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PUBLIC SECTOR SCIENCE AND THE STRATEGY OF THE COMMONS[†]

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We model the conditions under which incumbent firms may purposefully create an intellectual property (IP) commons such that no firm has the incentive to invest in new product development, despite the potential profitability of a public sector invention. The strategy of spoiling incentives to innovate by eliminating exclusive IP rights – the *strategy of the commons* – is motivated by a fear of cannibalization and supported by a credible threat. We show how the degree of potential cannibalization is related to this market failure and characterize the subgame perfect equilibrium in which the strategy of the commons is played.

Keywords: Entry deterrence; Intellectual property; University research; Welfare loss; Cannibalization

JEL Classification: L10; L12

1 INTRODUCTION

This article is motivated by an interesting puzzle. Over the past decade, several prominent public research institutions have been approached by a variety of large firms and private sector consortia that wish to sponsor particular research laboratories. In return for their sponsorship, these organizations have requested that all inventions generated by the sponsored labs be licensed openly, on a non-exclusive basis only. At first glance, this seems surprisingly generous – in fact, altruistic. Hence, the puzzle.

Consider three examples: (1) An incumbent camera film company sponsors research in areas related to digital photography; (2) an incumbent telecommunication services company sponsors research in areas related to communication, including Internet telephony; (3) a consortium,

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[1] The first two examples are drawn from interviews with staff at the MIT Technology Licensing Office in Cambridge, MA. The latter example refers to the SNP Consortium, which consists of several large pharmaceutical rivals including Novartis, Glaxo Wellcome, Pfizer, and SmithKline Beecham. This consortium was formed in 1999 for the sole purpose of sponsoring public sector research to identify and patent Single Nucleotide Polymorphisms (SNPs) in order to prevent smaller biotechnology firms from entering and obtaining exclusive rights to this genetic information. (*The Wall Street Journal* (03/04/1999), *US News & World Report*(10/18/99), *The Economist* (12/04/99)). SNPs are differences in the DNA of individuals that are likely to be important in tracking the genetic causes of disease.

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comprised of several of the world's largest pharmaceutical firms, sponsors research related to the Human Genome Project.[1] In each case, the sponsorship stipulates 'no exclusive licensing'. So, the puzzle is 'Why would sponsoring firms choose to disallow exclusive licensing – which has been the norm at universities since the Bayh-Dole Act of 1980[2] – especially since these firms would be prime candidates for licensing the inventions exclusively themselves?'

One simple hypothesis is that sponsoring firms are worried that competing firms might obtain the exclusive license first. This is certainly a reasonable explanation but not fully consistent with the evidence. Historically, sponsoring firms have enjoyed favorable information advantages regarding the research outcomes of the labs they sponsor since they often receive interim briefings *prior* to publications or conference presentations. So, in practice, they are usually 'first in line' for any related exclusive licenses.

In this essay, a second, less obvious explanation is examined. The hypothesis modeled here is that firms request non-exclusive licensing regimes in order to *prevent,* or at least retard, the commercial development of inventions in a particular area. In other words, firms sponsor research specifically because they do not want particular types of inventions to be commercialized. They purposely spoil the incentives for other firms to develop and commercialize inventions from the sponsored lab by creating a market failure. Sponsoring firms accomplish this by creating an intellectual property (IP) 'commons' under which no firm is able to obtain exclusive property rights.

Why would they do this? Under some conditions, if a new market is related to an old market such that the former will *cannibalize* the latter, it may be profitable for the entrant to develop the invention but harmful for the incumbent to do so. In other words, the incumbent's profits in the original market will be reduced if the entrant develops the invention or even if the incumbent itself does so. From this perspective, one can imagine reasons why an incumbent camera film company may want to delay the development of digital photography, an incumbent telecommunication services company the development of Internet telephony, and large pharmaceutical firms the development of processes for human gene mapping.

Under this threat of cannibalization, one might question why the incumbent does not license the patent and leave the technology dormant?[3] The answer lies in the licensing contract that is handcrafted for each agreement. Technical progress, the development of a business plan, the generation of a working model, the time to market for the first commercial product, and other milestones, including expenditure commitments associated with product development and commercialization, are specified in the contract. Technology licensing officers refer to these contractual conditions as 'use it or lose it' clauses that ensure that the mandate of the university is reflected in the conditions of the contract.[4] Licensing university inventions and not developing them no longer appears to be a feasible strategy for mitigating the effects of cannibalization.

The idea of market cannibalization has been well studied. The 'replacement effect' was first explicitly analysed by Arrow (1962), who argues that a monopolist incumbent would

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[2] The Bayh-Dole Act (Public Law 96-517) assigned ownership and control of patents derived from federally funded research to performing institutions rather than the sponsoring federal agency. Most relevant to this study, it granted non-profit organizations the right to offer *exclusive* licenses – a right that, as the Columbia University Technology Licensing Office describes, 'provided the incentives for the venture capital industry to invest in unproven technology [· · ·] The results have been dramatic. A trickle of university patents, 200 in 1980, has turned into a flood – now more than 3000 applications a year' (*21stC: The World of Research at Columbia*, Winter 1998).

[3] This is known as 'keeping a sleeping patent'.

[4] The mandate of most research universities, with respect to patent licensing, is to promote the development of their inventions, rather than to maximize profits. For example, the MIT Technology Licensing Office states: 'In our technology licensing endeavor, MIT is following the mandate of the US Congress when it gave universities title to inventions developed with federal funds: we use licenses to our IP to induce development of our inventions into products for the public good'. (MIT TLO promotional pamphlet, 1996).

have a lower willingness to pay for an innovation than an entrant since the incumbent would be concerned about replacing its sunk assets and thus have, relatively, less incentives to innovate. Since Arrow, many other scholars have examined particular economic effects of market cannibalization. For example, Abernathy and Utterback (1978) compare incremental and radical innovation and offer a number of reasons, including cannibalization, to explain why radical innovation is typically carried out by entrants rather than incumbents. Foster (1986) popularized the concept of the S-curve for technologies, the shape of which is defined by the increase in performance relative to the development effort expended. Discontinuities in the curve represent new technologies that are often developed by entrants because they have the potential to cannibalize the existing product market. Gans and Stern (1998) model the allocation of rents from innovation among incumbents and entrants that is dependent on the existence and terms available on the 'market for ideas' and use this framework to consider the way in which cannibalization affects the underlying incentives for either firm to conduct R&D. Finally, Christensen and Bower (1996) and Christensen (1997) examine the concept of 'disruptive' technologies in a number of product markets, most notably the disk drive industry. In these analyses, cannibalization is once again offered as an explanation – although not the primary explanation – for innovation by entrants but not incumbents.

The work presented here contributes to this stream of research by examining a particular market structure that is influenced by the effects of cannibalization. Specifically, it presents a model with two related markets, an old technology and a new technology market, and two players, an incumbent and an entrant, and seeks to identify the conditions under which the sponsoring incumbent selects a non-exclusive licensing regime in the new market. These conditions must allow it to credibly and effectively threaten to enter and invest in the invention if the entrant does. The threat is credible only if it is profitable for the incumbent to invest in licensing and developing the invention after the entrant has invested and it is effective only if the duopoly profits for the entrant are less than the costs of entry, deterring the entrant from entering. This strategy, in which the incumbent eliminates the incentives for any firm to develop an invention by selecting a non-exclusive licensing regime and, hence, creates an IP commons, is referred to here as the *Strategy of the Commons*.[5]

There has been significant research in the related areas of patent racing and patent licensing (Dasgupta and Stiglitz, 1981; Reinganum, 1982; Loury, 1979; Grossman and Shapiro, 1987; Harris and Vickers, 1987), particularly in the industrial organization literature. There is also a significant body of work that focuses on patent licensing such as Kamien and Tauman (1986), Katz and Shapiro (1985), and Gallini and Winter (1985).

Perhaps the most relevant literature, however, is that on patents and licensing in the context of entry deterrence. In their seminal article on the topic, Gilbert and Newbery (1982) develop a model of innovation and show the conditions under which an incumbent with monopoly power has an incentive to patent pre-emptively in order to deter entry. Within this context, the authors show that this activity can lead to patents that are neither used nor licensed to others. Reinganum (1983) builds on this work but models the inventive process as stochastic. In this model, when the innovation is sufficiently revolutionary, an equilibrium exists in which the entrant has a higher marginal incentive to invest in R&D than the incumbent. As such, this model suggests limitations to the conditions under which pre-emptive patenting leading to entry deterrence is an equilibrium solution. Adding yet another wrinkle, Gallini (1984) incorporates licensing into a model of inventive activity and shows that by licensing its production technology and

[5] The term 'Strategy of the Commons' is a play on the phonetically similar 'Tragedy of the Commons' popularized by Garret Hardin in an article on population control (Hardin, 1968). With regard to the origin of the term, Professor Hardin recognizes mathematical amateur William Forster Lloyd (1833) for an early discussion of the idea. In addition, Scott Gordon's 1956 essay on the problem of the commons closely resembles the 'Tragedy of the Commons' and thus it is ambiguous as to whom acknowledgments for this phrase should be made.

thus reducing incentives for the entrant to develop its own, possibly better, technology, an incumbent may deter entry.

These articles examine models in which the player making the licensing decision is also the recipient of licensing fees. Naturally, these decisions are made in a profit-maximizing manner. It is important to highlight the distinction that in the model presented in this article, the profit maximizing incumbent is afforded the licensing regime decision even though it is separate from the university, which is the inventor and the recipient of licensing fees. There is no element of competition modeled here at the sponsorship level. Sponsorship is exogenous.[6] As a result of this distinction, this article also may be considered relevant to the 'raising rivals costs' literature (Salop and Scheffman, 1983; Salop, 1993; Granitz and Klein, 1996), which investigates strategic decisions that may not benefit the decision maker directly but may harm potential competitors.

