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Madhuparna Ganguly

Indira Gandhi Institute of Development Research, Mumbai
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Email(corresponding author): madhuparna@igidr.ac.in

Abstract

This paper analyzes the implications of firms' intrinsic valuation for pro- environmental production on technology adoption and signaling outcome when adopting a costly pollution-free technology does not favour profit despite consumers' higher willingness to pay for the environment-friendly product. As growing environmental awareness makes individuals and businesses increasingly cognizant of the ramifications of their actions, acting pro-environmentally engenders feelings of contentment and boosts self-image. We find that, while under symmetric information the intrinsically motivated firm optimally adopts pollution-free production, under asymmetric information the same is true only when consumers are sufficiently generous for or incredulous regarding pro-environmental behaviour, such that signaling is feasible. Although the signaling outcome is environmentally desirable, firms face challenges in balancing environmental objectives with profit goals when information is asymmetric. We suppose post-production subsidization to buttress ethical initiatives of firms and show cost-equivalence of lumpsum and per-unit subsidy schemes.

Keywords: Environmental consciousness, Intrinsic motivation, Self-image, Signaling, Technology adoption

JEL Code: D63, D82, D91, L21, Q52

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Madhuparna Ganguly†

Indira Gandhi Institute of Development Research (IGIDR), India

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†**Corresponding Address:** Indira Gandhi Institute of Development Research (IGIDR), Film City Road, Santosh Nagar, Goregaon (E), Mumbai - 400065, India. Email: madhuparna.ganguly1994@gmail.com, madhuparna@igidr.ac.in.

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1 Introduction

Environmental consciousness has been a fundamental focus of major economies over the past few decades and recent times have seen growing environmental awareness among economic agents. While the primary importance of environmental conservation was initially acknowledged in the developed economies of U.S., Japan and Europe, with growing urbanization and economic development over the past decade, it is now a major concern worldwide (Cohen, 2015). Increasing evidence of environmental awareness among individuals is visible in their day-to-day life as well. According to a survey report published in a leading daily in China, regarding the impact of growing environmental concern on the lives of people, "63 percent said they reduced unnecessary trips and about 72 percent said they reduced their outdoor activities" (Cohen, 2015). Indeed individual consumers are taking on their eco-responsibility by "increasingly foregoing unnecessary trips, reducing their driving distances and cutting back on restaurant-dining", all of which are thought to have some positive impact on the environment (Kenyon, 2008). In the context of oligopoly markets, environmental consciousness of consumers manifests itself as a higher willingness to pay for the product produced with lower environmental damage. This provides an important incentive for firms to invest in the development or adoption of pollution reducing technologies. However, while higher willingness to pay of consumers may encourage corporate manufacturing firms to undertake environment-friendly production, it is also plausible that firms adopt such methods by virtue of their intrinsic motivation to act pro-environmentally. This paper studies the implications of intrinsic environmental consciousness of firms on adoption of a cost-augmenting environment friendly production technology, when consumers are environmentally conscious but uninformed about the actual technology employed.

The idea of intrinsic motivation emanates from an aspect of human behaviour that drives individuals to care not only about the opinion that others have of them but also about the image that they have of themselves. Businesses and organizations are no exception. Owners, managers and employees increasingly consider sustainable business practices to be the "moral and ethically right" thing to do. Further, sustainable business practices are more likely to be put in place by senior management and owners who are committed to sustainability for ethical reasons, even without a detailed assessment of the impact on revenue, costs, and profitability (Gittell, Magnusson, & Merenda, 2012)[1]. It follows, while the profit motive may be the fundamental motive of most corporate organizations in the long run, doing what is 'right' or 'appealing to the moral sense' adds to the overall satisfaction and feeling of content of a business. In this era of growing environmental concern, it is thus important to consider the aspect of environmental consciousness in firms' optimization objective.

Existing literature on behavioural psychology explains why doing what one believes to be right enhances feelings of satisfaction and intrinsically motivates prosocial behaviour from a notion of "self-image". Johansson-Stenman and Martinsson (2006) survey the environmental and status related concerns of owning a private car and find individuals' perception of their preferences to be favourably biased, thus portraying a more desirable self-image and augmenting utility. Dana, Weber, and Kuang (2007) suggest that fairness and altruism do not stem from welfare or equity concerns but rather from the need to comply with what "should" or "ought" to be done. They demonstrate, where guilt can be avoided through wilful ignorance, people choose to remain uninformed and make selfish choices, implying individuals care not so much about the effects of their choices as what these choices say about their self-image. These theories advocate egoism and posit the end goal of other-regarding behaviour as its ensuing enjoyment, i.e. a self-serving end. On

[1] Case studies on some environmentally sustainable businesses provide motivating examples. A classic example is that of Simply Green, which started out as a hydro-seeding business but entered the industry of biofuel supply solely driven by the passion and environmental concern of its founder Andrew Kellar. Another example is of one of the first companies for sustainable household and personal care products, Seventh Generation, that capitalized on consumers' need to make a "positive difference", which was also its founder, Jeffrey Hollender's personal objective. Green Mountain Coffee and Stonyfield Yogurt are other examples of businesses that designed a success story around their primary mission of environmental sustainability. See Gittell et al. (2012) for a detailed discussion on each case.

the contrary, theories propounding altruism assert that, the intended end is the prosocial act in itself and the self-benefit, an unintended consequence (Batson & Powell, 2003). Brekke, Kverndokk, and Nyborg (2003) incorporates altruism in the self-image view by proposing that while self-image concerns influence prosocial acts, returns from such acts are not unconditionally increasing. Instead, they are benchmarked against a "moral ideal" by evaluating their consequences on social welfare. In addition to the perception of personal norms advanced in the above theories, social norms may also drive intrinsically motivated behaviour. Posner and Rasmusen (1999) identify among the sanctions for violation of a social norm, personal guilt and shame, that arise from a moral sentiment or a feeling of being lowered in ones' own eyes. It follows, with the surge in environmental awareness being tantamount to a paradigm shift, businesses face an increasing pressure to balance the need for environmental conservation with profit motives (Cohen, 2015), perhaps not so much to enhance social welfare as to bolster their self-image by adhering to personal and social norms. The industrial organization literature has considered intrinsic motivation of firms in studying optimal incentive design. Bénabou and Tirole (2006) combine the concern for self-image with extrinsic and reputational motivations for prosocial behaviour, and study their interplay to identify optimal incentive design. Studies on incentives to induce environmental contribution with intrinsically motivated firms include - Banerjee and Shogren (2010), who analyze how reputational concerns affect equilibrium incentives, Qin and Shogren (2015), who introduce the concept of social norms, which include both personal ethics and public reputation, and Banerjee, Pal, and Shogren (2016), who further consider the interaction of honor, associated with a firms' true concern for the environment, and stigma, associated with doing good deeds solely for seeking reputation. This paper introduces intrinsic environmental concerns of firms as an enhancement of their pay-off over and above their monetary profit, when firms having polluting technologies decide to adopt a non-polluting technology at higher cost, and consumers value non-polluting production but may be uninformed.

