = pq - (C(q) + (1-\varphi)t\alpha q) = (\widehat{a} - bq - \widehat{c} - (1-\varphi)t\alpha)q - \varphi\, FC \tag{2}$$

and solving the first order condition we find the profit-maximizing quantity of a generic firm:

$$q^* = \frac{\widehat{a} - \widehat{c} - (1-\varphi)t\alpha}{2b} \tag{3}$$

Using this value in the inverse demand function, we find the equilibrium value of the price,

$$p^* = \frac{\widehat{a} + \widehat{c} + (1-\varphi)t\alpha}{2} \tag{4}$$

To see the impact of adopting a CN program on the firm's optimal policy, define $\Delta q := q^*_{\varphi=1} - q^*_{\varphi=0}$, the difference between the quantity produced by a certified and a non-certified firm, and define Δp accordingly, where

$$\Delta q = \frac{\theta - \Delta c + t\alpha}{2b} \tag{5}$$

$$\Delta p = \frac{\theta + \Delta c - t\alpha}{2} \tag{6}$$

From these expressions we conclude that, when the price premium θ increases, CN firms will produce more output and charge higher prices as compared to the baseline situation without certification. The intensity of this effect on quantity is stronger the flatter is the inverse demand function b.

Prices and quantities can also differ because of cost, which has two components. First, a non-CN firm has to pay the tax while a CN firm does not. This effect, which favors the production of CN goods versus non-CN ones, is stronger for more polluting activities (α is high) and when the carbon policy is stringent (the tax rate t is high). In case that $\Delta c < 0$, both cost components go in the same direction, and we always have $\Delta c - t\alpha < 0$. Thus, $\theta - \Delta c + t\alpha$ is unambiguously positive and the firm will always produce more output when it is certified than when it is not, because both effects (demand and cost) go in the same direction, while the impact on the price is undetermined because these effects go in opposite directions. Therefore, we would observe that certified firms tend to produce and sell more, but their prices could be higher or lower.

In the opposite case, $\Delta c > 0$, the cost effect depends on the balance $\Delta c - t\alpha$. In the most adverse case, if Δc is large enough to overcompensate the tax effect, we will observe that certified products are always more expensive, because the demand and the cost effect go in the same directions, but the impact of CN on quantity is undetermined because there are two opposing forces: consumers are more willing to pay but they may be deterred by higher prices.

2.2. Related literature

We now review some of the most significant studies that have analyzed the impact of adopting CN programs on the costs and revenues of the firm.

Regarding costs, as we explain with some detail in the next section, adopting a CN program entails some specific costs (that we label as CN-cost) directly linked to the fulfillment of the program's requirements. Apart from this type of cost, which is born only by CN firms, being CN-certified can also have an impact on operating costs, but the literature is not clear-cut about the sign and size of this impact.

On the one hand, some studies note that implementing a CN program entails some organizational costs, due to the necessity to keep additional records and documents, providing specific in-job-training, etc. Mundaca (2007) shows that, under a "Tradable White Certificate" scheme in UK, there are several sources of transaction costs, such as persuasion of customers, negotiation with business partners, and measurement and verification activities. Mundaca et al. (2013) argue that transaction costs accrued by, for instance, the search for information, due diligence, monitoring and verification activities, must be considered when assessing low-carbon technologies. In the case of CN companies in Costa Rica, Valenciano-Salazar et al. (2022) showed that, in the short term, "high investment costs in clean technologies", "finding information and preparing documentation" and "high costs of certification (external auditors, verification costs)" are perceived as barriers to entering the CN Program. Zeppel and Beaumont (2013) stated that cost, complexity, and lack of time are barriers that disincentive the participation of tourism companies in carbon reduction and offsetting programs.

Kortelainen et al. (2016, p. 1185)investigate the effectiveness of a carbon label using real market data from a major supermarket chain in UK. They underline some costs linked to the monitoring and assessment of CO_2 emissions as well as packaging costs. The company under study claims a minimum of several months' work to calculate the carbon footprint of a product.

According to Birkenberg et al. (2021) the annual certification costs for Coopedota (a coffee Cooperative of Costa Rica) to certify their coffee as CN were approximately € 7800, excluding variable costs of acquiring carbon credits and the investment in infrastructure to reduce CO_2 emissions, such as energy-efficient drying ovens. The corresponding cost of carbon neutral certification would amount to approximately € 0.61 per kg of green coffee.

Uğur and Leblebici (2018) showed that certification costs of the Leadership in Energy and Environmental Design (LEED) in Turkey includes additional design cost, Construction Cost, LEED Application, Certification, Consultancy and Commissioning Fee.

On the other hand, some studies claim that adopting a voluntary environmental program entails some organizational and technological changes that can foster efficiency and reduce cost. See e.g. Burnett and Hansen (2008); Fernández-Viñé et al. (2010); Porter and van der Linde (1995). André and Valenciano-Salazar (2020) showed that some companies in Costa Rica experienced some cost savings when they entered the CN program. These cost savings are due to features such as saving electricity, water, paper and gas (see also, Valenciano-Salazar et al., 2023).

Okereke (2007) shows that adopting companies generate energy efficiency benefits involving less energy-related expenses, and saving in the use of paper and other materials. Cadez and Guilding (2017) find similar cost cuts in energy use by some Slovenian firms operating in the European Union Emissions Trading Scheme. Zhang et al. (2020) present different cases studies with opposing signs: on the one hand, a firm became more efficient by route optimization, and this improved efficiency allowed to reduce fuel costs and attract more purchasers. Another firm suffered some increased cost pressure because of CN adoption.