Finally, it is important to note that there exists a rich literature on the general topic of university-to-industry knowledge transfer, a survey of which is provided in Agrawal (2001). To this end, it is also important to note that there are many channels other than patents through which IP moves from universities to industry (Cohen et al., 1998, 2002; Agrawal and Henderson, 2002). Our focus here, however, is purely on patenting and licensing.

The rest of the article proceeds as follows. In the next section, the licensing model and the dynamics of the game are introduced. In Section 3, the conditions under which the strategy of the commons is an equilibrium solution are described. The social welfare implications that result from this strategy are examined in Section 4, and, finally, implications for strategy and policy are discussed in Section 5. Appendix A contains proofs for all propositions.

2 THE MODEL

In this section, we develop a simple model to investigate the conditions under which it is possible to observe the 'strategy of the commons' as a result of profit-maximizing behavior of players in the licensing game.

2.1 Dynamics of the Licensing Game

At the beginning of the game, a sponsoring firm selects a licensing regime for the technology that will potentially be invented. We refer to this firm as the *incumbent.* We assume the incumbent firm has monopoly power in the existing, or 'old', market. The incumbent, when sponsoring university research, can decide to select either an *exclusive* or a *non-exclusive* licensing regime.

An exclusive licensing regime is one under which only one firm may license the right to use a patented technology at any given time. This also includes technologies that are protected by copyright, trademark, and other forms of legal IP protection. This is in contrast to a non-exclusive licensing regime under which more than one firm may simultaneously license the right to use a protected technology. For the sake of clarity and simplicity, issues such as sub-licensing and restricted fields of use are not considered here. The main implication that arises from the exclusivity distinction in licensing regimes is with regard to competition. In the exclusive case, the licensee maintains a monopoly of the technology, whereas in the non-exclusive case, the licensee faces either direct competition or at least the threat of competition from other firms.

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[6] This assumption reflects the observation that there are no reported cases of firms bidding to sponsor a particular research unit, at least at MIT.

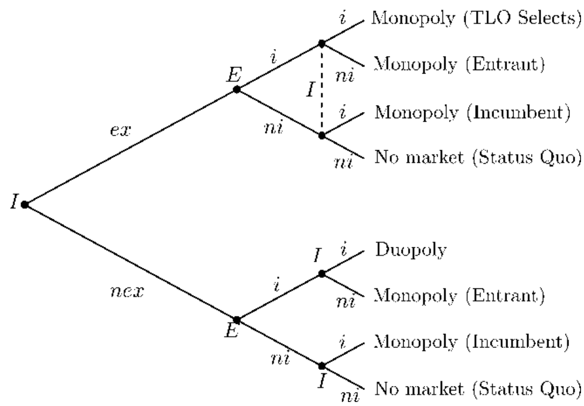

FIGURE 1 Dynamics of the licensing game. *E* indicates the entrant, *I* the incumbent; *ex* represents the exclusive licensing regime, *nex* the non-exclusive licensing regime; *i* indicates the decision to invest in the license, *ni* the decision not to invest in the license.

For tractability, we assume that there exists only one potential entrant in the new market. The resulting game is hence a two-player game in which an established incumbent and a potential entrant interact in the adoption of a new technology.

The two firms are equally efficient in the utilization of the new technology, which is used to develop a product that is a partial substitute for the one already produced by the incumbent. We will formalize the nature of this dependence shortly. Throughout the analysis, we also assume that patents are enforceable and cannot be 'invented around'. This means that a firm must license the patent in order to produce the new technology product.

The dynamics of the game are summarized in Figure 1.

If the incumbent selects an exclusive licensing regime, then both firms decide simultaneously whether or not to license. This is because at most only one firm may obtain rights to the license. In the non-exclusive regime, the licensing decisions are modeled as a sequential game with the entrant moving first since it is possible for both firms to have licensing rights to the invention simultaneously. It is important to note that the order of the sequential non-exclusive licensing subgame produces an outcome that is the same as that which would result if the subgame were infinitely repeated, with no specified order. In the infinitely repeated game, the entrant is always faced with the threat of subsequent entry by the incumbent. Therefore, what is critical is not which player is allowed to move first, but rather that both players are allowed to move after the other. The incumbent is only able to threaten the entrant with entry if it is able to license after the entrant has already done so. In other words, the conditions under which the incumbent will play the strategy of the commons are the same when there are no rules for the order of play in the infinitely repeated game as they are when the order of play is dictated as 'entrant first', as is modeled here.

The *strategy of the commons* outcome occurs when the incumbent selects a non-exclusive licensing regime and, in the ensuing sequential game, both the entrant and the incumbent decide optimally not to invest in the license, *even though* the new technology would be profitable under an exclusive licensing regime.

2.2 Demand and Industry Equilibrium Profits

We assume that the incumbent faces the following linear demand function in the market for the *old technology* ('O' for 'old'):

$$P_{\mathrm{O}} = b_{\mathrm{O}} - Q_{\mathrm{O}}, \quad b_{\mathrm{O}} > 0, \tag{1}$$

where P_{O} is the price of the product and Q_{O} the quantity. The incumbent faces a constant marginal production cost c_{O}. Since it is a monopolist in this market, its profit can be easily derived as

$$M_{\text{O}} = \frac{1}{4}(b_{\text{O}} - c_{\text{O}})^2, \quad 0 \leq c_{\text{O}} \leq b_{\text{O}}. \tag{2}$$

Similarly, we assume that in the *new technology* market ('N' for 'new'), the demand schedule is also linear:

$$P_{\text{N}} = b_{\text{N}} - Q_{\text{N}}, \quad b_{\text{N}} > 0. \tag{3}$$

Since the two firms are equally efficient in developing the new technology, they face the same constant marginal cost c_{N}. Hence, whoever gains a monopoly position in the new technology market will gain a monopoly profit M_{N} given by

$$M_{\text{N}} = \frac{1}{4}(b_{\text{N}} - C_{\text{N}})^2, \quad 0 \leq c_{\text{N}} \leq b_{\text{N}}. \tag{4}$$

We assume $c_{\text{N}} \leq c_{\text{O}}$, i.e., the new technology represents an improvement over the old one.

In case a duopoly emerges in the new technology market,[7] we assume that firms compete in quantity and that industry profits are determined as in a von Stackelberg duopoly game with the incumbent acting as the leader. It is important to stress that the Stackelberg leader is not necessarily the first to invest in the technology. In other words, we are keeping the licensing game separate from the product market game. We model the incumbent as a Stackelberg leader, who sets price by choosing a profit-maximizing quantity over the difference between market demand and the quantity offered by the entrant, to reflect the incumbent's advantage due to its monopoly in the related, existing market. The profit to the incumbent in a Stackelberg duopoly is

$$D_{\text{N}}^{\text{I}} = \frac{1}{8}(b_{\text{N}} - c_{\text{N}})^2, \tag{5}$$

whereas the profit to the entrant (follower) is

$$D_{\text{N}}^{\text{E}} = \frac{1}{16}(b_{\text{N}} - c_{\text{N}})^2. \tag{6}$$

2.2.1 Cannibalization

As noted earlier, the new market is 'related' to the old market. We now formalize this concept. The adoption of a new technology will not only create a potential new market but, to the extent in which the new product is a substitute for the old, it will attract some customers from the old market. When this happens, the old market is said to be 'cannibalized' by the emergence of the new market. The degree of this cannibalization will depend upon the degree of substitutability of the two products. We measure this quantity through the *cross-price elasticity* parameter η_{ON} defined as

$$\eta_{\text{ON}} = \frac{\partial Q_{\text{N}}/Q_{\text{N}}}{\partial P_{\text{O}}/P_{\text{O}}}. \tag{7}$$

Simply, the cross-price elasticity measures the percentage change in the quantity demanded of the new good given a percentage change in the price of the old good. Its value depends on the preference structure of individuals and is positive for substitutes and negative for complementary goods. In our analysis, we implicitly assume that the new technology is a

[7] We note that this is possible only in the non-exclusive regime case.

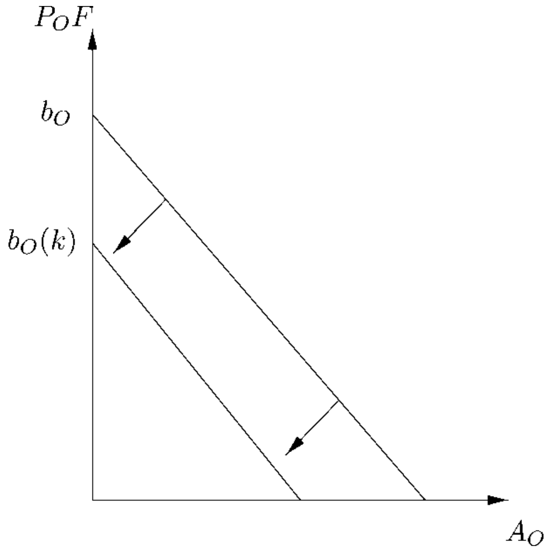

FIGURE 2 Effect of cannibalization on demand schedule. d represents the original demand schedule and $d(k)$ is the 'cannibalized' schedule with cannibalization ratio k.

partial substitute for the old. A thorough analysis of the demand side would require a more comprehensive (general equilibrium) approach, which is outside the scope of this article.