A few studies have explored pollution-alleviating technology adoption and signaling behaviour by firms when consumers are willing to pay higher for environment-friendly products. Sengupta (2012) and Sengupta (2015) analyze investment incentives in a potentially clean technology and corresponding signaling outcomes, under monopoly and duopoly respectively, in the presence of environmentally conscious consumers and a liability for producing dirty, when the final outcome of technology adoption is probabilistic and private information. Mahenc (2008) studies price distortions by a firm, with an exogenously determined level of cleanness, for signaling environmental quality of its good to uninformed environmentally conscious consumers. Arora and Gangopadhyay (1995) explain voluntary over-meeting of environmental standards in a two stage duopoly where firms first decide their level of environmental cleaning and then engage in price competition in the product market. They find that, since homogeneous firms earn zero profits under price competition, the profit motive induces the cleaner firm to overcomply and differentiate itself from the dirty firm. Our study investigates how the intrinsic motivation of firms to act pro-environmentally influences technology adoption behaviour. We consider a duopoly where firms vary in their levels of intrinsic concerns and are initially endowed with a polluting technology. Adoption of a costly pollution-free technology is the "moral ideal" or "ethical goal", achieving which augments firms' pay-off not just through higher willingness to pay of consumers but also through the intrinsic valuation for environmentally safe production. Firms decide whether to adopt this new technology and produce 'green' or continue with the polluting technology and produce 'brown' by weighing the monetary and non-monetary gains from green production against the cost increment. If consumers are completely informed about firms' production technology, the firm with high intrinsic motivation ('green' firm) finds it optimal to adopt the green technology even when increased consumer willingness to pay does not suffice to render adopting green production economically profitable, while the firm with low intrinsic motivation ('brown' firm) does not find it optimal to produce green. However, in the real world, it is difficult for consumers to be fully informed about firms' original production technologies, particularly for markets without any mandatory or voluntary disclosure mechanisms (for example, eco-labelling, third party certification, etc.) that enable at least partial disclosure of the actual environmental performance of firms

(Sengupta, 2015). Under asymmetric information, the green firm optimally employs green production only when it can credibly signal the true type of its product, and consequently, its own type, to consumers. Green production expands and brown production shrinks when signaling is feasible, thus making it a desirable outcome from an environmental perspective. It turns out, signaling is feasible when either, consumers' valuation of the green good is sufficiently high, or consumers' credulity regarding greenness of the good is sufficiently low. Otherwise, signaling is not feasible and asymmetry of information drives out environmentally ethical behaviour despite the presence of ethically concerned firms in the market.

The analysis highlights the importance of not only a firm's intrinsic motivation to act pro-environmentally but also its ability to send a signal of the same when it faces a purely profit-maximizing rival. However, when signaling is feasible, even though the green firms' pay-off is higher than that in the case of no signaling under asymmetric information, its profit is not necessarily higher. Further, the profit accruing to the firm under successful signaling is unambiguously lower than its symmetric information profit from producing green. Thus, with a minimum acceptable level of profit for the green firm, signaling - even if feasible otherwise - may be thwarted by the firm's profit considerations. Evidence indicates that companies, indeed, recognize the challenges in sustaining their profit goals while striving to maintain environmental sustainability to serve their ethical goals[2,3]. Investigating the implications of a minimum profit restriction, this paper identifies the need for a monetary incentive to drive the desired effect of the non-monetary stimulus. Considering a post-production subsidization scheme, we show that while a total subsidy amounting to the

[2]Companies mention the challenges of doing the right thing in a commercial set up (Green Mountain Coffee) and acknowledge that their business must make sense from a business point of view as well as an ethical one (Ford Motors) (Gittell et al., 2012).

[3]Referring back to the case of Simply Green, in discussing the limits of always doing the right thing, Andrew Kellar reveals that "I think my biggest mistake was I stayed so focused on the environmental and social mission of Simply Green, that I failed to stay focused equally on the fundamentals of the business. And the fundamental are the numbers, the profits and the losses and the working capital to operate the business." (Gittell et al., 2012).

shortfall in profit is required to overcome the minimum profit restriction, an equal or higher subsidy is necessary to incentivize technology adoption by a green firm that does not optimally adopt green production. The results indicate a cost-equivalence of lumpsum and per-unit subsidy schemes, thus suggesting equal effectiveness of either as a policy mechanism.

The rest of the paper is organized as follows. Section 2 presents the model and characterizes the equilibrium behaviour of firms under symmetric and asymmetric information. Section 3 compares the equilibrium outcome under each scenario and reports the results. Section 4 investigates the implications of a minimum profit restriction. Section 5 evaluates alternative subsidy schemes. Section 6 concludes the paper.

2 The Model

The model setup consists of two firms that produce a homogenous good and engage in Cournot quantity competition. The current production process is polluting in nature with emission levels commensurate to the level of output[4]. Suppose a new technology is available which reduces the environmental damage caused by the production process. Specifically, the use of this technology leads to zero emissions, such that, adopting the technology makes the production process entirely environment-friendly while not adopting it renders the production process polluting. Henceforth, we refer to the pollution-mitigating technology as 'green technology' and the good produced using this technology as 'green' good. The employment of the green technology, however, increases the marginal cost of production[5,6]. Each firm can either (a) use the green technology and make their production process environmentally friendly by incurring a higher marginal cost of production, or (b) produce using the cheaper production technology which is polluting in nature. The green technology

[4]See Mahenc (2008), Sengupta (2012), Sengupta (2015) for examples of a similar representation.

[5]This is a well-established supposition in the existing literature. See for example, Arora and Gangopadhyay (1995), Mahenc (2008), Sengupta (2012) and Sengupta (2015).

[6]The effective marginal cost of production includes any cost of liability due to environmental damage.

is assumed to be freely available to all firms. The total cost of firm i is given as:

$$C_i = c_i q_i = \begin{cases} cq, & \text{if firm } i \text{ uses the green technology for production} \\ 0, & \text{otherwise} \end{cases}, \ c > 0;$$

The post-production output is homogenous irrespective of the underlying technology of production. That is to say, consumers perceive both firms' goods as identical in their viability and differentiated only by the impact of their production on the environment. There is a uniform mass of environmentally conscious consumers in the market who have a higher valuation for a good which they perceive to be green. Firms can be of two types - green or brown - according as their intrinsic valuation of the green good is high or low. Let the intrinsic valuation of the i^{th} firm be γ_i, $i = G, B$ denoting green and brown respectively. Then $\gamma_G > \gamma_B \geq 0$. In this model with two firms, suppose one firm is green and the other one is brown. Without loss of generality, assume $\gamma_B = 0$ and $\gamma_G = \gamma$, $\gamma > 0$. This implies that, while the green firm is intrinsically motivated to undertake environment-friendly production, the brown firm is solely incentivized by probable profit gain due to consumers' valuation for the pro-environmental product. For the rest of the analysis, we refer to the green firm as firm 1 and the brown firm as firm 2. Firms face the following inverse linear demand function[7]:

$$p_i = a + \theta_i - q_i - q_j; \quad i, j = 1, 2; \quad i \neq j;$$

$$\text{where, } \theta_i = \begin{cases} \theta, & \text{if firm } i \text{ uses the green technology for production} \\ 0, & \text{otherwise} \end{cases}, \ \theta > 0;$$

q_i is the output of firm i and the parameter θ captures the environmental consciousness of consumers.

[7]The underlying utility function of the representative consumer is as follows:

$$U = (a + \theta_i)q_i + (a + \theta_j)q_j - \frac{1}{2}(q_i^2 + q_j^2 + 2q_i q_j) + m; \quad i, j = 1, 2; \quad i \neq j;$$

where m denotes the quantity of all other goods measured in terms of money.

Profit of firm $i\,(=1,2)$ is given by $\pi_i = p_i q_i - c_i q_i$, where c_i denotes the marginal cost of firm i. In addition to the profit earned from production and sale of the good, intrinsically motivated firms also receive a pay-off from production of the green good. Thus, the pay-off function of firm i is given as:

$$\Pi_i = \begin{cases} \pi_i + \gamma_i q_i, & \text{if firm } i \text{ uses the green technology for production} \\ \pi_i, & \text{otherwise} \end{cases}, \; i = 1, 2;$$

Given this setup, the game takes place in three stages:

Stage 1: Firms simultaneously and independently decide whether to adopt the green technology in their production process.

Stage 2: Firms learn the rival's decision of stage 1 and engage in simultaneous quantity competition to decide the level of output.

Stage 3: Market demand determines prices, and accordingly, profit and pay-off are realized.