On the side of revenues, it is well documented that (at least some) consumers are willing to pay a premium for CN-certified products or products produced by a CN-certified firm. The size of this price premium depends on several factors, such as the type of certification, the specific product, and the market environment (see e.g. Birkenberg et al., 2021; Loureiro and Lotade, 2005).

Choi and Ritchie (2014) measured the economic values of aviation carbon mitigation in Australia and found that respondents have a mean WTP of AU$21.38 per ton of CO_2 reduced in the form of voluntary carbon offsets. Mostafa (2016) conclude that consumers in Egypt are willing to pay a price premium between 75 and 90 Egyptian pounds for carbon-labeled products. Based on a sample of 6007 consumers in six European countries -France, Germany, Italy, Norway, Spain and UK- Feucht and Zander (2018) conclude that, in all these countries, the presence of a carbon label increases the probability of purchase and consumers are willing to pay a premium of up to 20% for a carbon label.

In a case study in Chengdu, China, Zhao et al. (2018) conclude that 70.9% of the 1132 respondents would consider buying carbon-labeled milk. Lombardi et al. (2017) show that consumers in Tuscany, Italy, are willing to pay for climate neutral fresh milk; moreover, after providing information about climate neutral labelling, the price premium increases. Also in Italy, Canavari and Coderoni (2020, p. 1) found that the WTP for lower Carbon Footprint is positively linked to the belief that buying greener products can help to combat climate change".

According to Zhao et al. (2020), students at a university in Chengdu, China are willing to pay a 3.2% price premium for carbon-labeled milk. Xu and Lin (2021) conducted a survey on consumers' perception of carbon-labeled electrical and electronic products in Chinese first-tier cities and found that 85.97% of respondents are willing to pay a 7.85% price premium for carbon-labeled products. Birkenberg et al. (2021) found that consumers in Germany are willing to pay € 1.77 premium, around 68% more for CN labeled coffee than for uncertified one. Valenciano-Salazar et al. (2021a) show that Costa Rican consumers are willing to pay a premium of 31% more for a package of CN-labeled coffee.

Firm-level surveys have shown that companies perceive that they can get higher prices or increase their market share by participating in voluntary CN programs (André and Valenciano-Salazar, 2020; Becker et al., 2020; Birkenberg and Birner, 2018; Zeppel and Beaumont, 2013). This effect is linked to the fact that CN programs tend to improve the green image, public recognition and social and environmental legitimacy of the firm (see, e.g., Kilian et al., 2012; Stokes and Turri, 2015; Valenciano-Salazar et al., 2021b).

3. Second stage: strategies to comply with the CN requirements

In Subsection 2.1 we assumed a cost function, but did not explain about how this cost is determined. In this section we address the problem of a firm that has decided to adopt a CN program. In such an event, the firm needs to decide how to comply with the requirements of the program, i.e., which strategy or combinations of strategies to follow in order to become carbon neutral. By doing so we provide some further insight about the determination of the firms' cost when adopting a CN program. In Section 3.1 we present the second building block of our model and then, in Subsection 3.2., we present a revision of the related literature in the light of the theoretical framework.

3.1. Modeling the firms' problem

We consider two types of cost. First, *regular cost* or operating cost, denoted as C_R, which any firm has to assume because of its activity. Second, CN-cost, denoted as C_{CN}, which is the extra cost associated with the fulfillment of the CN requirements, which a firm must assume only if it has adopted such a program. Therefore, in the case of a non-CN firm, total cost coincides with regular cost. In this subsection we care about the second kind of cost, C_{CN}, and the firm's strategy to deal with it.

Whatever the strategies followed to become CN, if a firm adopts the program has to assume some fixed administrative costs linked to the formal and bureaucratic aspects of the certification process (see Albersmeier et al., 2009; De Canio, 1998; Meyers et al., 2016; Valenciano-Salazar et al., 2022). Denote this component as *AC* (for "Administrative Cost").

Also, the firm needs to implement some strategy or combination or strategies to become CN. Denote as E the business-as-usual (BAU) emissions of the firm, i.e., its emissions prior to entering the program. To comply with the CN requisites, such emissions must be removed, abated or offset in such a way that the following condition holds:

$$E - S - A = B \quad (7)$$

where S represents *removal*, i.e., is the amount of emissions captured by carbon sinks (forests) owned by the company, A is *abatement*, i.e., the amount of emissions reduced by means of technological and organizational changes and B is *offset*, i.e., the number of carbon credits purchased. As is usual in microeconomic theory, we assume that the firm will choose its strategy or combination of strategies (i.e, the *optimal* value of S, A and B) with the aim of minimizing its cost.

Sometimes, from a business point of view, forests can be considered as an idle asset. This is the case, for example in Costa Rica, where the Forestry Law N° 7575 (1996), article 19, establishes that "on forest-covered land, no change in land use will be allowed" (Forestry Law of Costa Rica N° 7575, 1996) so, owners cannot use forests for other purposes other than nature conservation. Therefore, we assume that, for firms owning forests before entering the program, this is option as costless.[5]

We model abatement cost as a convex function:

$$C_A(A) = \frac{c_A}{2}A^2 \quad (8)$$

which implies increasing marginal cost. This represents the fact that firms will be willing to use first those technologies with a lower marginal cost and will move to higher-cost technologies only when the cheaper ones have been exhausted.

