An Economic Model of a Genetic Resistance Commons:

Effects of Market Structure Applied to Biotechnology in Agriculture

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Abstract: Genetic resistance resources represent an emerging class of environmental resources. These resources are the subject of increasing public interest, especially for resistance in agriculture and antibiotic use. This paper models genetic resistance resources as common-pool resources. The static model applies directly to the case of Bt corn, whose seeds are bioengineered to contain a pesticide. Firms produce an agricultural output, corn, using two inputs: Bt corn seeds and refuge areas. Production also depends on the common stock of environmental resistance. Seed use contributes to greater resistance, while refuge areas abate resistance. This costly form of abatement represents another (positive) externality, which allows for the optimal seed use to be greater than the competitive level. The use of seeds and refuge areas by other firms can be shown to be substitutes and compliments in production, respectively, for each firm. This simple model of externalities is complicated by introducing another important feature common to genetic resistance resources: monopoly supply in the biotechnology factor market. Monopoly provision of seeds, with imperfect price discrimination, leads the monopoly to act as a

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gatekeeper of the commons who tries to maximize its own rents rather than the rents from the resource. This divergence in interests leads to a deadweight loss as seed use is curtailed through higher monopoly prices. This equilibrium is compared to the competitive and the optimal cases. The way in which the resistance externality operates, through damaging others' output or through affecting their marginal productivities, suggests whether the monopoly improves the efficiency of the seed market. Further consideration is given to the possibility that the monopoly determines the firms' level of abatement. Assuming some enforcement mechanism, the monopoly chooses higher abatement levels to increase factor demand for seeds and increase its rents. The Under some plausible conditions, a monopoly supplier of the input that accesses the genetic resistance commons can be shown to actually improve welfare by mandating a higher level of care that also maximizes its profits. The distributional consequences of the different market structures are shown, noting how gains for the monopoly come at the expense of firms. In 2000, the EPA and Monsanto required purchasers of Bt corn to plant specific refuge areas in order to forestall resistance. This approach is readily extended to other cases, such as pesticides more generally or antibiotic use in the production of health services by households.

At the nexus of several burgeoning fields of research and public interest is genetic resistance. The rapid growth and application of biological science in the past century has ushered in dramatic advances in health care and high-yield agriculture. Health care and agriculture share important characteristics besides their biological roots and political prominence. They often evoke very passionate responses from environmentalists and international development policy analysts. Both fields have come under increasing scrutiny in areas concerning microbiological interactions between humans, food, bacteria, and other organisms. Tensions are mounting as antibiotics and pesticides fail, viral outbreaks and crop infestations occur, and a threat to the food supply looms. Perhaps their most important, and most overlooked, common link is their pervasive reliance on environmental genetic susceptibility in production. Whether it is a patient using antibiotics or a farmer spraying pesticides, they both rely on their assailant's inability to resist the treatment. Given that these stocks of genetic resistance are typically common-pool resources, it is little wonder that many people call for non-market responses to recent developments.

1. Background

Histories of human civilization would not be complete without prominent discussion of linkages between genetic resistance, agriculture, and health care. Jared Diamond's Pulitzer Prize-winning *Guns, Germs, and Steel* (1999) gives the ultimate influence of germs and agriculture its due. Throughout the course of human history, the relationship between gene pools and production has affected the way in which economies develop and ultimately which groups prosper. Although such a vantage is perhaps too broad for conventional economic analysis, human history is replete with examples of genetic resistance affecting welfare. Economies and gene pools are mutually adapting to each other, and have been doing so for many millennia. In modern times, this relationship becomes even more pronounced with scientific and economic progress. Just as animal domestication led to enhanced Eurasian resistance to disease (and the lack of such resistance in the Americas), the use of biotechnology enhances resistance at a much faster pace. The consequences of lacking certain resistance in the Americas after the rapid introduction of new organisms during colonization was catastrophic. At the root of this story, and countless smaller scale examples, are fundamental issues of genetic resistance and spillovers within and between communities.