2.1 Symmetric Information Scenario

Under symmetric information, consumers have complete knowledge of the production technology of firms and can accordingly value each firms' good differentially depending on whether it is green. Therefore, adopting the green technology in the production process gives firms the full benefit of consumers' higher willingness to pay for the green good while not adopting it deprives them of the same but enables cost saving. To solve for the equilibrium technology choice of firms, compute and compare the pay-off received by firms under four possible cases - (1) both firms use the green technology, (2) only firm 1 uses the green technology, (3) only firm 2 uses the green technology and (4) no firm uses the green technology, for production. Lemma 1 characterizes the equilibrium under the benchmark symmetric information scenario.

Lemma 1. *Let $\theta < c < \theta + \gamma$. The equilibrium choices of firms have the following characteristics:*

(i) Firm 1 adopts the green technology and firm 2 does not adopt the green technology.

(ii) Firm 1 sells the green good at a higher price and captures a larger market share as compared to firm 2.

Proof. See appendix.

Lemma 1 implies that, under symmetric information, the firm with the intrinsic valuation for green production chooses to adopt the green technology while the firm that does not intrinsically value greenness of production chooses to continue with the polluting production technology. The reason is as follows. A firm adopts the green technology when total willingness to pay for the same (and hence, for the green good) of consumers and the firm combined exceeds the excess cost incurred from adopting the green technology. Under complete information, a part of the increase in marginal cost from producing green is mitigated by consumers' higher willingness to pay for the green good for both firms. Additionally, the perceived benefit of producing green has a pay-off enhancing effect for firm 1. When $\theta + \gamma > c$, the combined increase in willingness to pay of consumers ($= \theta$) and the firm ($= \gamma$) exceeds the increase in cost ($= c$) per unit of output for firm 1, making it beneficial to adopt the green technology of production, irrespective of the technology choice of firm 2. On the other hand, since firm 2 does not intrinsically perceive green production as pay-off augmenting, when $\theta < c$, the excess willingness to pay of consumers for the green good only partially offsets the increase in marginal cost from producing green, thus rendering adopting the green technology suboptimal for firm 2. Since the gains accruing to firm 1 per unit of output from producing green exceed the excess marginal cost, effectively, firm 1 is more efficient than firm 2. As a result, it captures a larger market share as compared to firm 2. Further, consumers' higher willingness to pay for the green good induces its higher price.

2.2 Asymmetric Information Scenario

Under asymmetric information, consumers are unaware of the actual production technology of firms. With some probability, say $r \in (0,1)$, they believe a particular firm may have adopted the green technology. Consequently, the good produced by either firm is perceived as green with probability r, and in absence of a credible signal, adoption of green production does not afford the firms any additional willingness to pay from consumers (the following subsection explores the possibility of signaling). This prior belief of the consumers is common knowledge. Thus, the demand function facing both firms is given as:

$$p_i = a + r\theta - q_1 - q_2\,,\ \ i = 1, 2;$$

To identify the equilibrium technology choice of firms under asymmetric information without signaling, compute and compare the pay-off received by firms under the same four cases as in the symmetric information analysis. Lemma 2 characterizes the equilibrium.

Lemma 2. *Let $\gamma < c$. The equilibrium choices of firms have the following characteristics:*

(i) Neither firm 1 nor firm 2 adopt the green technology of production. Thus, the entire production is polluting in nature.

(ii) Both firms sell the brown good at the same price and capture equal market share.

Proof. See appendix.

Lemma 2 implies that, even though consumers value green consumption, under asymmetric information, no firm has an incentive to produce green, irrespective of whether its intrinsic valuation for the green technology is high or low. The reason is as follows. Since consumers are not able to perceive with certainty whether a good is green, their willingness to pay remains same across the green and brown goods. When $0 < \gamma < c$, firms' willingness to pay for the green technology is less than the excess cost incurred for adopting the same. Thus, neither firm finds it beneficial to produce green. Both firms continue production with the polluting technology and capture an equal market share by selling the brown good at an equal price.

It follows from Lemma 1 and Lemma 2 that if the representative consumer's and the green firm's valuation for green good are individually less than the marginal cost of adopting the technology, while their sum exceeds the same, asymmetry of information without signaling (a) eliminates green production despite consumers as well as firms being intrinsically environment-conscious, and (b) leads to environmental degradation despite a pollution reducing production technology being freely available. If the society as a whole is adversely affected by environmental damage, this implies a detrimental effect on social welfare. In this context, it is important to analyze the plausibility of a signaling equilibrium under the given parametric specifications.

2.3 Signaling

The possibility of signaling may arise when uninformed consumers prevent the firm from realizing the entitled gains of adopting the green technology. With successful signaling, the output of the firm credibly conveys its technology choice to consumers, thus fetching it a higher price for adopting the green technology. Recall that the firm with low valuation for the green good has no incentive to adopt the green technology even under complete information, and hence, the signal that conveys technology adoption by the firm which has high valuation for greenness is in itself a signal of the firm's intrinsic valuation for the green good. To identify the incentive for producing green under asymmetric information with signaling, the ensuing analysis focuses on the separating equilibrium where the firm with high intrinsic valuation (firm 1) finds it beneficial to adopt the green technology and the firm with low intrinsic valuation (firm 2) does not find it beneficial to contaminate the signal.

In this one period signaling game, consumers become fully informed about the technology choice of each firm by observing their output choice. Firm 1 chooses an output q_1^* such that if this output conveys full information to the consumers, it earns a higher pay-off than that under asymmetric information without signaling. Firm 2 can either dampen the signal by mimicking firm 1, in which case the consumers are unable to update their prior belief, or it can produce its symmetric information optimal output and allow consumers to believe with certainty that firm 1 is green and firm 2 is brown[8]. If the brown firm mimics the green firm, it is essentially pretending to be green. Although consumers never believe with certainty that the brown firm is green, it gains in terms of the benefit of doubt that it gets by preventing the consumers from updating their prior belief. Lemma 3 characterizes the Separating Equilibrium.

Lemma 3. *If $r < 3\left(\frac{\theta+\gamma-c}{\theta}\right)$ holds, the following beliefs and strategies constitute a Separating Equilibrium:*

(i) For $k > 0$, if $\delta_0 - \alpha_0 \geq 0$, firm 1 chooses $q_1^* \in \left[\frac{\alpha_0+\sqrt{\alpha_0^2-4\alpha_1}}{2}, \frac{\delta_0+\sqrt{\delta_0^2-4\delta_1}}{2}\right]$.

(ii) For $k = 0$, firm 1 chooses $q_1^* \in \left[\frac{\alpha_0+\sqrt{\alpha_0^2-4\alpha_1}}{2}, \frac{\delta_0+\sqrt{\delta_0^2-4\delta_1}}{2}\right]$.

(iii) For $k < 0$, if $\delta_0 - \alpha_0 > -k$, firm 1 chooses $q_1^* \in \left[\frac{\alpha_0+\sqrt{\alpha_0^2-4\alpha_1}}{2}, \frac{\delta_0+\sqrt{\delta_0^2-4\delta_1}}{2}\right]$, and if $\delta_0 - \alpha_0 \leq -k$, firm 1 chooses $q_1^* \in \left[\frac{\delta_0-\sqrt{\delta_0^2-4\delta_1}}{2}, \frac{\alpha_0-\sqrt{\alpha_0^2-4\alpha_1}}{2}\right] \cup \left[\frac{\alpha_0+\sqrt{\alpha_0^2-4\alpha_1}}{2}, \frac{\delta_0+\sqrt{\delta_0^2-4\delta_1}}{2}\right]$.

(iv) Following the Cho-Kreps criteria, in each case, the optimal choice of firm 1 is $q_1^* = \frac{\alpha_0+\sqrt{\alpha_0^2-4\alpha_1}}{2}$.

(v) Firm 2 chooses $q_2^* = \frac{a-\theta+c-\gamma}{3}$.