Finally, the company can offset emissions by buying carbon credits at price as P_B.[6] Therefore, the CN-cost is given by

$$C_{CN} = AC + \frac{c_A}{2}A^2 + P_B B \quad (9)$$

Since AC is constant, a CN firm with BAU emissions E faces the following problem:

$$\min_{\{S,A,B\}} \quad \frac{c_A}{2}A^2 + P_B B \qquad s.t.: \quad E - S - A = B. \quad (10)$$

According to these assumptions, those firms owning forests will use them as much as possible, as this option is costless. This conclusion is consistent with the empirical evidence in some cases, such as Costa Rica, where removal is shown to be the most used strategy to meet the CN requirements (see Table 2).

The remaining emissions, $E - S$, must be abated or offset. The resulting problem is

$$\min_{\{A,B\}} \quad \frac{c_A}{2}A^2 + P_B B \qquad s.t.: \quad A + B = E - S, \quad (11)$$

the solution of which is given by

$$A = \begin{cases} E - S & if \ \frac{P_B}{c_A} \geq E - S \\ \frac{P_B}{c_A} & if \ \frac{P_B}{c_A} < E - S \end{cases} \qquad B = \begin{cases} 0 & if \ \frac{P_B}{c_A} \geq E - S \\ E - S - \frac{P_B}{c_A} & if \ \frac{P_B}{c_A} < E - S. \end{cases} \quad (12)$$

According to (12), the firm will abate as long as its marginal cost is lower than the permit price. If condition $P_B/c_A \geq E - S$ holds, all the emissions can be abated before the marginal abatement cost reaches the permit price and no permits are purchased. Otherwise, the firm abates some emissions and buys permits for the rest. In such a case, expression $A = \frac{P_B}{c_A}$ reveals that the optimal amount of abatement is increasing in the permit price and decreasing in the abatement cost parameter.

Summing up, the minimum-cost strategy consists of using carbon sinks up to their full capacity, then use the least-cost abatement technologies up to a point where the marginal cost of introducing a new technology is equal to the permit price and, finally buy as many permits as needed to cover up the remaining emissions if any.

Assume that, in a BAU scenario, each unit of output generates α units of emissions, i.e., $E = \alpha q$. Thus, the CN-cost of a firm can be written in terms of output as

$$C_{CN}(q) = \begin{cases} AC & if \quad q \leq \frac{S}{\alpha} \\ AC + \frac{c_A}{2}(\alpha q - S)^2 & if \quad \frac{c_A S + P_B}{\alpha c_A} \geq q > \frac{S}{\alpha} \\ AC + \frac{c_A}{2}\left(\frac{P_B}{c_A}\right)^2 + P_B\left(\alpha q - S - \frac{P_B}{c_A}\right) & if \quad q > \frac{c_A S + P_B}{\alpha c_A}, \end{cases} \quad (13)$$

and the associated marginal cost is given by

$$MC_{CN}(q) = \begin{cases} 0 & if \quad q \leq \frac{S}{\alpha} \\ \alpha c_A(\alpha q - S) & if \quad \frac{c_A S + P_B}{\alpha c_A} \geq q > \frac{S}{\alpha} \\ \alpha P_B & if \quad q > \frac{c_A S + P_B}{\alpha c_A}, \end{cases} \quad (14)$$

which is represented in Fig. 2, where each range is associated to the marginal compliance strategy.

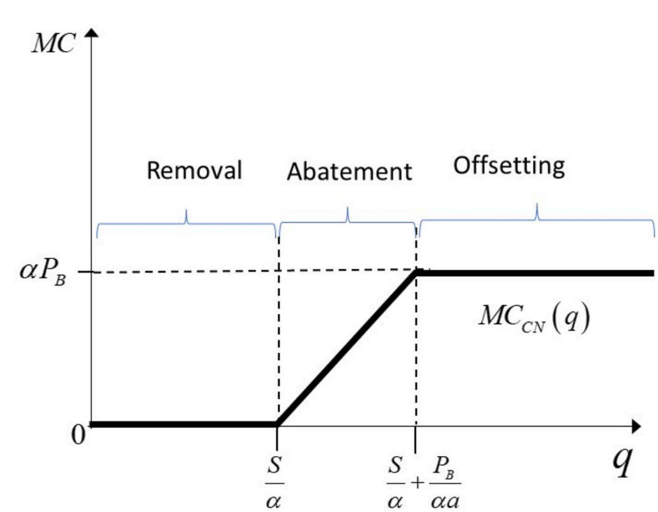

Fig. 2. Marginal cost associated to joining the CN program in terms or output.

[5] The cost is not literally zero in practice, as the firm needs to present a technical report verified by an engineer, which entails a certain cost. As this cost is well below that of the other alternatives, for simplicity we normalize it to zero.

[6] In some cases, the price of carbon credits fluctuates with supply and demand. In other cases, as in Costa Rica, the price of the carbon credits does not fluctuate in a free market but is set at an official value by FONAFIFO. Currently, such price is 7.5 $ per ton (MINAE et al., 2019). In systems where the price fluctuates, it can still be seen as fixed by "small" firms that cannot influence the price (if the number of participants is large).

We simplify the exposition by considering a firm that is in the third range, i.e., $q > \frac{S}{\alpha} + \frac{P_B}{\alpha c_A}$, meaning that its output is large enough, or it does not have (enough) forests to avoid using some abatement and buying some permits.[7] In this range, the CN-cost can be written as

$$C_{CN}(q) = \alpha P_B\, q + FC \quad \text{with } FC := AC - \frac{(P_B)^2}{2a} - P_B S \tag{15}$$

This expression shows that joining the CN program involves a variable cost and a fixed cost. The marginal cost is αP_B, which is given by the permit price and carbon intensity. The fixed cost is mostly determined by the administrative component, minus the cost saving that the firm can achieve by using removal and abatement.