Stories of genetic resistance fill the popular press, recanting the familiar story: farmer uses new weapon against pests that damage crops, and sooner than later the pests adapt a resistance to the weapon. The “superpests” then continue to plague farms. Many times this process is likened to an “arms race” against nature – where science's best technology is ultimately countered by natural adaptive forces, leaving society back where it started or worse. In agriculture, this race against nature's adaptation is being run on numerous fronts and has been run for ages. Perhaps today, the only difference is that we can run faster. Numerous farming techniques, from selective breeding to spraying insecticides to bio-engineering crops, capitalize on nature’s vulnerabilities to increase production. The effectiveness of these innovations, whether they are stronger plants or more lethal pesticides, is often observed to decline rapidly, becoming useless within a few years. The required dosages for pesticides increase over time, as pests turn into superpests, and even insect-resistant crop strains lose effectiveness.

Other technologies, especially in health care, also must grapple with genetic resistance. Increased antibiotic use has led to growing resistance among bacteria. Resistance to antibiotics has been observed both at large in communities and within particular hospitals. Resistance has been observed for antibiotics like azithromycin, ciprofloxacin, methicillin, metronidazole, penicillin, streptomycin, and vancomycin. This challenges effective treatments for infections caused by *E. coli*, *S. pneumoniae*, *Salmonella Typhimurium*, *M. tuberculosis*, and *N. gonorrhoeae* bacteria. Resistance has been found in diseases ranging from malaria to pneumonia. The use of antibiotics on livestock has produced similar resistance effects. The use of antiseptics and disinfectants may also cause resistance. The costs of resistance climbs with its incidence, as secondary treatments are frequently more costly or less effective (GAO 1999). Costs due to antimicrobial resistance in U.S. hospitals alone approach $10 billion (WHO 2000).

With heightened concern has come a widespread perception, especially in the health care field, that "overuse" or "misuse" of the biological tools (antibiotics, insecticides, biotech crops, etc.) is largely responsible for their decline in effectiveness. A third of all antibiotic prescriptions may be unneeded, and most doctors have apparently prescribed them against their better judgment (Levy 1998). Similar refrains sound out in agriculture: "wasteful" or "excessive" use of certain tools has accelerated natural adaptation. In the race to keep up, researchers have spent considerable time investigating the relationship between the use of these technologies and the eventual onset of superbugs. Practitioners are experimenting with techniques to slow down the onset of resistance in the environment. These include: rotating antibiotic use, hybrid insect-resistant crops, multiple-antibiotic drugs ("cocktails"), refuge areas, and more concentrated treatments of antibiotics and pesticides. Early results suggest that some techniques hold promise, while others do not.

2. An Economic Approach

What is the efficient level of antibiotic use? Under what conditions will biotechnology crops improve welfare? An economic approach to these genetic resistance problems provides a powerful analytical tool. Ultimately, this paper attempts to indicate *where* the "problem" lies and suggest *how* efficiency might be improved when optimal solutions are unavailable.

At issue is a common-pool of resources (namely, the susceptibility of "bugs" to certain technologies) that is depletable as more users tap into it. Like a common pasture or fishery, producers will over-exploit the pool's resources because they do not bear the full social cost for their actions. The costs of their appropriation of the pool's resources are borne in part by all users of the resource. With others footing the bill for their use of the common-pool, users can be expected to rationally over-exploit the resource.

The genetic resistance in the environment is a common-pool resource. The level of resistance, although a "bad," fits the two primary criteria for a common-pool resource: depletability and open-access. First, as more producers utilize the resource, it becomes less valuable to everyone. Second, there is no (direct) price for access to this resource – nobody owns it (Baden and Noonan 1998). Genetic commons pose particularly intractable problems. Usual solutions to commons problems include privatization, mergers, and taxation or regulation. Each conventional policy solution seems infeasible in the foreseeable future due to one or more of the following: moral and ethical problems, large group coordination and transaction costs, and information costs. Private ownership of gene pools appears as politically palatable as "merging" all corn farmers or as technically possible as picking the perfect tax. The unavailability of first-best solutions warrants this inquiry into unconventional approaches to managing the genetic commons.

The level of genetic resistance can be thought of as a stock of natural capital, G. The use of some inputs by producers can cause an increase in G. Technologies that rely on genetic susceptibilities in the environment (such as insecticides or some biotech crops) will become less effective as G increases. Although the inputs themselves may have a price (e.g., the price of bio-engineered seeds), the externality caused by their use is not priced by the market. Because a producer's use of the input can reduce the effectiveness of all other producers' technologies, producers will generally over-use the input and a socially sub-optimal level of G (too much resistance) prevails in equilibrium. The model below formalizes this story, after discussing some earlier literature on the subject. It is then extended to include mitigating behavior by producers and a monopoly supplier of the technology.