(vi) The consumers' updated belief structure regarding the greenness of the good produced by firm i is $\mu_G(i) = \begin{cases} \mu_G(1) = 1 \\ \mu_G(2) = 0 \end{cases}$, i.e. they believe that firm 1's good is green with probability 1 and firm 2's good is green with probability 0.

Here, $\delta_0 = \frac{2}{3}(a + 2\theta - 2c + 2\gamma)$, $\delta_1 = \left(\frac{a+r\theta}{3}\right)^2$, $\alpha_0 = \frac{4a+3r\theta-\theta+c-\gamma}{6}$, $\alpha_1 = \frac{(2a+\theta-c+\gamma)(a-\theta+c-\gamma)}{18}$,

[8]The game described here is of simultaneous signaling. Alternatively, in a game of sequential signaling, firm 2 uses its symmetric information reaction function to produce the best response to firm 1's signaling output and firm 1 decides the optimal signaling output by taking firm 2's reaction function as given. The resultant separating equilibrium is qualitatively similar to the one under simultaneous signaling described in this paper (derivation available from the author upon request).

$k = \sqrt{\alpha_0^2 - 4\alpha_1} - \sqrt{\delta_0^2 - 4\delta_1}$.

Proof. See appendix.

To understand the result, first consider the expression for k in the above equilibrium. k comprises two parts: the first part denotes the root of the discriminant of the equation formed from the incentive compatibility constraint of firm 2 and the second part denotes the same formed from that of firm 1. Hence, each part relates to the magnitude of the distance between the roots of the corresponding equations. From the nature of the incentive compatibility constraints, it can be inferred that the greater the discrimination between the roots for firm 2, the more the opportunities for it to dampen firm 1's signal, and the lesser the discrimination between the roots for firm 1, the smaller the choice set available to it for signaling. Therefore, the value of k measures the comparative leverage of firm 2 over that of firm 1 in the game of signaling. This intuitively explains the three cases ((i), (ii) and (iii)) characterized in the equilibrium in Lemma 3. A positive value of k implies a higher leverage for firm 2 relative to that of firm 1, indicating the possibility of a situation when there exists no feasible output choice for firm 1 to signal its true type. If $k \leq 0$, a separating equilibrium necessarily exists and the possible output choices for firm 1 increases as k becomes negative. Notice that when the comparative leverage of firm 2 over that of firm 1 is sufficiently small (i.e., k is sufficiently negative), both a higher and a lower level of output, as compared to the symmetric information output level, can signal quality. However, point (iv) in Lemma 3 implies that the higher output choice is unambiguously more efficient. Point (v) states the optimal output choice of firm 2, which is identical to that under symmetric information. Accordingly, (vi) defines how consumers update their belief in equilibrium to correctly perceive the type of each firm from their output choice.

The equilibrium in Lemma 3 entails firm 1 to adopt the green technology as well as increase production beyond its symmetric information profit maximizing level in order to differentiate itself from the technologically polluting firm. Furthermore, if signaling is successful, firm 2 optimally reduces production from its equilibrium output under asymmetric information to that under symmetric information, thus allowing consumers to perceive it as technologically dirty. Let q_i^s, q_i^a and q_i^* denote the output of firm i under symmetric information, asymmetric information without signaling and asymmetric information with signaling, respectively. Based on Lemma 1, Lemma 2 and Lemma 3, we have the following result.

Proposition 1. *A comparison of outputs of firms across the three scenarios imply the following.*

(i) Signaling leads to a higher level of green production relative to both symmetric information and asymmetric information without signaling.

(ii) The industry's production is less polluting with signaling as compared to that without signaling under asymmetric information.

Proof. We have already established that q_1^s and q_1^* are green while q_1^a, q_2^s, q_2^a and q_2^* are brown. It follows from Lemma 2 that under asymmetric information without signaling, both firms produce brown. Lemma 3 states that firm 1 adopts the green technology under signaling. Thus, the comparison of green production between signaling and no signaling under asymmetric information follows trivially. Again, Lemma 1 and Lemma 3 imply $q_1^* > q_1^s$ and hence, the resultant comparison between symmetric information and signaling equilibrium. We conclude that the level of green production is maximum in the signaling equilibrium. To see why polluting production decreases under asymmetric information when signaling takes place, compare $q_2^* = \frac{a-\theta+c-\gamma}{3}$ and $q_2^a = \frac{a+r\theta}{3}$: (a) $c < \theta + \gamma \implies a + (c - \theta - \gamma) < a$, and (b) $0 < r < 1$ and $\theta > 0$ imply $a + r\theta > a$. Therefore, $q_2^* < q_2^a$. Further, firm 1 switches from brown to green production when signaling occurs. As a result, total emission level of the industry, which is proportional to the level of output, falls when signaling is possible. ■

Proposition 1 elucidates that, in the context of a duopoly, the existence of a firm with high intrinsic valuation for greenness reduces emission damages by not only adopting a relatively expensive green technology, but also causing the brown competitor to shrink its level of production, provided it can successfully signal its type. While a comprehensive analysis of the effect on social welfare requires further investigation, one thing is certain: the possibility of signaling suggests an augmenting effect on social welfare through better environmental quality.

In the presence of information asymmetry, the green firm adopts the pollution reducing technology only when it can optimally signal its technology choice, and hence, its valuation for the green good, to the consumers. The necessary condition for Lemma 3 to hold is $r < 3\left(\frac{\theta+\gamma-c}{\theta}\right)$. It implies that the environmentally conscious firm can never find it optimal to adopt the green technology in equilibrium if this condition is not satisfied, and therefore, a signaling equilibrium under asymmetric information will not be feasible. Corollary 1 interprets the necessary condition for signaling.

Corollary 1. $r < 3\left(\frac{\theta+\gamma-c}{\theta}\right)$ *holds when either* θ *is sufficiently high or* r *is sufficiently low. This implies:*

(i) High consumer valuation for the green good increases the propensity to adopt the green technology.

(ii) High consumer credulity with regard to greenness reduces the propensity to adopt the green technology.

Proof. For part (i), note that if $3\left(\frac{\theta+\gamma-c}{\theta}\right) \geq 1$ implying $\theta \geq 3\left(\frac{c-\gamma}{2}\right)$, the condition will hold trivially since $0 < r < 1$. However, if $\theta < 3\left(\frac{c-\gamma}{2}\right)$ implying $3\left(\frac{\theta+\gamma-c}{\theta}\right) < 1$, then r must be small enough to satisfy $r < 3\left(\frac{\theta+\gamma-c}{\theta}\right) < 1$, explaining part (ii). ■

The first part is intuitive. If consumer's valuation for the green good is sufficiently high as compared to the excess of cost incurred for green production over the firm's valuation for green technology, the green firm will have enough incentive to deviate from its otherwise optimal output choice and signal its true type. The second part implies that if consumers' valuation for the green good is not sufficiently high, a separating equilibrium will exist only if the prior probability with which consumers believe any firm is green is sufficiently low. The intuition is as follows. If the prior belief of consumers is inclined towards believing any firm is green, then the green firm does not significantly gain from signaling its true type. In addition, the brown firm is more willing to dampen the signal as it incurs higher loss from revelation of its true type. It follows, if the specified condition on the prior belief of consumers does not hold, a separating equilibrium does not exist.

3 Comparison of Equilibrium

So far, we discussed the optimal choice of technology and output of firms under symmetric and asymmetric information, and investigated the implications. This section compares the complete equilibrium specifications under symmetric information with that under asymmetric information where signaling occurs. Define $(q_i^x,\, p_i^x,\, \Pi_i^x)$, $i = \{1, 2\}$, $x = \{s, *\}$, as a complete equilibrium specification consisting of output, price and pay-off. Proposition 2 compiles the results.