By summing up regular costs and CN-costs, we obtain the total costs of a CN firm given by $C^{CN}(q) = C_R^{CN}(q) + C_{CN}(q)$, or using (15),

$$C^{CN}(q) = c^{CN} q + FC, \tag{16}$$

where $c^{CN} := c_R^{CN} + \alpha P_B$, which captures the overall marginal cost of a CN-certified firm, including marginal regular cost and marginal CN-cost. *FC* represents the fixed costs associated to the participation in the CN program (see Subsection 2.2).

3.2. Related literature

We now review the papers related to the three main strategies to become CN, removal, abatement and offsetting.

In terms of the first strategy, Mulligan et al. (2020) notes that the most used carbon removal activities include forest conservation (afforestation and reforestation), managing soil for carbon sequestration through crops with deeper roots (making them more resistant to drought, while depositing more carbon into the soil), and bioenergy with carbon capture and storage, carbon mineralization, and ocean-based carbon removal (e.g., restoring coastal ecosystems such as salt marshes, mangroves, and seagrasses). In some programs, conserving forests on company land or planting new trees are considered as eligible carbon removal strategies (MINAE et al., 2019; Mulligan et al., 2018; WBCSD & WRI, 2004).

It is documented that, in the tropics, carbon storage through forests or reforestation is considered the cheapest strategy. 51 renowned scientists published a study in Science Advances stating that in the case of Latin America "coupled with avoided deforestation and sustainable forest management, natural regeneration of second-growth forests provides a low-cost mechanism that yields a high carbon sequestration potential with multiple benefits for biodiversity and ecosystem services" (Chazdon et al., 2016, p1). Similar conclusions are obtained by Raihan et al. (2018), who state that forest management, afforestation and reforestation can decrease the carbon price up to 80% and reduce the emission reduction costs up to 40%, whereas afforestation is be the lowest-cost carbon sequestration option.

Kilian et al. (2012) reviews company Dole's strategy to use own forestry projects to reduce CO_2 emissions and obtain CN bananas and pineapples. Zeppel and Beaumont (2013) state that the most popular carbon management alternative for tourism enterprises in Queensland, Australia, is bio-sequestration, with tree planting on their own property. Looking for pathways to carbon-neutrality for the Australian red meat sector, Mayberry et al. (2019) find that afforestation and revegetation of grazing land are likely to become the main methods for sequestering carbon in the short to medium term.

Carbon removal, mainly through forests and planting of new trees, is one of the strategies used by companies that are part of the Costa Rican CN Program (see Jiménez-Castro, 2016; Valenciano-Salazar et al., 2022; Valenciano-Salazar et al., 2023). Paniagua-Ramirez et al. (2021) estimate high amounts of carbon storage in a Costa Rican tropical forest located at the Council on International Educational Exchange.

Mayberry et al. (2019, p.12)show that, through changes in land management, improvements in vegetation management and application of technologies to reduce enteric methane emissions from grazing livestock it is possible for the Australian red meat industry to substantially reduce GHG emissions, and even become CN.

Technological change is making new carbon removal options available, such as bioenergy with carbon capture and storage, direct air capture and terrestrial enhanced rock weathering (Beerling et al., 2020; Consoli, 2019; Regufe et al., 2021). However, according to Cox et al. (2020), the response given by these strategies to the climate crisis is too slow and fail to address the root causes of climate change as they and do not reflect long-term hopes for a sustainable world.

Let us move on the second strategy, abatement. In a study of carbon management strategies by 100 UK FTSE companies, Okereke (2007) found mainly three paths of carbon cuts: behavioral change, basic technological change and fundamental technological shift and innovations. The former includes actions such as double-sided printing and reducing the printing rate, switching off the lights during non-office hours, separating and recycling waste, turning off or turning low heating and cooling systems, telecommuting and reducing the travelling rate. Basic technological change includes using low energy bulbs, installation of hand driers, changing operating systems and replacement of windows. Fundamental technological shift requires switching to more efficient and less polluting technologies and procedures, including the use of renewable energy -mainly throw solar panels, increasing the use of hybrid and electric vehicles or implementing better waste management technologies. Valenciano-Salazar et al. (2023) identified similar strategies for the companies in the Costa Rican CN Program. Also in Costa Rica, Birkenberg and Birner (2018) identified the following abatement strategies for CN coffee: composting coffee pulp, installing a biodigester and producing ethanol from sugar rich wastewater.

Das (2012) identified the following strategies to achieve carbon neutrality in the Global Aluminum Industry: increase use of green electrical energy grid by 8%, reduce process energy needs by 16%, deploy 35% of products in "in-use'' energy saving applications, divert 6.1 million metric tons/year from landfills, and mine 4.5 million metric tons/year from aluminum-rich urban mines. Zeppel and Beaumont (2013) showed that energy efficiency and renewable energy use are the main reduction measures for some Australian tourist's firms. Cadez and Guilding (2017) found that the main firms' actions combine basic technological change, such as installing more efficient boilers, and fundamental technological shift such as switching fuel.

Opel et al. (2017) argued that Leuphana University invested in renewable energy systems and efficient buildings looking for climate-neutral behavior. In the same line, Osorio et al. (2022) showed the path followed by two private higher education institutions in Colombia includes sustainable infrastructure, energy management, improved waste management, renewable energy use, reducing fossil fuels and shifting toward the use of electric vehicles, among others. Tian et al. (2022, p.1) present a sustainable design of CN energy systems in Cornell University campus; strategies consider earth source heat, lake source cooling, on-site renewable electricity generation, mainly from geothermal energy and sustainable peak heating systems.