The degree of cannibalization occurring in the original market is captured by the *cannibalization ratio, k.* This ratio is assumed to be a monotonic, non-decreasing function of the absolute value, $|\eta_{\mathrm{ON}}|$, of the cross-price elasticity:

$$k : [0, \infty] \longrightarrow [0, 1), \tag{8}$$

where $k(0) = 0$. Thus, when the two markets are unrelated ($\eta_{\mathrm{ON}} = 0$), the introduction of the new technology does not cannibalize the old market. At the other extreme, when the two markets are perfect substitutes, the introduction of the new technology totally cannibalizes the original market ($\lim_{\eta_{\mathrm{ON}} \to +\infty} k(\eta_{\mathrm{ON}}) = 1$). Formally, the effect of k is to translate the old market demand curve downwards. We show this in Figure 2.[8]

The new, cannibalized demand schedule therefore will be

$$P_{\mathrm{O}}(k) = b_{\mathrm{O}}(k) - Q_{\mathrm{O}}, \tag{9}$$

where $b_{\mathrm{O}}(k) : [0, 1] \to [0, b_{\mathrm{O}}]$ is a monotonic decreasing function of k with $b_{\mathrm{O}}(0) = b_{\mathrm{O}}$ and $b_{\mathrm{O}}(1) = 0$. We assume the following simple functional form for $b_{\mathrm{O}}(k)$[9]:

$$b_{\mathrm{O}}(k) = (1 - k) b_{\mathrm{O}}. \tag{10}$$

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[8] It is important to note that the incumbent may behave differently than the entrant in the new market since the incumbent is subject to cannibalization in the old market. For tractability, we have made the simplifying assumption that both behave the same in the new market – choosing quantities to maximize monopoly profits in that market – and the incumbent's profits from the old market are cannibalized accordingly. This simplification treats the incumbent firm as if it has two divisions, one of which produces for the old market and the other for the new, and that both maximize profits independently. An alternative, more realistic way of modeling the connection between the two markets is to use demand functions in which prices are determined by the quantities produced in both markets. In this case, the incumbent and entrant would make profit maximizing decisions by jointly accounting for the quantities in the old and new markets. Unfortunately, the realism this model would allow comes at the expense of a complex structure of payoffs in the ensuing game, which is hard to interpret in terms of economically relevant conditions. We leave this extension for future research.

[9] Any functional form that generates a monotonic non-increasing function of k would do. We are not concerned at this point about the empirical validity of this assumption.

Note that since k is a monotonic, non-decreasing function of η_{ON}, then $b_O(k)$ can equivalently be considered either a non-increasing function of k or a non-increasing function of η_{ON}.

Once cannibalization occurs in the original market, the equilibrium quantity, price, and profits must be adjusted to reflect the new cannibalized demand. If the new demand is Eq. (9), then the incumbent's monopoly profit in the cannibalized market, according to Eq. (2), will simply be

$$M_O(k) = \frac{1}{4}(b_O(k) - c_O)^2, \tag{11}$$

where $b_O(k)$ is defined in Eq. (10). To ensure economic viability in the old market, we impose an upper bound on the cannibalization, i.e., $b_O(k) \geq c_O$, or, if we assume Eq. (10):

$$k \leq 1 - \frac{c_O}{b_O}.$$

It is important to recognize, though, that the degree of cannibalization in the old market is not only a function of the cross-price elasticity but also of the industry structure of the new market. The prevailing industry structure, within our game, will be determined by the licensing regime selected by the consortium at the beginning of the game. It is reasonable to assume that the degree of cannibalization in the old monopoly market will be higher if a duopoly rather than a monopoly emerges in the new market. This is because the equilibrium industry quantity will be higher under duopoly conditions. In other words, when the new market is a duopoly, a higher fraction of the old technology customer base will be diverted to the new technology market.

Let us denote by k_D the cannibalization ratio in the old market when a *duopoly* emerges in the new market and with k_M the cannibalization ratio when a *monopoly* emerges in the new market. The above argument implies that

$$0 \leq k_M(\eta_{ON}) \leq k_D(\eta_{ON}) \leq 1, \quad \text{for all } \eta_{ON} \in [0, \infty). \tag{12}$$

Once we take the industry structure of the new market into account, we need to redefine cannibalized monopoly profits (11) in the old market. If the new market is a monopoly (which can happen in either the exclusive or the non-exclusive licensing regime), then Eq. (11) becomes

$$M_O(k_M) = \frac{1}{4}(b_O(k_M) - c_O)^2 \tag{13}$$

with $b_O(k_M)$ defined according to Eq. (10). Similarly, if the new market is a duopoly (which can happen only in the non-exclusive licensing regime), then Eq. (11) becomes

$$M_O(k_D) = \frac{1}{4}(b_O(k_D) - c_O)^2, \tag{14}$$

where $b_O(k_D)$ is defined according to Eq. (10).

We now have all the necessary ingredients to derive the payoffs in the licensing game and, subsequently, the conditions that guarantee that the strategy of the commons can emerge as an equilibrium solution.

2.3 Payoffs in the Licensing Game

Let us denote by R the licensing regime chosen by the incumbent. The regime can be either exclusive or non-exclusive, therefore $R \in \{ex, nex\}$, where ex refers to the exclusive licensing regime and nex to the non-exclusive regime. Let J be the set of players, $J \in \{E, I\}$, where E

indicates the entrant and I the incumbent. Finally, we indicate with A^J the action set of player J once the licensing regime has been selected. Each player $J = E, I$ can decide whether to invest in the license for the new invention (i for 'Invest') by paying the licensing fee F or not to license (ni for 'Not Invest'). Formally, $A^J = \{i, ni\}$, $J = E, I$. The actions selected by player J will be indicated with a^J, $J = E, I$, i.e., $a^J \in \{i, ni\}$.

We denote with

$$^{J}\Pi^{R}_{(a^{\mathrm{I}},a^{\mathrm{E}})} \quad J \in \{E, I\}, \quad R \in \{ex, nex\}, \quad (a^{\mathrm{I}}, a^{\mathrm{E}}) \in \{i, ni\}^2, \tag{15}$$

the payoff to player J when the incumbent selects the regime R, the incumbent plays action a^{I}, and the entrant plays action a^{E}.

In the next subsections, we specify quantities (15) for the possible outcomes of the game in the exclusive and non-exclusive licensing regimes.

2.3.1 Payoffs in the Exclusive Licensing Regime

If the incumbent selects an exclusive licensing regime at the beginning of the game (upper branch in Figure 1), then the only possible outcome in the new technology market is either a monopoly (held by either the incumbent or the entrant) or the status quo with no entry in the new market and no new technology adoption.

In the *status quo* case ($a^{\mathrm{I}} = a^{\mathrm{E}} = ni$), the payoff from this outcome is obviously zero for both players. Formally

$$^{\mathrm{I}}\Pi^{ex}_{(ni,ni)} = 0, \tag{16}$$

$$^{\mathrm{E}}\Pi^{ex}_{(ni,ni)} = 0. \tag{17}$$

If only the incumbent invests in the license ($a^{\mathrm{I}} = i, a^{\mathrm{E}} = ni$), then it will be cannibalized and lose the amount $M_{\mathrm{O}} - M_{\mathrm{O}}(k_{\mathrm{M}})$ in the old market (Eq. (13)),[10] but it will enjoy a monopoly profit, M_{N}, in the new market (Eq. (4)) net of the licensing and development fee F. The payoff or the entrant will still be 0. Formally

$$^{\mathrm{I}}\Pi^{ex}_{(ni,i)} = \frac{1}{4}(b_{\mathrm{O}}(1 - k_{\mathrm{M}}) - c_{\mathrm{O}})^2 - \frac{1}{4}(b_{\mathrm{O}} - c_{\mathrm{O}})^2 + \frac{1}{4}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 - F, \tag{18}$$

$$^{\mathrm{E}}\Pi^{ex}_{(i,ni)} = 0. \tag{19}$$

Notice that rather than computing payoff s as the absolute profits generated by the incumbent (sum of the profits from both the old and new markets), we compute the *change* in payoff's relative to the status quo (where the incumbent has monopoly profits in the old market and the entrant has nothing). Thus, the incumbent's payoff described in Eq. (18) reflects the reduction in monopoly profits from the old market ($-[M_{\mathrm{O}} - M_{\mathrm{O}}(k_{\mathrm{M}})]$), as opposed to the reduced monopoly profits in that market. In other words, the model accounts for the effect of the new market on the old market; the sum of the first two terms in payoff (18) indicates the amount by which the status quo profits to the incumbent are reduced due to cannibalization.

If only the entrant decides to invest in the new license ($a^{\mathrm{I}} = ni, a^{\mathrm{E}} = i$), then it will earn the profit M_{N} (Eq. (4)) from a monopoly position in the new market, net of the licensing fee F, while the incumbent will be cannibalized and lose the difference $M_{\mathrm{O}} - M_{\mathrm{O}}(k^{\mathrm{M}})$ in the old

[10] The cannibalization ratio is k_{M} since only a monopoly is possible in the new market under the exclusive regime.

market. Formally

$$ {}^{\mathrm{I}}\Pi^{ex}_{(ni,i)} = \frac{1}{4}(b_{\mathrm{O}}(k_{\mathrm{M}}) - c_{\mathrm{O}})^2 - \frac{1}{4}(b_{\mathrm{O}} - c_{\mathrm{O}})^2, \tag{20} $$

$$ {}^{\mathrm{E}}\Pi^{exs}_{(ni,i)} = \frac{1}{4}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 - F. \tag{21} $$

Finally, if both firms decide to invest in the license for the new invention ($a^{\mathrm{I}} = a^{\mathrm{E}} = i$), under the exclusive regime only one is able to obtain the license. We assume that the Technology Licensing Office (TLO) undertakes a selection process similar to, but not exactly the same as, an auction. We do not model this 'auction' formally but simply assume a probability $\lambda(1-\lambda)$ for the incumbent (entrant) to be assigned the license. We also assume that the fee F' paid by the winner is higher than the one paid to the licensing office in the absence of competition. This reduced form model of the auction process allows us to capture the uncertainty around the potential winner of the license (λ) and the (likely) higher bid ($F' > F$) that the winner ends up paying for the license. Under these conditions, the incumbent will be a monopolist in the new market with probability λ and the entrant will be a monopolist with probability $1-\lambda$. Using payoffs (18) and (20), we obtain the following payoffs:

$$ \begin{aligned} {}^{\mathrm{I}}\Pi^{ex}_{(i,i)} &= \lambda\left(\frac{1}{4}[(b_{\mathrm{O}}(k_{\mathrm{M}}) - c_{\mathrm{O}})^2 - (b_{\mathrm{O}} - c_{\mathrm{O}})^2] + \frac{1}{4}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 - F'\right) \\ &\quad + (1-\lambda)\left(\frac{1}{4}[(b_{\mathrm{O}}(k_{\mathrm{M}}) - c_{\mathrm{O}})^2 - (b_{\mathrm{O}} - c_{\mathrm{O}})^2]\right), \end{aligned} \tag{22} $$

$$ {}^{\mathrm{E}}\Pi^{ex}_{(i,i)} = (1-\lambda)\left(\frac{1}{4}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 - F'\right). \tag{23} $$