Proposition 2. *In the signaling equilibrium, relative to the symmetric information equilibrium, the following hold.*

(i) $q_1^* > q_1^s$, $q_2^* = q_2^s$*: Output of firm 1 is higher, output of firm 2 remains same. Hence, industry output rises.*

(ii) $p_1^* < p_1^s$, $p_2^* < p_2^s$*: Price charged by both firms is lower.*

(iii) $\Pi_1^* < \Pi_1^s$, $\Pi_2^* < \Pi_2^s$*: Pay-off of each firm is lower implying lower industry returns.*

Proof: The proof of (i) directly follows from Lemma 1 and Lemma 3, as discussed in the previous section. Consider (ii). The price of the green good is given by $p_1^x = a + \theta - q_1^x - q_2^x$ and that of the brown good is given by $p_2^x = a - q_1^x - q_2^x$. Using (i), compare to see that $p_1^* < p_1^s$ and $p_2^* < p_2^s$. For (iii), first note that firm 1 deviates from its symmetric information optimal output to signal its true type. Since the symmetric information output choice is pay-off maximizing, with firm 2's output remaining same under both scenarios, any deviation from this output level implies a lower pay-off. The proof of Lemma 3 depicts this. The pay-off of firm 2 is $\Pi_2^x = p_2^x q_2^x$. Since output remains constant and price falls under signaling, as compared to that under the symmetric equilibrium, pay-off is lower. ■

We have already seen how the output choice of firms, that convey full information about their production technology to consumers, follows from the signaling equilibrium in Lemma 3. While firm 1 augments production to signal its true type, firm 2 resorts to the same output level as under symmetric information. However, both the green and the brown good, produced by firm 1 and firm 2 respectively, are offered at a lower price under signaling as compared to that under symmetric information. The intuition behind this result is as follows. Under asymmetry of information, when the green firm adopts the pollution reducing technology, it expands its output beyond the symmetric information optimal level to credibly signal its true type to consumers. This expansion in output entails a higher demand, which is achieved by a lower price of the green variety product. Further, as firm 1 competes more aggressively to transmit a credible signal, industry output expands causing the price of the brown product to plummet as well. It follows that, both the environmentally friendly and the environmentally polluting variety are offered at a lower price when information is asymmetric as compared to that when information is complete, provided both varieties are produced in equilibrium. Finally, to understand the reason behind the lower pay-off of firms, recall that firm 1 sacrifices some pay-off by deviating from the symmetric information optimal and competing more aggressively to enable successful signaling. Consequently, the repercussions of aggressive competition leaves firm 2 worse off. Hence signaling, while indicating social benefits by enhancing green production, turns out to be the second best outcome from individual firms' perspective.

4 Minimum Profit Restriction

The analyses in the preceding sections are based on pay-off accruing to the firms, which include not only firms' profit but also an additional amount measuring firms' satisfaction from producing an environment-friendly good. This augmentation of the pay-off function is a result of the firms' intrinsic valuation for the green good. However, even though firms are interested in maximizing their pay-off, it is natural for them to expect a minimum level of profit from the production process such that if profits are reduced below this threshold level, they would prefer to not undertake production at all, implying a restriction on the maximization problem of firms. This section analyzes how such minimum profit restrictions alter the behaviour of firms from that established in the previous sections.

Since the primary interest of this paper is on green technology adoption, the analysis focuses on the minimum profit restriction of firm 1 as it is the only firm that intrinsically values green production and thus has an incentive to adopt the green technology. In addition, the simplifying assumptions specified in the model imply that the pay-off and profit functions for firm 2 are identical. Following the model notations, Π_1^x, π_1^x and q_1^x, $x = \{s, a, *\}$, denotes the pay-off, profit and optimal output choice of firm 1 under scenario x, where $\{s, a, *\}$ indicates symmetric information, asymmetric information without signaling and the separating equilibrium, respectively. In the separating equilibrium, firm 1 over-produces as compared to its symmetric information pay-off maximizing level. Hence $\Pi_1^* < \Pi_1^s$ and $q_1^* > q_1^s$. Given this, from the pay-off equation $\Pi_1^x = \pi_1^x + \gamma q_1^x$, we have $\pi_1^* < \pi_1^s$. Next, consider information asymmetry - (a) under asymmetric information without signaling, firm 1 does not adopt green production in equilibrium, implying $\Pi_1^a = \pi_1^a$, and (b) under the separating equilibrium, IC_1 implies $\pi_1^* + \gamma q_1^* > \Pi_1^a = \pi_1^a$. Hence, either $\pi_1^* \geq \pi_1^a$ or $\pi_1^* < \pi_1^a$ may hold. Let $\bar{\pi}_1$ be the minimum level of profit acceptable by firm 1 to participate in the production process and suppose $\bar{\pi}_1 < \min(\pi_1^s, \pi_1^a)$. When $\pi_1^* < \pi_1^a$, there is a possibility that $\pi_1^* < \bar{\pi}_1$. If this holds, then even though firm 1 intrinsically values green production and has the incentive to produce green, it will not be able to adopt the green technology when there is information asymmetry. In such a case, policy intervention by the government becomes necessary to sustain green production. Thus, minimum profit restrictions have important implications for government policy design.

5 Implications for Subsidization

To enable green technology adoption when minimum profit restrictions are binding, we suppose government subsidization of the green firm's production, after execution of the production process, to compensate for reduction in profit below firm's minimum acceptable level. Since subsidization is costly, assume that the government will provide subsidy to a firm only if it is certain that the firm has used the green technology in its production process. For simplicity, suppose the government is as (un)informed as the consumers and hence its belief structure is same as that of the consumers[9]. That is to say, the government's prior belief is that either firm has adopted the green technology with probability r. Thus, in order to obtain the subsidy, the green firm must be able to credibly signal its true type such that the brown firm does not find it profitable to mimic. It is worth noting here that if the brown firm does mimic the green firm, it gains in terms of the benefit of doubt that it gets from consumers, but it is never perceived to be green with certainty. Therefore, mimicking the green firm does not make the brown firm eligible for obtaining a subsidy. Consider two types of subsidy schemes: lumpsum and per-unit. The subsequent analysis calculates the optimal level of subsidy under each type and evaluates their relative cost-effectiveness.

5.1 Lumpsum Subsidy

Under the lumpsum subsidy scheme, the government transfers a lumpsum amount to the firm post-production to facilitate green technology adoption. The amount of transfer remains constant irrespective of the level of green output produced.

Let S^* be the amount of lumpsum subsidy to be provided by the government. Firm 1 is aware that successfully signaling green production will entitle it to the subsidy. With this belief, the updated incentive compatibility constraint of firm 1 is as follows:

$$IC_1 : \Big(a + \theta - q_1^* - \frac{a - \theta + c - \gamma}{3}\Big)q_1^* - (c - \gamma)q_1^* + S^* \geq \Big(\frac{a + r\theta}{3}\Big)^2$$
$$\implies \delta_0 q_1^* - (q_1^*)^2 \geq \delta_1 - S^*$$

Given the government's belief structure and the rule of subsidy provision mentioned above,

[9]Using a more (or less) informed belief structure for the government does not alter our qualitative results.

the incentive compatibility constraint of firm 2 remains unchanged:

$$IC_2 : \Big(a - q_1^* - \frac{a-\theta+c-\gamma}{3}\Big)\Big(\frac{a-\theta+c-\gamma}{3}\Big) \geq (a + r\theta - q_1^* - q_1^*)q_1^*$$
$$\implies \alpha_0 q_1^* - (q_1^*)^2 \leq \alpha_1$$

First, consider the case where a separating equilibrium exists without the subsidy, but the minimum profit restriction does not allow firm 1 to signal. Thus, with the subsidy, IC_1 ans IC_2 are trivially satisfied. In this case the only purpose of the subsidy is to ensure that firm 1 earns a profit level at least as much as its threshold profit. Hence, the subsidy must be such that $S^* \geq \bar{\pi}_1 - \pi_1^*$. Since subsidy is costly, the optimal subsidy choice of the government is $S^* = \bar{\pi}_1 - \pi_1^*$. However, it may happen that a separating equilibrium does not exist without the subsidy. Then the purpose of the subsidy is two-fold: (a) to enable signaling by firm 1, and (b) to ensure that the minimum profit restriction is not binding. With IC_2 unchanged, the optimal output choice of firm 1 under signaling remains $q_1^* = \frac{\alpha_0+\sqrt{\alpha_0^2-4\alpha_1}}{2} = \eta$ (say). Initially IC_1 is not satisfied, implying $\delta_0\eta - \eta^2 < \delta_1$. To fulfil the first objective, the subsidy S^* should be such that $\delta_0\eta - \eta^2 \geq \delta_1 - S^*$. Additionally, the second objective requires $S^* \geq \bar{\pi}_1 - \pi_1^*$. The optimal subsidy amount is the minimum value that satisfies both objectives. Lemma 4 characterizes the optimal value of S^*.