Becker et al. (2020, p.7) investigated actions for a company in the French spirits sector and concluded that transportation is the main

[7] Empirically, this is the case for all (or, at least, most) of the firms in the Costa Rican program. From the firms' reports and the FONAFIFO website (see FONAFIFO, 2020), we found out that virtually all the firms enrolled in the program had to buy some credits, which, in terms of our model, means that they are in the third range. For a firm that is in the first range, the development of the rest of the model would be identical (just by changing the value of the fixed term and setting the marginal CN-cost to zero). In the second range, things would be slightly different as the marginal cost is increasing. We omit the discussion of this case because it would make the exposition more cumbersome without any relevant additional insight.

source to reduce emissions. Reducing the weight of bottles from 710 to 640 g may cut emissions by 10% due to glass manufacturing (minus 0.5 tons) and transportation (minus 15 tons). In a study of carbon neutrality in European airports, Falk and Hagsten (2020) mention from some general-purpose strategies, such as the use of renewable energy, energy savings, energy efficiency, fuel switching and improved waste management, and some specific channels, such as environmentally friendly passenger access to the airport and reduction of emissions from aircraft arrivals and departures.

Typically, the last option offered by CN programs to participants is to offset the remaining emissions, i.e., those that cannot be removed in own company land or abated by buying carbon credits (Ball et al., 2009; Das, 2012; Falk and Hagsten, 2020; Okereke, 2007; Zeppel and Beaumont, 2013). In most cases, CN programs allow to offset GHG emissions through international carbon credits, such as Voluntary Emissions Reductions (VERs), Verified Carbon Units (VCUs), Certified Emission Reductions (CERs) among others. All of the carbon offsetting instruments must comply with the principles of transparency, relevance, reliability, continuity and accuracy (Osorio et al., 2022).

Some programs, as the one in Costa Rica, allow the use of local carbon offset credits. In this case, each credit guarantees the removal of one ton of GHG emissions on private farms and forests (not belonging to the company). In Costa Rica, the revenue from selling carbon credits is used to promote forest protection and compensate private landowners for the ecosystem services provided by their land (Sánchez-Azofeifa et al., 2007).

4. First stage: deciding to adopt a CN program

Now, we move on to the first stage of the firm's problem. At this stage, the firm can anticipate the implications of its decision and evaluate the expected[8] profit associated with the decision to adopt or not adopt a CN program. As usual, we assume that the firm will choose the option that provides higher profits. We address this decision in theoretical terms in Subsection 4.1, and review the related literature in Subsection 4.2.

4.1. Modelling the adoption decision

Using the values of price and quantities derived in Subsection 2.1., profit is given by

$$\pi^* = \frac{(\widehat{a} - \widehat{c} - (1-\varphi)t\alpha)^2}{2b} \tag{17}$$

To see the impact of the certification on profit, define $\Delta\pi := \pi^*_{\varphi=1} - \pi^*_{\varphi=0}$, which is equal to

$$\Delta\pi = \frac{(\theta - \Delta c + t\alpha)[2(a-c) + (\theta - \Delta c + t\alpha)]}{4b} - FC. \tag{18}$$

and so, a firm will adopt a CN program if the following conditions holds:

$$\Delta\pi \geq 0 \Leftrightarrow (\theta - \Delta c + t\alpha)[2(a-c) + (\theta - \Delta c + t\alpha)] \geq 4\ b\ FC \tag{19}$$

From this expression, we can identify the factors that determine CN adoption. Recall (Section 2.1) that any change in the baseline intercept of the demand (a) or the baseline marginal cost (c) has the same impact on the quantity and the price of a certified and a non-certified firm and, thus, the differentials Δq and Δp remain unchanged. Nevertheless, we see now that any increase in the differential $(a-c)$ favors the certification decision, i.e., those firms with a larger demand and/or a lower marginal cost are ceteris paribus more prone to adopt the certification. Importantly, a large demand can be identified with a larger market and, presumably, with larger firms. This is an important empirical implication as it is discussed in the literature revision below.

Now, we consider the balance between WTP and cost elements. The most favorable case for adoption is $\Delta c < 0$, which implies that $\theta - \Delta c + t\alpha$ is unambiguously positive. Then, as we know from Subsection 2.1, a firm will always produce more output if certified, and equation (19) shows that this case also tends to increase the profit of a CN firm vis-à-vis a non-certified one.

In the less favorable situation $\Delta c > 0$, this cost disadvantage must be compared to the positive effect stemming from the price premium θ and the fact of being exempt from the carbon tax, $t\alpha$. Actually, the term $\theta - \Delta c + t\alpha$ being positive is a necessary condition for a rational firm to be willing to adopt a CN certification. The sufficient condition requires it, not only being positive, but also to be large enough to compensate for the fixed adoption cost, which is the main deterring factor in our model. On the right-hand side of condition (24), this factor appears multiplied by the slope of the inverse demand function which, as shown in Subsecion 2.1, tends to dilute the positive impact on output.

Wrapping up, our model helps us illustrate that CN programs are more prone to be adopted by large firms (or, equivalently, firms facing a large demand). Also, in sectors or markets in which the consumers are more prone to pay higher price premiums, when the state-of-the art production is very polluting and/or carbon is heavily taxed. Related to this impact, firms might decide to adopt a CN program anticipating a tighter future carbon regulation (see e.g., Tian et al., 2022). Finally, voluntary CN programs are more prone to be adopted by firms or sectors with low baseline unit costs and/or enjoying a cost advantage when adopting CN or, at least, with a cost disadvantage that is low enough compared with the price premium that consumers are willing to pay.