2.3.2 Payoffs in the Non-Exclusive Licensing Regime

The payoffs in the non-exclusive regime (lower branch of Figure 1) are similarly derived.[11] The only deviation from the exclusive licensing case is that a duopoly is now possible in the new technology market. In this case, as we noted earlier, the cannibalization ratio will be $k_{\mathrm{D}} \geq k_{\mathrm{M}}$. This will affect the equilibrium monopoly profits in the original market $M_{\mathrm{O}}(k_{\mathrm{D}})$ and, consequently, the payoffs in the game. The payoffs are identical to the payoffs derived above when at most one player decides to invest in the new technology. Thus, we only focus on the duopoly outcome here. When a duopoly emerges ($a^{\mathrm{I}} = i,\ a^{\mathrm{E}} = i$), the incumbent enjoys the Stackelberg profit $D^{\mathrm{I}}_{\mathrm{N}}$ of a leader in the new market (Eq. (5)) and the entrant – the Stackelberg profit $D^{\mathrm{E}}_{\mathrm{N}}$ of a follower (Eq. (6)), net of the licensing and development fee F. The incumbent also loses the difference between the original monopoly profit and the cannibalized monopoly profit $M_{\mathrm{O}}(k_{\mathrm{D}})$ (Eq. (14)) in the old market. Formally

$$ {}^{\mathrm{I}}\Pi^{nex}_{(i,i)} = \frac{1}{4}(b_{\mathrm{O}}(k_{\mathrm{D}}) - c_{\mathrm{O}})^2 - \frac{1}{4}(b_{\mathrm{O}} - c_{\mathrm{O}})^2 + \frac{1}{8}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 - F, \tag{24} $$

$$ {}^{\mathrm{E}}\Pi^{nex}_{(i,i)} = \frac{1}{16}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 - F. \tag{25} $$

[11] It is important to note that the licensing game in the non-exclusive regime is a sequential move game. Potentially many rounds of play will occur before an equilibrium is reached. If we ignore issues related to the timing of appropriation of payoffs, then the analysis in this section is similar to the previous one, under the assumption of a flat term structure with zero interest rates. If, however, time is important in the determination of payoffs, then this issue needs to be addressed in the development of the sequential game. We leave this investigation for future research.

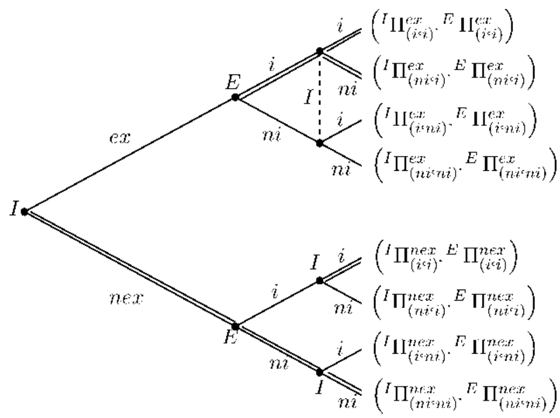

FIGURE 3 Payoffs in the licensing game. E indicates the entrant, I the incumbent; *ex* represents the exclusive licensing regime, *nex* the non-exclusive licensing regime; i indicates the decision to invest in the license, *ni* the decision not to invest in the license. The double branches indicate the strategy of the commons solution.

All the other payoffs are the same as in the exclusive regime. We summarize the payoffs in Figure 3.

3 THE STRATEGY OF THE COMMONS AS AN EQUILIBRIUM SOLUTION

In this section, we show that under certain conditions the strategy of the commons is a subgame perfect equilibrium.

The strategy of the commons occurs when the incumbent selects a non-exclusive regime and then credibly threatens the entrant with entry if the entrant enters. The social outcome is therefore a situation in which, despite the potential profitability to the entrant, nobody decides to invest in the license and the invention is not put into use. In Figure 3, we indicate with a double branch the sequence of moves that corresponds to the strategy of the commons. We formalize it in the following definition.

DEFINITION 1 *The strategy of the commons is characterized by the following conditions*:

1. *Non-exclusive regime*

$$a^{\mathrm{E}} = ni, \quad a^{\mathrm{I}}(a^{\mathrm{E}}) = \begin{cases} i & \text{if } a^{\mathrm{E}} = i, \\ ni & \text{if } a^{\mathrm{E}} = ni. \end{cases} \tag{26}$$

2. *Exclusive regime*

$$a^{\mathrm{E}} = i, \quad a^{\mathrm{I}} \in \{i, ni\}, \tag{27}$$

3. *Regime selection*

$$R = nex, \tag{28}$$

where a^{I}, a^{E}, *and* R *are defined in Eq.* (15).

We now show that there exists a subgame perfect equilibrium in the licensing game in which the strategy of the commons is played. We characterize first (Lemma 1) the equilibrium in the non-exclusive regime subgame, and then (Propositions 1 and 2) we provide conditions on the licensing fees F and F' for which the strategy of the commons is an equilibrium.

Proposition 3 characterizes the equilibrium in terms of the cannibalization ratios k_{D} and k_{M}. We provide proofs for the Lemma and all propositions in Appendix A.

LEMMA 1 *A sufficient condition for the existence of a strategy of the commons equilibrium in the non-exclusive subgame is that*

$$\frac{1}{8}b_{\mathrm{N}}^2 + \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) \geq \max\left\{\frac{1}{4}b_{\mathrm{N}}^2 + \gamma(k_{\mathrm{M}}), \frac{1}{16}b_{\mathrm{N}}^2\right\}, \tag{29}$$

where $\xi(k_{\mathrm{M}}, k_{\mathrm{D}}) = M_{\mathrm{O}}(k_{\mathrm{D}}) - M_{\mathrm{O}}(k_{\mathrm{M}}) < 0$ *and* $\gamma(k_{\mathrm{M}}) = M_{\mathrm{O}}(k_{\mathrm{M}}) - M_{\mathrm{O}} < 0$.

In the next two propositions, we provide conditions on the licensing fees F' such that the strategy of the commons is a subgame perfect equilibrium. We recall that F' is the licensing and development fee paid by the winner of the 'technology auction' in the exclusive regime, as described in Section 2. For simplicity, we assume $F' = \alpha F$, $\alpha > 1$. Proposition 1 refers to the case in which, off-equilibrium, both firms wish to invest in the new technology, while Proposition 2 addresses the case in which only the entrant invests off-equilibrium.

PROPOSITION 1 *Let* $\xi(k_{\mathrm{M}}, k_{\mathrm{D}})$ *and* $\gamma(k_{\mathrm{M}})$ *be the quantities defined in Lemma* 1, $F' = \alpha F$, $\alpha > 1$, *and* λ *be the probability that the incumbent will be assigned the license when competing with the entrant. Then the following conditions characterize the strategy of the commons as a subgame perfect equilibrium in the licensing game in which*, *off-equilibrium*, *both firms invest in the new technology*:

1. *If* $\lambda\alpha < 1$, *the strategy of the commons is an equilibrium if* $F'/F < 4$, *i.e.*, $1 < \alpha < 4$.
2. *If* $\lambda\alpha < 1$, *the strategy of the commons is an equilibrium if* $\gamma(k_M)/\lambda(4-\alpha) > 16\xi(k_{\mathrm{M}}, k_{\mathrm{D}})$.

PROPOSITION 2 *Let* $\xi(k_{\mathrm{M}}, k_{\mathrm{D}})$ *and* $\gamma(k_{\mathrm{M}})$ *be the quantities defined in Lemma* 1 *and let* $F' = \alpha F$, $\alpha > 1$. *Then the strategy of the commons is a subgame perfect equilibrium supported*, *off-equilibrium*, *by only the entrant investing in the new technology if* $\alpha > \Gamma(\gamma, \xi)$ *where*

$$\Gamma(\gamma, \xi) = \begin{cases} \dfrac{2\xi - 2\gamma}{2\xi - \gamma} & \text{if } \dfrac{1}{8}b_{\mathrm{N}}^2 \geq \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) - \gamma(k_{\mathrm{M}}), \\ \dfrac{1}{1/2 + 4\xi/b_{\mathrm{N}}^2} & \text{if } \dfrac{1}{8}b_{\mathrm{N}}^2 < \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) - \gamma(k_{\mathrm{M}}). \end{cases}$$

Note that for $1 < \alpha < 2$, the only equilibrium in the exclusive regime (off-equilibrium condition) is (i, i) and that for $\alpha > 4$, the only equilibrium in the exclusive regime is (ni, i). For $2 < \alpha < 4$, either (i, i) or (ni, i) can be an off-equilibrium conditions. It is important to emphasize, however, that this does not mean multiplicity of equilibria. The equilibrium in which the strategy of the commons is played is always unique, given the level of new technology costs c_{N} and licensing and development fees F. Moreover, note that the off-equilibrium condition (ni, i) requires a competitive fee F' at least twice as high as the base fee F.

We now characterize the condition in Lemma 1 in terms of the cannibalization ratios k_{M} and k_{D}.