Lemma 4. *Under a lumpsum subsidy scheme, the optimal amount of lumpsum transfer from the government to the green firm is given as* $S^* = \max[\delta_1 + \eta^2 - \delta_0\eta\,,\, \bar{\pi}_1 - \pi_1^*]$.

5.2 Per-unit Subsidy

Under the per-unit subsidy scheme, the government transfers a constant amount per unit of green output to the firm post-production. The total amount of transfer varies with the variation in the level of output.

Let s^* be the rate of per-unit subsidy to be provided by the government. Proceeding similarly as before, IC_1 is updated and IC_2 remains same, as follows:

$$IC_1 : \Big(a + \theta - q_1^* - \frac{a - \theta + c - \gamma}{3}\Big) q_1^* - (c - \gamma) q_1^* + s^* q_1^* \geq \Big(\frac{a + r\theta}{3}\Big)^2$$
$$\implies (\delta_0 + s^*) q_1^* - (q_1^*)^2 \geq \delta_1$$

$$IC_2 : \Big(a - q_1^* - \frac{a - \theta + c - \gamma}{3}\Big)\Big(\frac{a - \theta + c - \gamma}{3}\Big) \geq (a + r\theta - q_1^* - q_1^*) q_1^*$$
$$\implies \alpha_0 q_1^* - (q_1^*)^2 \leq \alpha_1$$

Consider the same two cases: (a) when separating equilibrium exists but the minimum profit restriction prevents signaling, and (b) when separating equilibrium does not exist and the subsidy must both enable signaling and ensure profit restriction is non-binding. In the first case, the total amount of subsidy required is $\bar{\pi_1} - \pi_1^*$. Hence, the optimal per-unit rate is $s^* = \frac{\bar{\pi_1} - \pi_1^*}{\eta}$, where η is the output of firm 1 under separating equilibrium. In the second case, initially signaling is not possible, implying $\delta_0 \eta - \eta^2 < \delta_1$. Subsidy must ensure $(\delta_0 + s^*)\eta - \eta^2 \geq \delta_1 \implies s^* \geq \frac{\delta_1}{\eta} + \eta - \delta_0$. In addition, $s^* \geq \frac{\bar{\pi_1} - \pi_1^*}{\eta}$ must hold. Combining the requirements in both cases, Lemma 5 characterizes the optimal per-unit subsidy rate of the government.

Lemma 5. *Under a per-unit subsidy scheme, the optimal rate of transfer from the government to the green firm is given as* $s^* = \max\big[\frac{\delta_1}{\eta} + \eta - \delta_0 \, , \, \frac{\bar{\pi_1} - \pi_1^*}{\eta}\big]$.

5.3 Comparison between Lumpsum and Per-unit Subsidy

To evaluate which of the two subsidy programs discussed above is a more efficient choice to aid green production, we compare the relative cost-effectiveness of the lumpsum and per-unit subsidy schemes. The total subsidy expenditure of the government is equal to S^* under lumpsum subsidy and ηs^* under per-unit subsidy, where η is the equilibrium level of output. Proposition 3 reports the result of the comparison.

Proposition 3. *In equilibrium,* $S^* = \eta s^*$*, i.e. the total expenditure incurred under the lumpsum and per-unit subsidy regimes is equal in equilibrium.*

Proof. Lemma 4 gives the total expenditure under lumpsum subsidy as $S^* = \max[\delta_1 + \eta^2 - \delta_0\eta\,,\, \bar{\pi}_1 - \pi_1^*]$. To obtain the total expenditure under per-unit subsidy, multiply the subsidy rate in Lemma 5 by the equilibrium output level η to get $\eta s^* = \max[\delta_1 + \eta^2 - \delta_0\eta\,,\, \bar{\pi}_1 - \pi_1^*]$. Hence $S^* = \eta s^*$, implying the same cost to the government under either type of subsidy. ■

Proposition 3 manifests equal cost-effectiveness of lumpsum and per-unit subsidies in the present context. To understand the result, observe that, with either scheme operational, subsidization does not alter the optimal output choice of the green firm under separating equilibrium. Therefore, the aggregate shortfall in monetary incentives for producing green is equal under both regimes. It follows that, the sole purpose of the subsidy is to induce the firm that has the intrinsic motivation to produce green, to signal its true type when monetary restrictions prevent it from doing so, and the lumpsum and per-unit subsidy regimes accomplish this objective equally efficiently.

6 Conclusion

Recent literature on behavioural economic theory suggests that psychological attributes play an important role in influencing strategic behaviour of economic agents (Banerjee & Shogren, 2010). This paper constructs a theoretical framework to explore the implications of intrinsic environmental concern of firms on the decision to adopt an available, but not obligatory, green technology in their production process, when such adoption makes the produced good more valuable to consumers but the production process cost-extensive. We find that an intrinsically motivated firm may adopt the green technology when faced with competition in a market with uninformed green consumers, provided consumers are sufficiently environmentally concerned and incredulous. Further, industry emissions are lower if the green firm, in competing with a brown rival, adopts the non-polluting production process and successfully signals its true type. Thus, with dire environmental concerns demanding immediate action worldwide, morally motivated firms may indeed be what the society needs aplenty. However, restrictions imposed by a minimum acceptable profit level or an incapacity to optimally signal inhibits a firm from implementing pollution reducing techniques in production despite being intrinsically motivated to do so. Our analysis highlights the challenges that businesses driven by intrinsic concerns face while acting morally or ethically, and points towards possible policy considerations. In a report revealing concerns over pollution and climate change issues, 10 percent of global respondents believe business and industry should take the primary lead on eco-responsibility while about 33 percent are counting on national governments to steer the cause (Kenyon, 2008). It follows, while intrinsically motivated firms can be a blessing for the society and environment, policies must aim to ensure that pressing profit goals do not become a burden on firms' environmental actions.

This study heeds the high prominence of present environmental issues on a nation's list of concerns and hence, supposes environment conservation to form a primary component of social welfare. A further scope of study is to explicitly model the effect of subsidization on social welfare and examine whether the benefit of sustaining green production exceeds the cost of providing a subsidy under varying importance of cleaner environment in the overall welfare of the society.