For the sake of connection with the literature it is also worth to provide an alternative interpretation for the carbon tax t. This term can also be understood as a measure of the firm's social corporate responsibility (CSR). Then, the term $t\alpha q$ can be seen as a penalty that the firm includes in its profit function to represent its concern about its own carbon emissions. More generally, t can be seen as a measure of the firms' urge to reduce emissions, whether such an urge comes from an intrinsic motivation, the threat of a penalty, or a combination of both.

4.2. Related literature

We can find two main strands of studies about the adoption of CN programs: first, studies about the main motivators that lead firms to make the adoption decision, and second, about the main characteristics of firms, or the market or environment in which they operate, that make they more prone to adopt a voluntary program.

Regarding the first strand, the literature identifies two big blocks of motivators that can be classified in economic and non-economic. Economic motivators, in one way or another, refer to the expectation of a larger profit. To a large extent such expectation comes via improved reputation and social image, and the fact that aware consumers are willing to pay premiums for CN products. Non-economic motivations are of an ethical, environmental and social nature, and typically have to do with firms' CSR. A further source of motivation, that is somehow between the other two, has to do with social and political pressure and the urge to comply with the existing regulation or the anticipation of a tougher regulation in the future.

According to Okereke (2007), the first motivation behind company's carbon management programs is profit. This author shows that many organizations within the FTSE 100 companies find a clear link between their reputation and the value of their portfolio. For most of them, costumers' trust translates into market advantages. Green image and public recognition are drivers for tourist companies in New Zealand (Zeppel and Beaumont, 2013); UK FTSE 100 companies (Okereke,

[8] As we discuss in Section 5, in a more general framework the decision can be subject to some uncertainty and then, the value of profit becomes itself an uncertain variable. Thus, the firm cannot maximize its profit but its *expected profit*. In the basic version that we are laying out, there is no uncertainty and then the expected profit is also the realized profit.

2007), and for a case of CN coffee in Costa Rica (Birkenberg and Birner, 2018).

To achieve public recognition and social legitimacy, companies must disclose the specific actions they take to achieve carbon neutrality. This disclosure of information gives an idea of firms' transparency about their environmental actions and provides credibility to the CN label (Fernandez-Feijoo et al., 2014). Liesen et al. (2015) argued that stakeholder pressure drives companies to report GHG emissions and thus achieve social legitimacy. In addition, Galán-Valdivieso et al. (2019) argued that stakeholders need to be aware of corporate carbon management activities, as an important source of information for conceding legitimacy. Under the threat of losing legitimacy, firms may react by engaging in sustainable initiatives and disclosing their environmental performance.

Ethical motivations appear alongside economic ones for CN adoption. About the Costa Rican voluntary CN program, Valenciano-Salazar et al. (2022) identify as the first driver "commitment to the quality of the environment and the sustainable development goals of the country", which is non-economic, whereas the second and third drivers are economic: "improving green image, enhancing public recognition and social legitimacy" and "improving the relationship with stakeholders". Dole company announced its intention to go CN in Costa Rica in ten years "as a strategy for differentiation and CSR". According to the firm, the main motivations for the initiative were first, a natural extension of its environmental programs; second, customer inquiries about the company's carbon footprint and plans, and third, the Costa Rican Government's commitment to carbon neutrality" (Kilian et al., 2012). Zeppel and Beaumont (2013, 14), reported "personal concern about the environmental impacts of climate change" and the willing to do "the right thing for the environment" as motivations to adopt carbon offseting programs. Becker et al. (2020) suggest that prioritizing sustainable development by reducing emissions is a winning situation for the entire industry in the French spirits sector.

Regarding social pressure and political regulation, Zhang et al. (2020) identifies coercive pressures from customer enforcement, environmental normative pressures and mimetic pressures from competitors as primary incentives for carbon neutrality among the early movers. This study also reveals that the shareholders' and top management's sustainable business value plays a pivotal role in the commitment to carbon neutrality".

Although the literature specifically addressing the adoption of CN programs is scarce (see Table 3 for a survey), the results are reinforced by the fact that similar conclusions are obtained in studies about other voluntary programs that share some common features. Khanna (2001) identifies the following drivers to adopt voluntary environmental approaches: anticipating mandatory regulations, technical assistance and financial opportunities, cost efficiency, and improving the relation with stakeholders, including government, consumers, shareholders, communities and other firms in the industry.

Table 3
Literature about drivers to adopt voluntary CN programs.

Authors	Location	Sample	Drivers
Kilian et al. (2012)	Costa Rica	1	D_2, D_4, D_6
Okereke (2007)	UK	100	D_1, D_2, D_6
Zeppel and Beaumont (2013)	Queensland, Australia	83	D_2, D_3, D_6
Cadez and Guilding (2017)	Slovenia	76	D_1, D_6
Birkenberg and Birner (2018)	Costa Rica	1	D_2, D_3,D_4
André and Valenciano-Salazar (2020)	Costa Rica	24	D_1, D_2, D_3, D_6
Becker et al. (2020).	France	1	D_3, D_6
Osorio et al. (2022)	Colombia	2	D_4, D_6
Tian et al. (2022)	USA	1	D_5, D_6
Valenciano-Salazar et al. (2022)	Costa Rica	11	D_1, D_2, D_3, D_4, D_6
Zhang et al. (2020)	Bulgaria, Pakistan, and UK	7	D_1, D_2, D_4, D_6

Notes: D_1: Cutting cost or increasing productivity, D_2: Increasing green image and social legitimacy, D_3: Increasing sales, market shares or prices, D_4: Improving relation with stakeholders, D_5: Preparing for institutional regulations and carbon fees, D_6: Ethical issues and concern about the future and environmental problems.