PROPOSITION 3 (ni, ni) *is a Nash equilibrium in the non-exclusive regime subgame*, *compatible with the strategy of the commons* (*Definition* 1), *if and only if the following conditions are satisfied for all* $0 \leq k_{\mathrm{M}} \leq 1 - c_{\mathrm{O}}/b_{\mathrm{O}}$:

1. *For* $b_{\mathrm{N}}^2 < (b_{\mathrm{O}} - c_{\mathrm{O}})^2$, $k_{\mathrm{M}} \le k_{\mathrm{D}} \le k_{\mathrm{D}}(k_{\mathrm{M}})$ *with*

$$k_{\mathrm{D}}(k_{\mathrm{M}}) = \begin{cases} \hat{k}_{\mathrm{D}}(k_{\mathrm{M}}) & \text{if } 0 \le k_{\mathrm{M}} < k_{\mathrm{M}}^*, \\ \hat{\hat{k}}_{\mathrm{D}}(k_{\mathrm{M}}) & \text{if } k_{\mathrm{M}}^* \le k_{\mathrm{M}} < \hat{\hat{k}}_{\mathrm{M}}, \\ 1 - c_{\mathrm{O}}/b_{\mathrm{O}} & \text{if } \hat{\hat{k}}_{\mathrm{M}} \le k_{\mathrm{M}} \le 1 - c_{\mathrm{O}}/b_{\mathrm{O}}. \end{cases} \tag{30}$$

2. *For* $b_{\mathrm{N}}^2 > (b_{\mathrm{O}} - c_{\mathrm{O}})^2$, $k_{\mathrm{M}} \le k_{\mathrm{D}} \le k_{\mathrm{D}}(k_{\mathrm{M}})$ *with*

$$k_{\mathrm{D}}(k_{\mathrm{M}}) = \begin{cases} \hat{k}_{\mathrm{D}}(k_{\mathrm{M}}) & \text{if } 0 \le k_{\mathrm{M}} < \hat{k}_{\mathrm{M}}, \\ 1 - c_{\mathrm{O}}/b_{\mathrm{O}} & \text{if } \hat{k}_{\mathrm{M}} \le k_{\mathrm{M}} \le 1 - c_{\mathrm{O}}/b_{\mathrm{O}}, \end{cases} \tag{31}$$

where

$$\hat{k}_{\mathrm{D}}(k_{\mathrm{M}}) = 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}} - \frac{\sqrt{(4/3)(b_{\mathrm{O}}(1-k_{\mathrm{M}}) - c_{\mathrm{O}})^2 - (1/3)(b_{\mathrm{O}} - c_{\mathrm{O}})^2}}{b_{\mathrm{O}}}, \tag{32}$$

$$\hat{\hat{k}}_{\mathrm{D}}(k_{\mathrm{M}}) = 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}} - \frac{\sqrt{(b_{\mathrm{O}}(1-k_{\mathrm{M}}) - c_{\mathrm{O}})^2 - (1/4)b_{\mathrm{N}}^2}}{b_{\mathrm{O}}}, \tag{33}$$

$$k_{\mathrm{M}}^* = 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}} - \frac{1}{b_{\mathrm{O}}}\sqrt{(b_{\mathrm{O}} - c_{\mathrm{O}})^2 - \frac{3}{4}b_{\mathrm{N}}^2}, \tag{34}$$

$$\hat{k}_{\mathrm{M}} = \frac{1}{2}\left(1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}}\right), \tag{35}$$

$$\hat{\hat{k}}_{\mathrm{M}} = 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}} - \frac{b_{\mathrm{N}}}{2b_{\mathrm{O}}}. \tag{36}$$

Figure 4 shows the region $(k_{\mathrm{M}}, k_{\mathrm{D}})$ described in the above proposition. Panel A refers to the case in which $b_{\mathrm{N}}^2 > (b_{\mathrm{O}} - c_{\mathrm{O}})^2$ while panel B refers to the case in which $b_{\mathrm{N}}^2 > (b_{\mathrm{O}} - c_{\mathrm{O}})^2$.

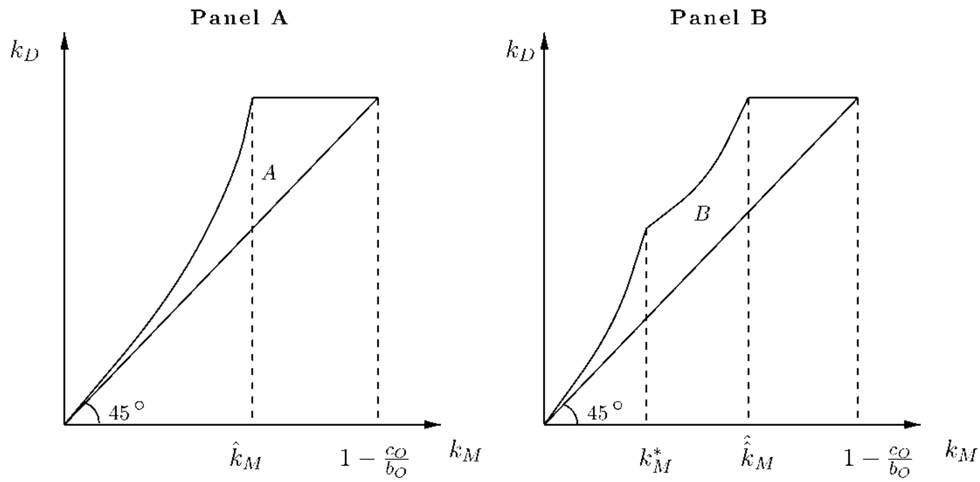

FIGURE 4 Cannibalization and strategy of the commons. Regions of $(k_{\mathrm{M}}, k_{\mathrm{D}})$ for which (ni, ni) is an equilibrium in the non-exclusive subgame, compatible with the strategy of the commons. In panel A, $b_{\mathrm{N}}^2 > (b_{\mathrm{O}} - c_{\mathrm{O}})^2$ and Lemma 1 holds for $(k_{\mathrm{M}}, k_{\mathrm{D}}) \in$ A, while in panel B, $b_{\mathrm{N}}^2 < (b_{\mathrm{O}} - c_{\mathrm{O}})^2$ and Lemma 1 holds for $(k_{\mathrm{M}}, k_{\mathrm{D}}) \in B$.

It is easy to show that, in Eq. (30):

$$\hat{k}_{\mathrm{D}}(k_{\mathrm{M}}^*) = \hat{\hat{k}}_{\mathrm{D}}(k_{\mathrm{M}}^*) = 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}} - \frac{\sqrt{(b_{\mathrm{O}} - c_{\mathrm{O}})^2 - b_{\mathrm{N}}^2}}{b_{\mathrm{O}}}$$

and that

$$\left.\frac{\partial \hat{k}_{\mathrm{D}}(k_{\mathrm{M}})}{\partial k_{\mathrm{M}}}\right|_{k_{\mathrm{M}}=k_{\mathrm{M}}^*} > \left.\frac{\partial \hat{\hat{k}}_{\mathrm{D}}(k_{\mathrm{M}})}{\partial k_{\mathrm{M}}}\right|_{k_{\mathrm{M}}=k_{\mathrm{M}}^*},$$

therefore, the pasting in k_{M}^* between $\hat{k}_{\mathrm{D}}(k_{\mathrm{M}})$ and $\hat{\hat{k}}_{\mathrm{D}}(k_{\mathrm{M}})$ is not smooth.

We conclude this section with a corollary which follows immediately from the previous results.

COROLLARY 1 *If* $0 < k_{\mathrm{M}} = k_{\mathrm{D}}$, *then there always exists an equilibrium in which the strategy of the commons is played. On the other side, if* $0 = k_{\mathrm{M}} = k_{\mathrm{D}}$ *or* $0 = k_{\mathrm{M}} < k_{\mathrm{D}}$, *the strategy of the commons cannot be a subgame perfect equilibrium.*

The corollary shows that cannibalization is indeed the crucial factor that guarantees the emergence of the strategy of the commons as an equilibrium solution. It is interesting to note that if the original monopoly is cannibalized only by a duopoly ($0 = k_{\mathrm{M}} < k_{\mathrm{D}}$), then there cannot be an equilibrium in which the strategy of the commons is played. This is intuitive since under these conditions the duopoly is less attractive and therefore the incumbent loses the possibility of credibly threatening the entrant in the non-exclusive game.

4 WELFARE IMPLICATIONS OF THIS STRATEGY

When the incumbent plays the strategy of the commons and eliminates the ability to obtain exclusive IP rights, a market failure occurs. It is well known that market failures result in a loss of social welfare. In this section, we consider the welfare implications of the strategy of the commons. Specifically, we set out to prove that social welfare losses will indeed occur when the strategy of the commons is played.

The welfare analysis is accomplished by comparing the welfare that results in the nonexclusive regime under which the strategy of the commons is played with that which would otherwise result from the exclusive regime. Let W_{O}^R (W_{N}^R) denote the social welfare in the old (new) technology market under the licensing regime $R = ex, nex$. The strategy of the commons generate social welfare loss when

$$W_{\mathrm{O}}^{nex} + W_{\mathrm{N}}^{nex} < W_{\mathrm{O}}^{ex} + W_{\mathrm{N}}^{ex}. \tag{37}$$

Under monopoly conditions, given a linear demand function and a constant marginal cost, the equilibrium quantity in the old market is $b_O - c_O/2$ and the social welfare under the non-exclusive regime W_O^{nex} is defined as

$$W_{\mathrm{O}}^{nex} = \int_0^{(b_{\mathrm{O}}-c_{\mathrm{O}})/2} (b_{\mathrm{O}} - Q - c_{\mathrm{O}})\,\mathrm{d}Q = \frac{3}{8}(b_{\mathrm{O}} - c_{\mathrm{O}})^2, \quad 0 \le c_{\mathrm{O}} \le b_{\mathrm{O}}. \tag{38}$$

We recall that there is no welfare generated from the new technology under the non-exclusive regime because the strategy of the commons prevents this invention from being developed and thus prevents this market from existing. This implies

$$W_{\mathrm{N}}^{nex} = 0. \tag{39}$$

Similarly, the welfare quantities in the exclusive regime W_{O}^{ex} and W_{N}^{ex} are derived as follows

$$W_{\mathrm{O}}^{ex} = \frac{3}{8}(b_{\mathrm{O}}(1 - k_{\mathrm{M}}) - c_{\mathrm{O}})^2, \quad 0 \leq k_{\mathrm{M}} \leq 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}}, \tag{40}$$

$$W_{\mathrm{N}}^{ex} = \frac{3}{8}(b_{\mathrm{N}} - c_{\mathrm{N}})^2, \quad 0 \leq c_{\mathrm{N}} \leq b_{\mathrm{N}}. \tag{41}$$

The following proposition shows when the strategy of the commons will result in a welfare loss.