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Appendix

Proof of Lemma 1

Computing the equilibrium pay-off of both firms under four possible cases:

1. Both firms use the green technology for production

Maximize the pay-off of firm 1, $\Pi_1 = (a + \theta - q_1 - q_2)q_1 - cq_1 + \gamma q_1$, with respect to q_1, to get the reaction function of firm 1 as $q_1 = \frac{a+\theta-q_2-(c-\gamma)}{2}$. Maximize the pay-off of firm 2, $\Pi_2 = (a + \theta - q_1 - q_2)q_2 - cq_2$, with respect to q_2, to get the reaction function of firm 2 as $q_2 = \frac{a+\theta-q_1-c}{2}$. The equilibrium quantities, prices and profits are:

$$q_1 = \frac{a + \theta - c + 2\gamma}{3}; \quad q_2 = \frac{a + \theta - c - \gamma}{3}; \quad p_1 = p_2 = \frac{a + \theta + 2c - \gamma}{3};$$
$$\Pi_1 = \Big(\frac{a + \theta - c + 2\gamma}{3}\Big)^2; \quad \Pi_2 = \Big(\frac{a + \theta - c - \gamma}{3}\Big)^2;$$

2. Only firm 1 uses the green technology for production

The pay-off and reaction function of firm 1 is same as case 1, i.e. $q_1 = \frac{a+\theta-q_2-(c-\gamma)}{2}$. Maximize the pay-off of firm 2, $\Pi_2 = (a - q_1 - q_2)q_2$, with respect to q_2, to get the reaction function of firm 2 as $q_2 = \frac{a-q_1}{2}$. The equilibrium is:

$$q_1 = \frac{a + 2\theta - 2(c - \gamma)}{3}; \; q_2 = \frac{a - \theta + c - \gamma}{3}; \; p_1 = \frac{a + 2\theta + c - \gamma}{3}; \; p_2 = \frac{a - \theta + c - \gamma}{3};$$
$$\Pi_1 = \Big(\frac{a + 2\theta - 2(c - \gamma)}{3}\Big)^2; \; \Pi_2 = \Big(\frac{a - \theta + c - \gamma}{3}\Big)^2;$$

3. Only firm 2 uses the green technology for production

The pay-offs under this case are $\Pi_1 = (a - q_1 - q_2)q_1$ and $\Pi_2 = (a + \theta - q_1 - q_2)q_2 - cq_2$ for firm 1 and firm 2 respectively. Accordingly, the reaction functions are $q_1 = \frac{a-q_2}{2}$ and $q_2 = \frac{a+\theta-q_1-c}{2}$. The equilibrium solution is:

$$q_1 = \frac{a - \theta + c}{3}; \; q_2 = \frac{a + 2\theta - 2c}{3}; \; p_1 = \frac{a - \theta + c}{3}; \; p_2 = \frac{a + 2\theta + c}{3};$$
$$\Pi_1 = \Big(\frac{a - \theta + c}{3}\Big)^2; \; \Pi_2 = \Big(\frac{a + 2\theta - 2c}{3}\Big)^2;$$

4. No firm uses the green technology for production

The pay-off of firm i is $\Pi_i = (a - q_i - q_j)q_i$ and the reaction function is $q_i = \frac{a-q_j}{2}$. The reaction functions for the two firms solve to give:

$$q_1 = q_2 = \frac{a}{3}; \;\; p_1 = p_2 = \frac{a}{3};$$
$$\Pi_1 = \Pi_2 = \left(\frac{a}{3}\right)^2;$$

To decide whether either firm will adopt the green technology for production, construct the pay-off matrix as follows:

Firm 2

Firm 1		T	NT
	T	$\left(\frac{a+\theta-c+2\gamma}{3}\right)^2, \left(\frac{a+\theta-c-\gamma}{3}\right)^2$	$\left(\frac{a+2\theta-2(c-\gamma)}{3}\right)^2, \left(\frac{a-\theta+c-\gamma}{3}\right)^2$
	NT	$\left(\frac{a-\theta+c}{3}\right)^2, \left(\frac{a+2\theta-2c}{3}\right)^2$	$\left(\frac{a}{3}\right)^2, \left(\frac{a}{3}\right)^2$

T is a dominant strategy for firm 1 if $\theta + \gamma > c$. Further, if this condition holds, firm 2 will choose NT when $\theta < c$. Thus, when $\theta < c < \theta + \gamma$, (T, NT) is the unique Nash equilibrium. Compare the equilibrium prices and quantities under case 2 to see that $q_1 > q_2$ and $p_1 > p_2$. Hence, the proof. ■

Proof of Lemma 2

Computing the equilibrium pay-off of both firms under four possible cases:

1. Both firms use the green technology for production

In this case, each firm has marginal cost equal to c. However, firm 1 intrinsically values green production at γ per unit of output and hence its effective marginal cost is $c - \gamma$. The standard Cournot solution gives the following equilibrium:

$$q_1 = \frac{a + r\theta + 2\gamma - c}{3}; \;\; q_2 = \frac{a + r\theta - c - \gamma}{3}; \;\; p_1 = p_2 = \frac{a + r\theta + 2c - \gamma}{3};$$
$$\Pi_1 = \Big(\frac{a + r\theta + 2\gamma - c}{3}\Big)^2; \; \Pi_2 = \Big(\frac{a + r\theta - c - \gamma}{3}\Big)^2;$$

2. Only firm 1 uses the green technology for production

The effective marginal cost for firm 1 is same as the case 1. Since firm 2 is not using the technology, its marginal cost is zero. Accordingly, the Cournot solution gives:

$$q_1 = \frac{a + r\theta - 2(c - \gamma)}{3}; \;\; q_2 = \frac{a + r\theta + c - \gamma}{3}; \;\; p_1 = p_2 = \frac{a + r\theta + c - \gamma}{3};$$
$$\Pi_1 = \Big(\frac{a + r\theta - 2(c - \gamma)}{3}\Big)^2; \; \Pi_2 = \Big(\frac{a + r\theta + c - \gamma}{3}\Big)^2;$$

3. Only firm 2 uses the green technology for production

In this case, the marginal cost of firm 1 is 0. Further, since it does not adopt green production, it does not intrinsically value the output. Firm 2 uses the technology and has a marginal cost of c. The Cournot solution is:

$$q_1 = \frac{a + r\theta + c}{3}; \;\; q_2 = \frac{a + r\theta - 2c}{3}; \;\; p_1 = p_2 = \frac{a + r\theta + c}{3};$$
$$\Pi_1 = \Big(\frac{a + r\theta + c}{3}\Big)^2; \; \Pi_2 = \Big(\frac{a + r\theta - 2c}{3}\Big)^2;$$

4. No firm uses the green technology for production

Since no firm adopts the technology, the marginal cost of both firms is 0. The solution in this case is:

$$q_1 = \frac{a + r\theta}{3}; \;\; q_2 = \frac{a + r\theta}{3}; \;\; p_1 = p_2 = \frac{a + r\theta}{3};$$
$$\Pi_1 = \Big(\frac{a + r\theta}{3}\Big)^2; \; \Pi_2 = \Big(\frac{a + r\theta}{3}\Big)^2;$$

The pay-off matrix under asymmetric information without signalling is as follows:

		Firm 2	
		T	NT
Firm 1	T	$\left(\frac{a+r\theta+2\gamma-c}{3}\right)^2, \left(\frac{a+r\theta-c-\gamma}{3}\right)^2$	$\left(\frac{a+r\theta-2(c-\gamma)}{3}\right)^2, \left(\frac{a+r\theta+c-\gamma}{3}\right)^2$
	NT	$\left(\frac{a+r\theta+c}{3}\right)^2, \left(\frac{a+r\theta-2c}{3}\right)^2$	$\left(\frac{a+r\theta}{3}\right)^2, \left(\frac{a+r\theta}{3}\right)^2$

NT is a dominant strategy for firm 1 when $\gamma < c$. For firm 2, NT is always the preferred choice. Hence, given firm 1 chooses NT, firm 2's optimal strategy is to choose NT. Thus, when $\gamma < c$, the unique Nash equilibrium is (NT, NT). Notice that under case 4, $q_1 = q_2$ and $p_1 = p_2$. Hence, the proof. ■