Morrow and Rondinelli (2002) studied the motivations of five German energy and gas firms for EMS implementation and certification. Firms were primarily motivated by the desire to improve documentation, ensure regulatory compliance, and increase the efficiency of their operations.

Santos et al. (2016) notice that small and medium-sized Portuguese companies that obtained the EMS certification were also driven by economic and non-economic motives: obtaining benefits in addition to marketing such as the prevention of environmental risks, the protection of the environment, the improvement of the company's image, compliance with the legislation and the efficient use of natural resources.

The second strand of the literature has to do with the main features that make firms more prone to adopt a voluntary program. Consistent with our theoretical predictions, some articles show that larger firms are more prone to adopt CN programs or, more generally, any voluntary environmental initiative. For example, Zeppel and Beaumont (2013) indicates that the main enterprises entering in carbon offset programs in Queensland, Australia, were larger transport and tour operators, as measured by the number of workers.

Some of the participants in the Costa Rican CN program are recognized and influential multinational companies (Valenciano-Salazar et al., 2022). In addition, many companies that have CN-certified products are producing in developing countries but sell their products in high income countries. See, for example, Kilian et al. (2012) for the case of pineapples and bananas or Birkenberg and Birner (2018) and Birkenberg et al. (2021) for the case of coffee.

Using a Cox proportional hazard model based on almost 600 European airports for the period 2009 to 2017, Falk and Hagsten (2020) conclude that the likelihood and timing of participation in emission reduction programmes increase with the size of the airport (number of passengers). Li et al. (2021) conclude that firm size correlates positively with a more positive effect on the cultivation of green core capabilities from the low-carbon technological innovation of Chinese manufacturing companies.

Firms of certain sectors that are intensive in the use of renewable and non-renewable resources, most likely subject to stringent environmental regulations also tend to join carbon neutrality programs; among them, steel (Fu et al., 2014), aluminum (Das, 2012), agriculture and agroindustry (Becker et al., 2020; Birkenberg; Birner; 2018; Kilian et al., 2012; Meyers et al., 2016), and cattle raising (Mayberry et al., 2019).

Grolleau et al. (2007) presented empirical estimates of the impacts of various potential drivers of ISO 14001/EMAS certification among agrifood firms in France. They suggest that firm size, previous ISO 9000 certification, customer demands, human resource management and regulatory compliance play a significant role in the certification decision. Blackman and Guerrero (2012) show that the ISO 14001 certification program in Mexico attracts relatively dirty plants and it has the potential to improve environmental performance. These firms are more likely to sell their goods in overseas markets, to use imported inputs, to be relatively large, and to belong to certain sectors such as manufacturing and mining.

5. Further issues

There is number of further issues and complexities that we have intentionally omitted in our conceptual framework for the sake of brevity and tractability. In this section we offer a glimpse of some of these extensions.

Adopting a dynamic approach and considering the time dimension brings a number of additional relevant issues. A first one has to be with the discount of the future. To capture this element, consider that the fixed adoption cost is paid upfront (say, at time 0) whereas the revenues and the operating costs are distributed along the lifetime of the certification (say, periods 1, 2, etc.). In a Cost-Benefit-Analysis logic, the decision of the firm should be based on the difference of the discounted net profit between both situations, given by

$$\Delta\Pi = -FC + \Delta\pi_0 + \frac{\Delta\pi_1}{1+r} + \dots + \frac{\Delta\pi_T}{(1+r)^T} = -FC + \sum_{t=0}^{T} \frac{\Delta\pi_t}{(1+r)^t}, \quad (20)$$

Where $\Delta\Pi$ is the difference in discounted profit, $\Delta\pi$ is the difference in yearly operating profit (net of the adoption cost), r represents the discount rate, T is the time horizon and t refers to any specific period. As a first approximation, assume that $\Delta\pi_t = \Delta\pi$ has a constant value across periods and the time horizon is infinity. Then, (20) can be written as

$$\Delta\pi = -FC + \frac{(1+r)\Delta\pi}{r}, \quad (21)$$

where we have used the fact that $\sum_{t=0}^{\infty}\frac{1}{(1+r)^t}$ corresponds to the infinite terms of a convergent geometric series. From equation (21) we can see that a necessary condition for a rational firm to adopt a CN program is that the differential operating profit $\Delta\pi$ is positive, i.e., the CN price premium overcomes any possible disadvantage in yearly cost. Provided that this necessary condition holds, a sufficient condition is

$$r < \frac{\Delta\pi}{FC - \Delta\pi} \quad (22)$$

which implies that the discount rate must be low enough or, in other words, the firm puts enough weight on future values with respect to present values. This has a purely economic interpretation as the firm being more forward-looking. Such behavior is more prone to be found in firms involved in innovative sectors. It can also be claimed that larger firms are more likely to be forward-looking. Both of these insights are consisted with the empirical evidence as large and innovative firms show a higher propensity to adopt CN initiatives (see e.g. Joppa et al., 2021).

A low discount rate can also be interpreted as a preference for intergenerational equity and/or for environmental preservation. This type of motivation is non-purely economic, but of a more social and environmental nature, which can be connected with the discussion in Subsection 4.2 about non-market motivations being essential to understand many companies' decisions to adopt CN initiatives.