PROPOSITION 4 *If* $(b_{\mathrm{N}} - c_{\mathrm{N}}) \geq (b_{\mathrm{O}} - c_{\mathrm{O}})$, *then the strategy of the commons will result in a social loss for every value of the cannibalization ratio* $k_{\mathrm{M}} \in [0, 1 - c_O/b_O]$. *If* $(b_{\mathrm{N}} - c_{\mathrm{N}}) < (b_{\mathrm{O}} - c_{\mathrm{O}})$, *then there exists an upper bound* $k_{\mathrm{M}}^S \leq 1 - c_{\mathrm{O}}/b_O$ *of cannibalization ratios such that the strategy of the commons will result in a social loss for every* $k_{\mathrm{M}} \in [0, k_{\mathrm{M}}^S]$.

Proposition 4 identifies the values of the cannibalization ratio k_M under which the strategy of the commons results in a social welfare loss. On the one hand, if the new technology dominates the old (i.e., the monopoly profit in the new market $(1/4)(b_{\mathrm{N}} - c_{\mathrm{N}})^2$ is greater than the non-cannibalized monopoly profit in the old market $(1/4)(b_{\mathrm{O}} - c_{\mathrm{O}})^2$) then the strategy of the commons always leads to a welfare loss. This is intuitive since, by definition, the strategy of the commons prevents the implementation of a more efficient technology.

On the other hand, if the new technology is less efficient than the old, the strategy of the commons, by preventing the adoption of an inefficient technology, prevents the economy from moving toward an equilibrium with lower social welfare. This market failure generates a serendipitously positive welfare effect. As Proposition 4 shows, this happens only in the (unlikely) case that the cannibalization ratio K_{M} is sufficiently high.[12] Specifically, the threshold above which the strategy of the commons does not result in a welfare loss is given by k_{M}^S (Eq. (A35) in Appendix A). As shown, this critical value is lower the less efficient the new technology is.

5 CONCLUSIONS

This research suggests that, under certain conditions, private sector firms may have incentives to diffuse potential threats from public research programs likely to produce cannibalizing innovations. One strategy for accomplishing this is to create a market failure by dismantling the legal architecture that offers the IP protection that is often critical to entrants for purposes of raising capital and attracting early adopters.

If they are unlikely to license resultant inventions, why would incumbent firms sponsor external research at all? Firms may be motivated to do this for several reasons. First, sponsoring university research may be significantly less costly than performing it in-house. Sponsorship often only covers a fraction of the total costs of a project. Professors' salaries and the majority of infrastructure and general equipment is usually paid for by the research institution. Second, company scientists and engineers may not be experienced in the areas associated with the new technology, which represent new frontiers and are precisely the

[12] We would not expect the cannibalization ratio to be high for a less efficient technology.

types of topics that attract academic interest. Third, incumbents often need not control all of the IP associated with a new technology; rather, they only need to prevent an entrant from controlling it all. In fact, in many cases it is necessary for entrants to acquire a thicket of related patents around a key patent in order to generate the required confidence from early-stage investors.

Thus, the strategy of the commons does not require an incumbent to sponsor all research in a particular area to be effective, only enough to prevent an entrant from obtaining exclusive rights to all the IP for a potentially threatening substitute. In most cases, a tightly protected IP position is significantly more important for an entrant than for an incumbent. Consequently, the incumbent's strategy need only prevent the entrant from establishing a complete and robust IP position.

From a policy perspective, governments and university administrations may seek to protect particular areas of research from firms playing the strategy of the commons. Policymakers may consider some areas of innovation particularly likely to produce threatening technologies that might not be developed by incumbent firms but would likely be developed by entrants. These will be technologies that will enable products that have high cannibalization coefficients (high cross-price elasticity with existing products). In such cases, protection of the legal architecture that establishes private IP rights may be important from a welfare perspective.

In this context, it is important to note that most research universities have a mandate to generate knowledge for the public good. This is why the reward structure for academics (e.g., tenure) is so heavily weighted toward publication, since this provides the incentive for researchers to publish their findings and thus widely disseminate the new knowledge they have created. Public sector research institutions play a particular role in the production of knowledge since much of their research is basic.

Basic research may be valuable for multiple applications, many of which are not even recognized until after the initial discovery. Few firms have the scope of products to be able to fully appropriate the value of such research. Furthermore, profit-maximizing firms will only conduct research up to the point where the marginal value equals the marginal cost and thus will under-invest in the production of basic research since they are unable to realize its full value. As a result, universities are unique in that they focus on the production of basic research with appropriate incentive structures to facilitate knowledge externalities.

Thus, in keeping with their mandate of providing knowledge externalities, universities may attempt to prevent the strategy of the commons by manipulating the licensing fee. As shown in Lemma 1 and illustrated in Figure 5, the university may be able to prevent the strategy of the commons by lowering the fee such that the payoff to the entrant is high enough that the entrant will enter despite the threat that the incumbent will also enter. To include these dynamics in our model, we would need to include the university as a third player in the game. This is a useful extension that we will pursue in future research.

Another benefit to including the university as a player in the model is to examine the outcome when it is forward-looking and able to anticipate the incumbent engaging in the strategy of the commons. The university could (and should) require the incumbent to pay at least as much for sponsorship (and the right to determine the licensing regime) as it would forfeit in future licensing fees. Arguably, the aggressive university could charge even more than the forfeited licensing fees; it could collect up to the amount that the incumbent would otherwise lose if the technology were to be developed and licensed to an entrant on an exclusive basis.

However, we offer two caveats. First, the mandate of most universities is not to maximize profits but rather to maximize the utilization of the knowledge created therein. Second, universities often have separate offices for sponsorship and licensing with little obvious coordination

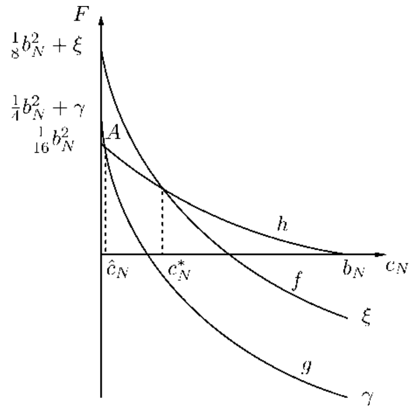

FIGURE 5 Strategy of the commons equilibrium in the non-exclusive regime. For every $(c_\mathrm{N}, F) \in A$, (ni, ni) is an equilibrium in the non-exclusive subgame, compatible with the strategy of the commons.

between the two. As such, it may be the case that sponsorship arrangements are made independently of future licensing revenue considerations, even though the licensing regime is restricted through agreements made by the sponsorship office.

Public sector science is a critical component of the national innovation system. To the extent that the line between public and private research becomes blurred in terms of both research objectives and sources of funding, such as in fields including electrical engineering, computer science, and biotechnology, firms will respond to the indirect competitive threat posed by research conducted in the public domain. The model presented in this article suggests that there may be an important role for policy in order to fulfill the mandate of public sector science institutions and enhance national welfare.

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APPENDIX A

A.1 Proofs

Proof of Lemma 1 According to Definition 1, we need to show that there exists a non-empty region of cost of the new technology (C_{N}) and licensing fee (F) such that (ni, ni) is a Nash equilibrium supported by an off-equilibrium credible threat of investing in the license by the incumbent. This occurs when

$$ {}^{\mathrm{I}}\Pi^{nex}_{(i,i)} > {}^{\mathrm{I}}\Pi^{nex}_{(ni,i)}, \tag{A1} $$

$$ {}^{\mathrm{I}}\Pi^{nex}_{(ni,ni)} > {}^{\mathrm{I}}\Pi^{nex}_{(i,ni)}, \tag{A2} $$

$$ {}^{\mathrm{E}}\Pi^{nex}_{(ni,ni)} > {}^{\mathrm{E}}\Pi^{nex}_{(i,i)}. \tag{A3} $$

Using the definition of payoffs given above, Eq. (A1) can be rewritten as

$$ F < \frac{1}{8}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 + \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) \equiv f(c_{\mathrm{N}}). \tag{A4} $$

Similarly, (A2) and (A3) can be written as

$$ F > \frac{1}{4}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 + \gamma(k_{\mathrm{M}}) \equiv g(c_{\mathrm{N}}) \tag{A5} $$

and

$$ F > \frac{1}{16}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 \equiv h(c_{\mathrm{N}}). \tag{A6} $$

Therefore, (A1)–(A3) can be restated as follows

$$ F < f(c_{\mathrm{N}}), \tag{A7} $$

$$ F > g(c_{\mathrm{N}}), \tag{A8} $$

$$ F > h(c_{\mathrm{N}}). \tag{A9} $$

Conditions (A7)–(A9) are compatible if, for some F and c_N,

$$ \max\{g(c_{\mathrm{N}}), h(c_{\mathrm{N}})\} \ll f(c_{\mathrm{N}}). $$

Note that $f(c_{\mathrm{N}})$, $g(c_{\mathrm{N}})$, and $h(c_{\mathrm{N}})$ are convex functions of c_{N} decreasing for $c_{\mathrm{N}} < b_{\mathrm{N}}$ and with a global minimum at $c_{\mathrm{N}} = b_{\mathrm{N}}$. Since $h(b_N) = 0$ while $f(b_{\mathrm{N}}) = \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) < 0$ and $g(c_{\mathrm{N}}) =$

$\gamma(k_{\mathrm{M}}) < 0$, a sufficient condition for the existence of a non-empty region (c_{N}, F) satisfying Eqs. (A7)–(A9) is that

$$f(0) > \max\{g(0), h(0)\}.$$

Using the definition of $f(c_{\mathrm{N}})$, $g(c_{\mathrm{N}})$, and $h(c_{\mathrm{N}})$ above, we obtain condition (29). Moreover, the upper bound of c_{N} such that an equilibrium in the non-exclusive regime exists is given by

$$c_{\mathrm{N}}^{*} = b_{\mathrm{N}} - \sqrt{-\xi(k_{\mathrm{M}}, k_{\mathrm{D}})} > 0, \tag{A10}$$

obtained by solving $f(c_{\mathrm{N}}) = h(c_{\mathrm{N}})$ there exists a unique c_{N}^{*}.