Proof of Lemma 3

Following are the incentive compatibility constraints of firm 1 and firm 2 respectively:

$$IC_1 : \Big(a + \theta - q_1^* - \frac{a - \theta + c - \gamma}{3}\Big)q_1^* - (c - \gamma)q_1^* \geq \Big(\frac{a + r\theta}{3}\Big)^2$$

$$IC_2 : \Big(a - q_1^* - \frac{a - \theta + c - \gamma}{3}\Big)\Big(\frac{a - \theta + c - \gamma}{3}\Big) \geq (a + r\theta - q_1^* - q_1^*)q_1^*$$

Rearranging and simplifying:

$$IC_1 \implies \delta_0 q_1^* - (q_1^*)^2 \geq \delta_1$$
$$\implies \psi(q_1^*) \geq \delta_1,\ \psi'' < 0$$

where $\delta_0 = \frac{2}{3}(a + 2\theta - 2c + 2\gamma)$ and $\delta_1 = \Big(\frac{a + r\theta}{3}\Big)^2$.

$$IC_2 \implies \alpha_0 q_1^* - (q_1^*)^2 \leq \alpha_1$$
$$\implies \phi(q_1^*) \leq \alpha_1,\ \phi'' < 0$$

where $\alpha_0 = \dfrac{4a + 3r\theta - \theta + c - \gamma}{6}$ and $\alpha_1 = \dfrac{(2a + \theta - c + \gamma)(a - \theta + c - \gamma)}{18}$.

By comparing the parameter values, it can easily be checked that $\delta_1 > \alpha_1$. Now, if $\alpha_0 \geq \delta_0$, then $\alpha_0 q_1^* - (q_1^*)^2 \geq \delta_0 q_1^* - (q_1^*)^2 \geq \delta_1$(if IC_1 holds) $> \alpha_1$, that is, there is no q_1^* for which IC_1 and IC_2 hold simultaneously. Hence, for a separating equilibrium to exist, parameter values should be such that $\alpha_0 < \delta_0 \implies r < 3\Big(\frac{\theta + \gamma - c}{\theta}\Big)$.

The second-degree equation formed by taking the incentive compatibility constraint of firm 1 with an equality has roots $\frac{\delta_0 \pm \sqrt{\delta_0^2 - 4\delta_1}}{2}$. Thus IC_1 is satisfied in the range $q_1 \in \Big[\frac{\delta_0 - \sqrt{\delta_0^2 - 4\delta_1}}{2}, \frac{\delta_0 + \sqrt{\delta_0^2 - 4\delta_1}}{2}\Big]$. Similarly, the second-degree equation formed by taking the incentive compatibility constraint of firm 2 with an equality has roots $\frac{\alpha_0 \pm \sqrt{\alpha_0^2 - 4\alpha_1}}{2}$. Thus IC_2 is satisfied in the range $q_1 \in \Big[0, \frac{\alpha_0 - \sqrt{\alpha_0^2 - 4\alpha_1}}{2}\Big] \cup \Big[\frac{\alpha_0 + \sqrt{\alpha_0^2 - 4\alpha_1}}{2}, \infty\Big]$. The discriminants are positive under specified model conditions, confirming real roots. For simplicity of notation, denote the ranges implied by IC_1 and IC_2 as $q_1 \in [d_1, d_2]$ and $q_2 \in [0, a_1] \cup [a_2, \infty]$ respectively, where d_1 and d_2 are the roots of the second-degree equation formed from IC_1 and a_1 and a_2 are those from IC_2. A separating equilibrium exists if $d_2 \geq a_2$ or $d_1 \leq a_1$ or both. The first condition implies that:

$$\delta_0 - \alpha_0 \geq \sqrt{\alpha_0^2 - 4\alpha_1} - \sqrt{\delta_0^2 - 4\delta_1} = k \text{ (say)} \tag{1}$$

The second condition implies that:

$$\delta_0 - \alpha_0 \leq \sqrt{\delta_0^2 - 4\delta_1} - \sqrt{\alpha_0^2 - 4\alpha_1} = -k \tag{2}$$

Recall that the existence of a separating equilibrium requires $\delta_0 > \alpha_0$. It follows that, if $k > 0$ then only (1) can hold, if $k = 0$ then (1) certainly holds, (2) cannot hold for $k \geq 0$, and if $k < 0$ then either only (1) holds or both (1) and (2) hold. The following delineation summarises the results:

1. $k > 0$: Separating equilibrium (if exists) is $q_1^* \in [a_2, d_2]$
2. $k = 0$: Separating equilibrium is $q_1^* \in [a_2, d_2]$
3. $k < 0$: Separating equilibrium is either $q_1^* \in [a_2, d_2]$ or $q_1^* \in [d_1, a_1] \cup [a_2, d_2]$

Figure 1 illustrates the analysis, considering the case when both $\delta_0 > \alpha_0$ (necessary condition) and $k \leq 0$ (sufficient condition) are satisfied and separating equilibria exist on higher as well as lower values of output.

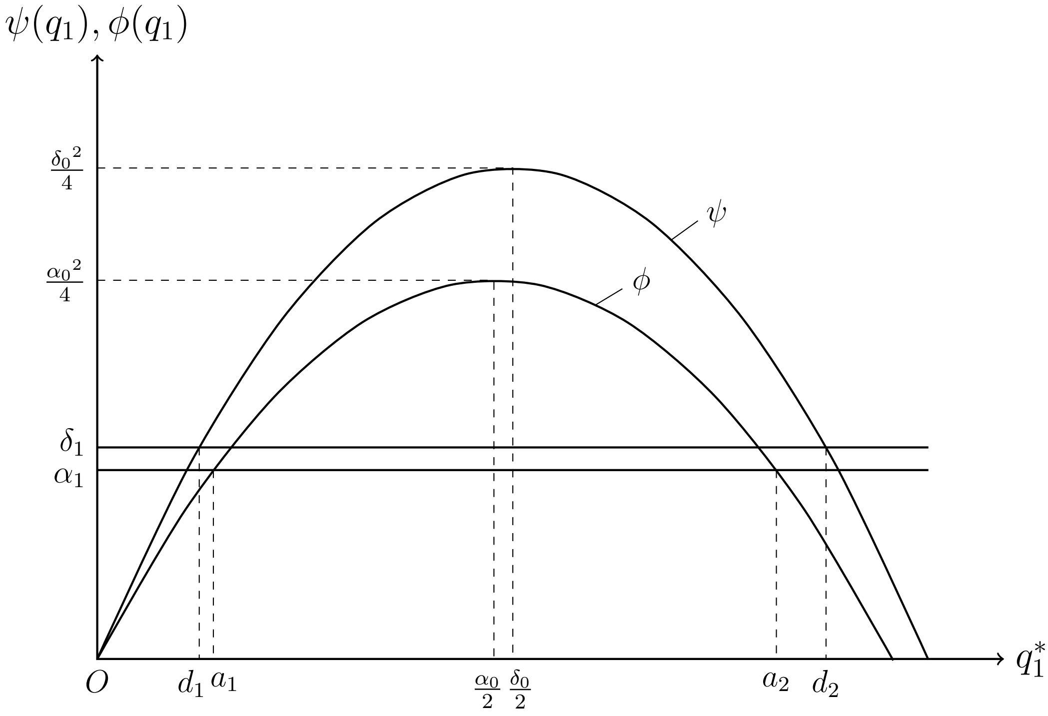

Figure 1: Incentive compatibility constraints of both firms

The function ψ implies that any deviation from $\frac{\delta_0}{2}$ reduces the pay-off of firm 1. Note that the points a_1 and a_2 are equidistant from $\frac{\alpha_0}{2}$, and $\frac{\delta_0}{2}$ lies to the right of $\frac{\alpha_0}{2}$. Therefore a_2 is relatively nearer to $\frac{\delta_0}{2}$ than a_1. It follows that, although there are typically multiple separating equilibria, the optimal choice of output for firm 1 is $q_1^* = a_2$. Clearly, this is also the optimal choice when separating equilibria exist for only the higher values of output. Hence, the proof. ■