Another issue that is intrinsically linked to the time dimension is technological change. This kind of progress is likely to affect (reduce) abatement cost rather than the other two strategies, removal and offsetting (IRENA., 2016; 2020). As a first implication CN adoption may become profitable after a technical advance, even it was not before. Therefore, we may empirically observe an increasing number of adopting firms (Wang et al., 2021). Secondly, for adopting firms the optimal mix of strategies to comply with the CN requirements may change. If the price of permits is roughly constant and abatement becomes cheaper, we can expect to see that CN firms will adapt their strategy by doing more abatement and buying less permits. This is illustrated in Fig. 3. If the supply of permits is fixed and the price is determined by demand and supply, we could observe, consequently, a decrease in the equilibrium price of permits as far as the impact of the technical change is strong enough and/or the affected firms have a significant weight in the market. This would not be case in a system as the one in Costa Rica, where the permit price is legally fixed rather than determined in the market.

An additional relevant issue is the presence of uncertainty coming from different sources. Firstly, adopting a voluntary program could entail some uncertainty about the exact size of the costs and the reactions of consumers, which in turn implies uncertainty about profit.

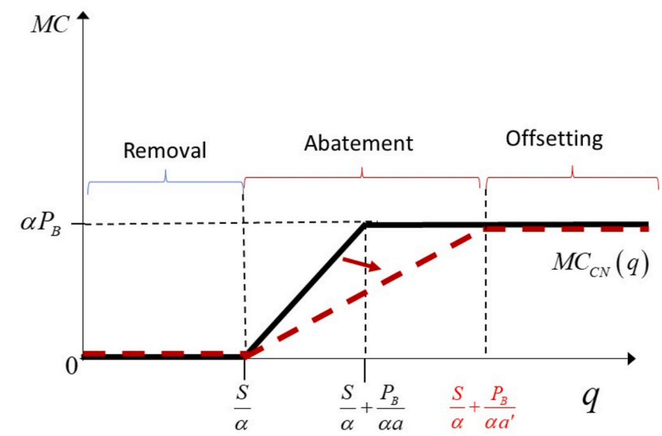

Fig. 3. Change of the Marginal Cost function due to a reduction in abatement cost.

Arguably, a large uncertainty of this type could act as a negative incentive for adoption, especially for small firms and those that are more sensitive to risk. On the other hand, the firm can be doubtful about possible future changes in environmental policy. The expectation of a tougher future policy against carbon emissions could encourage firms to become CN in anticipation for a worse scenario. In general, the balance of these opposing forces will be determined by the specific business scenario and the firm's expectations.

Finally, in this revision we have only addressed the decision of an individual firm. In practice, an important driver for firms' adoption decision is the interaction with other firms. Although this consideration is outside the scope of this article, it is useful to point down two opposing strategic forces that may play in different directions. On the one hand, the tendency to diversify and cover different market niches my result in a scenario in which some firms become CN and try to address more concerned consumers, while other firms continue producing cheaper products using BAU technology. On the other hand, the fact that a large number in the same industry have become CN, together with social pressure, can force non-certified firms to become also CN in order to avoid the social stigma (Dai et al., 2018).

6. Concluding remarks

Voluntary CN programs are playing an increasingly relevant role to put into practice the countries' commitments to curb carbon emissions and contribute to the UN SDGs on climate change and sustainability, not only in developed countries, but also in developing ones. The non-mandatory nature of these initiatives brings out the crucial role of consumer's awareness and firms' engagement. For this reason, the proper design of these policy instruments, and the incentives that they generate deserve being carefully studied.

In this review, we have gathered some of the most prominent aspects of CN programs and shown how they are likely to impact on firms results and behavior. To understand how these initiatives work, it is important to bear in mind that there are several channels by which the adoption of a voluntary CN initiative can affect a firm's benefits and costs. On the positive side, joining a CN program may come along with a positive price premium paid by aware consumers, associated to an improved image and legitimacy of the firm. On the negative side, participant firms face administrative cost, as well as investing in GHG emissions abatement technologies and/or purchasing carbon credits. Such costs represent a negative incentive for CN adoption, especially for small companies. Nevertheless, it is not unrealistic to assume that these programs may bring some efficiency gains and costs reductions.

Once a CN program has been adopted, firms have different options to comply with the requirements of the program. The least cost strategy is typically to dedicate unused lands as carbon sinks, either by planting new trees or by maintaining previously existing ones. Subsequently, companies can use emission abatement technologies while their marginal cost is less than or equal to the price of carbon credits, which is the final option.

The relative weight of these positive and negative forces can be strongly contingent on specific circumstances (country, market, activity sector). Moreover, both in theoretical and empirical terms, size seems to be a key factor because a large volume of output will make it easier to recover the fixed adoption costs. By including a time dimension, we have shown that "patience", i.e., a lower discount rate makes firms more prone to adopt CN programs whose benefits are typically delayed in time while adoption costs are paid upfront. This "patience" effect can be linked to several firms' features such as size, innovation and a pro-environment attitude. An immediate policy implication of this fact is that promoting innovation, as well as education and sensitization appear to be key strategies to engage firms, but also consumers, in the adoption of voluntary environmental initiatives and curb carbon emissions. Considering the dynamic dimension also opens some relevant issues such as the possibility of technical change and uncertainty.

The lack of systematic studies, along with the important role of these policy approaches are important arguments to keep on studying and getting a better understanding of voluntary CN programs.

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Author contribution

Francisco J. André : Theoretical model, writing, Jorge A. Valenciano-Salazar: Literature revision, writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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