Figure 5 shows a non-empty region A such that for every $(c_{\mathrm{N}}, F) \in A$, Lemma 1 holds.

Proof of Proposition 1 To find a subgame perfect equilibrium, we need to solve the game by backwards induction. Lemma 1 provides conditions for the existence of an equilibrium in the non-exclusive subgame. We now derive similar conditions for (i, i) to be a Nash equilibrium in the exclusive regime and, finally, for *nex* to be the optimal regime selection implemented by the incumbent.

(i, i) is a Nash equilibrium in the simultaneous move game characterizing the exclusive licensing regime if:

$$^{\mathrm{I}}\Pi_{(i,i)}^{ex} > {}^{\mathrm{I}}\Pi_{(ni,i)}^{ex}, \tag{A11}$$

$$^{\mathrm{E}}\Pi_{(i,i)}^{ex} > {}^{\mathrm{E}}\Pi_{(i,ni)}^{ex} \tag{A12}$$

or

$$F < \frac{1}{4\alpha}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 \equiv \hat{f}(c_{\mathrm{N}}). \tag{A13}$$

Finally, the incumbent will select the non-exclusive regime when

$$^{\mathrm{I}}\Pi_{(ni,ni)}^{nex} > {}^{\mathrm{I}}\Pi_{(i,i)}^{ex} \tag{A14}$$

or

$$F > \frac{1}{4\alpha}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 + \frac{1}{\lambda\alpha}\gamma(k_{\mathrm{M}}) \equiv \hat{g}(c_{\mathrm{N}}). \tag{A15}$$

Hence, the strategy of the commons is a subgame perfect equilibrium if Eqs. (A7)–(A9), (A13), and (A15) are satisfied.

Since $\hat{f}$ is convex, decreasing in $[0, b_{\mathrm{N}}]$ and $\hat{f}(b_{\mathrm{N}}) = 0$, we immediately note that Eq. (A13) is compatible with Eqs. (A7)–(A9) if and only if $\hat{f} > h$ or

$$\frac{1}{4\alpha}(b_{\mathrm{N}} - c_{\mathrm{N}})^2 > \frac{1}{16}(b_{\mathrm{N}} - c_{\mathrm{N}})^2,$$

which implies $1 < \alpha < 4$.

The constraint (A15) is never incompatible if $1 < \alpha < 4$. Note, in fact, that if $\lambda\alpha < 1$, then $\hat{g} < g$ and hence the constraint is not binding. If $\lambda\alpha > 1$, let c_{N}^{**} be the unique intersection between $\hat{g}$ and h. By Lemma 1, c_{N}^{*} (Eq. (A10)) is the upper bound of c_N for which an equilibrium exists in the non-exclusive regime, and the only way Eq. (A15) can be compatible with the equilibrium is if $c_{\mathrm{N}}^{**} < c_{\mathrm{N}}^{*}$. Solving explicitly for c_{N}^{**}, we find

$$c_{\mathrm{N}}^{**} = b_{\mathrm{N}} - \sqrt{-\frac{\gamma(k_{\mathrm{M}})}{\lambda(4-\alpha)}}.$$

Hence, Eq. (A15) is compatible with the other constraints if $c_{\mathrm{N}}^{**} < c_{\mathrm{N}}^{*}$ or $\gamma(k_{\mathrm{M}})/\lambda(4-\alpha) > 16\xi(k_{\mathrm{M}}, K_{\mathrm{D}})$.

Proof of Proposition 2 The proof is similar to the previous proposition. (ni, i) is a Nash equilibrium in the simultaneous move game characterizing the exclusive licensing regime if:

$$^{\mathrm{I}}\Pi^{ex}_{(i,i)} < {}^{\mathrm{I}}\Pi^{ex}_{(ni,i)}, \tag{A16}$$

$$^{\mathrm{E}}\Pi^{ex}_{(ni,i)} > {}^{\mathrm{E}}\Pi^{ex}_{(ni,ni)} \tag{A17}$$

or

$$F > \hat{f}(c_{\mathrm{N}}) \tag{A18}$$

and

$$F < M_{\mathrm{N}}(c_{\mathrm{N}}) \tag{A19}$$

Consequently, the incumbent will select the non-exclusive regime when

$$^{\mathrm{I}}\Pi^{nex}_{(ni,ni)} > {}^{\mathrm{I}}\Pi^{ex}_{(ni,i)} \tag{A20}$$

or

$$0 > \gamma(k_{\mathrm{M}}). \tag{A21}$$

Hence, the strategy of the commons is a subgame perfect equilibrium if Eqs. (A7)–(A9), (A18), (A19), and (A21) are satisfied. Evidently, Eq. (A21) is always satisfied if $k_M > 0$, and Eq. (A19) is never binding since $(1/4)(b_{\mathrm{N}} - c_{\mathrm{N}})^2 > \max_{c_{\mathrm{N}} \in [0, b_{\mathrm{N}}]}\{f(c_{\mathrm{N}}), g(c_{\mathrm{N}}), h(c_{\mathrm{N}})\}$. Therefore, the equilibrium is characterized only by condition (A18). Let us distinguish two cases:

1. $f(0) < g(0)$ or $(1/8)b_{\mathrm{N}}^2 > \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) - \gamma(k_{\mathrm{M}})$.
   Let $\bar{c}_{\mathrm{N}}$ be the unique intersection between g and f (since $f(0) < g(0)$, then $\bar{c}_{\mathrm{N}} > 0$), and let $\hat{\hat{c}}_{\mathrm{N}}$ be the unique intersection between $\hat{f}$ and g. Solving explicitly, we find

   $$\bar{c}_{\mathrm{N}} = b_{\mathrm{N}} - 2\sqrt{2(\xi - \gamma)}, \quad \hat{\hat{c}}_{\mathrm{N}} = b_{\mathrm{N}} - 2\sqrt{\frac{\alpha}{1-\alpha}\gamma}.$$

   Since $\bar{c}_N > 0$, an equilibrium exists if $\hat{\hat{c}}_{\mathrm{N}} > \bar{c}_{\mathrm{N}}$, i.e., if:

   $$\alpha > \frac{2\xi - 2\gamma}{2\xi - \gamma}, \tag{A22}$$

   which is the first condition in the proposition. Note that the right-hand side of Eq. (A22) is always larger than 2 for $0 > \xi > \gamma/3$ (i.e., when (ii) of Lemma 1 is true).
2. $f(0) > g(0)$ or $(1/8)b_{\mathrm{N}}^2 < \xi(k_{\mathrm{M}}, k_{\mathrm{D}}) - \gamma(k_{\mathrm{M}})$.
   In this case, an equilibrium exists if $\hat{f}(0) < f(0)$ or

   $$\alpha > \frac{1}{1/2 + 4\xi/b_N^2},$$

   which proves the second half of the proposition.

Proof of Proposition 3 Let k^*_{M} be such that $\gamma(k^*_{\mathrm{M}})/3 = 1/16b_{\mathrm{N}}^2$, i.e., from the definition of $\gamma(k_{\mathrm{M}})$:

$$k^*_{\mathrm{M}} = 1 - \frac{c_{\mathrm{O}}}{b_{\mathrm{O}}} - \frac{\sqrt{(b_{\mathrm{O}} - c_{\mathrm{O}})^2 - (3/4)b_N^2}}{b_{\mathrm{O}}}. \tag{A23}$$

Note that k^*_{M} is well defined only if $(1/4)b_{\mathrm{N}}^2 \leq (1/3)(b_{\mathrm{O}} - c_{\mathrm{O}})^2$. Then, given conditions (i) and (ii) of Lemma 1, we can distinguish two cases:

1. *Case A.* $(1/4)b_N^2 \leq (1/3)(b_\mathrm{O} - c_\mathrm{O})^2$. This implies $(1/16)b_\mathrm{N}^2 > -\gamma(k_\mathrm{M})/3$ for all $0 \leq k_\mathrm{M} \leq 1 - c_\mathrm{O}/b_\mathrm{O}$, and therefore condition (ii) is the only binding constraint.
2. *Case B.* $(1/4)b_\mathrm{N}^2 \leq (1/3)(b_\mathrm{O} - c_\mathrm{O})^2$. This implies the existence of *a* k_M^* as defined in Eq. (A23) such that

$$\frac{1}{16}b_\mathrm{N}^2 > -\frac{\gamma(k_\mathrm{M})}{3}, \quad \text{for all } 0 \leq k_\mathrm{M} \leq k_\mathrm{M}^* \tag{A24}$$

and

$$\frac{1}{16}b_\mathrm{N}^2 < -\frac{\gamma(k_\mathrm{M})}{3}, \quad \text{for all } k_\mathrm{M}^* < k_\mathrm{M} \leq 1 - \frac{c_\mathrm{O}}{b_\mathrm{O}}. \tag{A25}$$

Therefore, condition (ii) is binding for $k_\mathrm{M} \in [0, k_\mathrm{M}^*]$ and condition (i) is binding for $k_\mathrm{M} \in [k_\mathrm{M}^*, 1 - c_\mathrm{O}/b_\mathrm{O}]$.

Let us consider case A first. We are interested in the relationship between k_D and k_M such that an equilibrium compatible with the strategy of the commons exists in the non-exclusive regime. Condition (ii) is the only binding constraint. Rewriting it using the definitions of $\xi(k_\mathrm{M}, k_\mathrm{D})$ and $\gamma(k_\mathrm{M})$ and rearranging, we obtain

$$\frac{1}{4}(b_\mathrm{O}(1 - k_\mathrm{D}) - c_\mathrm{O})^2 > \frac{1}{3}(b_\mathrm{O}(1 - k_\mathrm{M}) - c_\mathrm{O})^2 - \frac{1}{12}(b_\mathrm{O} - c_\mathrm{O})^2. \tag{A26}$$

By inspection of Eq. (A26), we note that there exists a unique:

$$\hat{k}_\mathrm{M} = \frac{1}{2}\left(1 - \frac{c_\mathrm{O}}{b_\mathrm{O}}\right) \tag{A27}$$

such that Eq. (A26) is always satisfied for $k_\mathrm{M} > \hat{k}_\mathrm{M}$. For $k_\mathrm{M} < \hat{k}_\mathrm{M}$, Eq. (A26) is satisfied for every $k_\mathrm{D} \in [k_\mathrm{M}, \hat{k}_\mathrm{D}(k_\mathrm{M})]$, where the schedule $\hat{k}_\mathrm{D}(k_\mathrm{M})$ is directly obtained from Eq. (A26) and is equal to

$$\hat{k}_\mathrm{D}(k_\mathrm{M}) = 1 - \frac{c_\mathrm{O}}{b_\mathrm{O}} - \frac{\sqrt{(4/3)(b_\mathrm{O}(1 - k_\mathrm{M}) - c_\mathrm{O})^2 - (1/3)(b_\mathrm{O} - c_\mathrm{O})^2}}{b_\mathrm{O}}. \tag{A28}$$

Hence, for $(1/3)(b_O - c_O)^2 < (1/4)b_\mathrm{N}^2$ there exists a $\hat{k}_\mathrm{M}$ and a schedule:

$$k_\mathrm{D}(k_\mathrm{M}) = \begin{cases} \hat{k}_\mathrm{D}(k_\mathrm{M}) & \text{if } k_\mathrm{M} < \hat{k}_\mathrm{M}, \\ 1 - c_\mathrm{O}/b_\mathrm{O} & \text{if } k_\mathrm{M} \geq \hat{k}_\mathrm{M} \end{cases} \tag{A29}$$

such that Lemma 1 is satisfied for $k_\mathrm{M} \leq k_\mathrm{D} \leq k_\mathrm{D}(k_\mathrm{M})$, for all $0 \leq k_\mathrm{M} \leq 1 - c_\mathrm{O}/b_\mathrm{O}$.

Note that $\hat{k}_\mathrm{D}(0) = 0$, $\hat{k}_\mathrm{D}(\hat{k}_\mathrm{M}) = 1 - c_\mathrm{O}/b_\mathrm{O}$. Moreover, $(\partial \hat{k}_\mathrm{D}(k_M)/\partial k_\mathrm{M})|_{k_\mathrm{M}=0} = (8/3) > 1$, which guarantees that for every $k_\mathrm{M} \in [0, 1 - c_\mathrm{O}/b_\mathrm{O}]$ there exists a k_D such that condition (ii) is satisfied.

We now turn to case B. If $k_\mathrm{M} < k_\mathrm{M}^*$ then (ii) is binding and $k_\mathrm{D}(k_\mathrm{M})$ is determined as in Eq. (A26). We distinguish two subcases, depending on whether $\hat{k}_\mathrm{M} > \hat{k}_\mathrm{M}^*$ or $\hat{k}_\mathrm{M} < k_\mathrm{M}^*$. Using Eqs. (A23) and (A27), we notice that $\hat{k}_\mathrm{M} > k_\mathrm{M}^*$ for $b_\mathrm{N}^2 < (b_\mathrm{O} - c_\mathrm{O})^2$ and $\hat{k}_\mathrm{M} < k_\mathrm{M}^*$ for $b_\mathrm{N}^2 > (b_\mathrm{O} - c_\mathrm{O})^2$. Therefore, for $K_\mathrm{M} < k_\mathrm{M}^*$ we have the following cases:

B1. For $(1/4)b_N^2 \leq (1/4)(b_\mathrm{O} - c_\mathrm{O})^2 \leq (1/3)(b_\mathrm{O} - c_\mathrm{O})^2$, $k_\mathrm{M}^* < \hat{k}_\mathrm{M}$ and Lemma 1 is satisfied for $k_\mathrm{M} \leq \hat{k}_\mathrm{D}(k_\mathrm{M})$, $k_\mathrm{M} < k_\mathrm{M}^*$.

B2. For $(1/4)(b_O - c_O)^2 \leq (1/4)b_N^2 \leq (1/3)(b_O - c_O)^2$, $\hat{k}_M < \hat{k}_M^*$ and the schedule $k_D(k_M)$ is defined as follows

$$k_D(k_M) = \begin{cases} \hat{k}_D(k_M) & \text{if } 0 \leq k_M \leq \hat{k}_M, \\ 1 - \dfrac{c_O}{b_O} & \text{if } \hat{k}_M \leq k_M \leq k_M^*. \end{cases}$$

Finally, we look at $k_M > k_M^*$. In this case, (i) is the binding constraint. Rewriting it using the definitions of $\xi(k_M, k_D)$ and rearranging, we obtain

$$\frac{1}{4}(b_O(1 - k_D) - c_O)^2 > \frac{1}{4}(b_O(1 - k_M) - c_O)^2 - \frac{1}{16}b_N^2. \tag{A30}$$

By inspection of Eq. (A30), we note that there exists a unique

$$\hat{\hat{k}}_M = 1 - \frac{c_O}{b_O} - \frac{b_N}{2b_O} \tag{A31}$$

such that Eq. (A30) is always satisfied for $k_M > \hat{\hat{k}}_M$. For $k_M < \hat{\hat{k}}_M$ Eq. (A30) is satisfied for every $k_D \in [k_M, \hat{\hat{k}}_D(k_M)]$ where the schedule $\hat{\hat{k}}_D(k_M)$ is directly obtained from Eq. (A30) and is equal to

$$\hat{\hat{k}}_D(k_M) = 1 - \frac{c_O}{b_O} - \frac{\sqrt{(b_O - (1 - k_M) - c_O)^2 - (1/4)b_N^2}}{b_O}. \tag{A32}$$

As before we need to distinguish between two subcases: $\hat{\hat{k}}_M < k_M^*$ and $\hat{\hat{k}}_M > k_M^*$. From Eqs. (A23) and (A31), $\hat{\hat{k}}_M < k_M^*$ if $b_N^2 > (b_O - c_O)^2$ and $\hat{\hat{k}}_M > k_M^*$ if $b_N^2 < (b_O - c_O)^2$. Therefore, for $k_M > k_M^*$ we have the following cases:

B3. For $(1/4)b_N^2 \leq (1/4)(b_O - c_O)^2 \leq (1/3)(b_O - c_O)^2$, $k_M^* < \hat{\hat{k}}_M$ and Lemma 1 is satisfied for $k_D \leq k_D(k_M)$ where

$$k_D(k_M) = \begin{cases} \hat{\hat{k}}_D(k_M) & \text{if } k_M^* \leq k_M \leq \hat{\hat{k}}_M, \\ 1 - \dfrac{c_O}{b_O} & \text{if } \hat{\hat{k}}_M \leq 1 - \dfrac{c_O}{b_O}. \end{cases}$$

B4. For $(1/4)(b_O - c_O)^2 \leq (1/4)b_N^2 \leq (1/3)(b_O - c_O)^2$, $\hat{\hat{k}}_M < k_M^*$ and the schedule $k_D(k_M) = 1 - c_O/b_O$ for all $k_M > k_M^*$.

From conditions B1 and B3 we obtain Eq. (30), and from (A29), B2, and B4 we obtain condition (31).

Proof of Corollary 1 The first part follows by noting that when $k_M = k_D$, then $\xi(k_M, k_D) = 0$. Since $\gamma(k_M) < 0$. this implies that there always exists a region (c_N, F) such that Lemma 1 is satisfied. The second part of the corollary is immediate since if $k_M = 0$ then $\gamma(k_M) = 0$ and consequently, according to Eqs. (A4) and (A5) $g(c_N) > f(c_N)$. This is incompatible with conditions (A7)–(A9) in Lemma 1.

Proof of Proposition 4 The proof is immediate. By looking at condition (37) and Eqs. (38)–(41), a social loss occurs when

$$(b_O - c_O)^2 < (b_O(1 - k_M) - c_O)^2 + (b_N - c_N)^2, \quad 0 \leq c_N \leq b_N \tag{A33}$$

or

$$(b_O - c_O)^2 - (b_N - c_N)^2 < (b_O(1 - k_M) - c_O)^2. \tag{A34}$$

If $(b_N - c_N) \geq (b_O - c_O)$, then Eq. (A34) is always true for every $k_M \in [0, 1 - c_O/b_O]$ since the left-hand side is non-positive and the right-hand side is non-negative.

If $(b_N - c_N) < (b_O - c_O)$, then there is a unique level of cannibalization:

$$k_M^s = 1 - \frac{c_O}{b_O} - \frac{\sqrt{(b_O - c_O)^2 - (b_N - c_N)^2}}{b_O} \tag{A35}$$

such that Eq. (A34) is satisfied for every $0 \leq k_M \leq k_M^s$.