3. Brief literature review

Formal inquiries into the theoretical nature of environmental externalities and common pools are numerous. Beginning with H. Scott Gordon (1954) through most intermediate microeconomic textbooks today, common property resources or impure public goods have received considerable attention. A lengthy discussion of various externality models like this can be found in Baumol and Oates (1988).

The bulk of the environmental economics literature addresses this fundamental issue of externalities in one of two ways. Pigouvian taxes and Coasian property rights occupy a central place in environmental economics and policy. While both approaches to solving the externality problem face considerable practical problems – owing predominantly to information and transaction costs, respectively – researchers have analyzed the implications of numerous different assumptions. One prominent strain in the literature examines the effect of market structure on externalities and optimal taxation policy. Buchanan (1969) opens the door for externalities in non-competitive market structures. The monopoly's desire to set $MR = MC$ creates the possibility that a Pigouvian tax actually reduces welfare when the final products market remains distorted. Barnett (1980) shows how taxing a monopoly equal to its marginal damages (a Pigou approach) might exacerbate the deadweight loss owing to the monopoly's restricted output. Ideally, a two-part tax would correct both the under-supply of the output by the monopolist and the over-supply of the externality separately and simultaneously.

In addition to their role in generating externalities, monopolies can plan a role in managing externalities. A common intuition, expressed by Knight (1924) in regards to road congestion, holds that granting ownership of a common-pool resource is akin to internalizing an externality. The owner could theoretically charge firms their full marginal costs (including spillovers) and thereby optimize production. In practice, however, the owner possesses monopoly power. A monopoly would choose to limit access to the commons, above and beyond correcting any externality, in order to equate marginal revenue and marginal cost for the final output. A price-discriminating monopoly would profit most by charging users equal to their marginal external damages (in order to equate the value of their marginal products to their social costs). They would then extract a franchise fee equal to users' rents. A monopoly owner of a commons could achieve the socially optimal outcome in this way. A monopoly capable of only a single price would partially account for the spillover amongst its customers with respect to their interdependent demands for the monopoly's resource. Nonetheless, it would still restrict output based on marginal revenue rather than price at social marginal cost. Mills (1981) demonstrates this for congestion-prone facilities.

4. The formal model

A. Competitive Allocation of *g*

To see this formally, begin with a simple model where competitive firms produce q. They use g as an input in production, with factor price w. Firms also use a common, environmental resource G as an input, where the level of G is jointly determined by the firm's own use of g and other firms' use of g, denoted by $\tilde{g}$. Thus, their production function is $q = f\left(g, G(g, \tilde{g})\right)$. Each firm takes $\tilde{g}$ as exogenous. G is a "bad" input (e.g. genetic resistance) that impairs production. The marginal product of G is negative ($\partial f/\partial G < 0$) and decreasing ($\partial^2 f/\partial G^2 < 0$). Assume that the marginal product of g is non-increasing in G ($\partial^2 f / \partial g \partial G \leq 0$). The use of g contributes to G at a rate increasing in g (i.e. $\partial G/\partial g > 0$, $\partial G/\partial \tilde{g} > 0$, $\partial^2 G/\partial g^2 > 0$, $\partial^2 G/\partial \tilde{g}^2 > 0$, $\partial^2 G/\partial g \partial \tilde{g} > 0$). Firms sell q for a fixed price p. A typical firm's profit function is:

$$\Pi = pf\left(g, G(g, \tilde{g})\right) - wg .$$

The firm maximizes $\prod$ by choosing g. Assume throughout this paper that profit functions are negative semidefinite at the optimum choice in order to satisfy the second-order conditions. The first-order condition for the representative firm using $g > 0$ is:

$$p\frac{df}{dg} = p\left[\frac{\partial f(g,G)}{\partial g} + \frac{\partial f(g,G)}{\partial G}\frac{\partial G(g,\tilde{g})}{\partial g}\right] = w . \qquad (1)$$

The marginal revenue product has a positive component from *g*'s direct use and a negative component indirectly from *g*'s contribution to *G*. The firm's choice depends jointly on all users of *g*'s choices.

An aside on the existence of well-behaved factor demand functions is in order. Equation (1) implicitly defines a factor demand function, $g^*(p, w, \tilde{g})$. Cornes and Sandler (1986) discuss the nature of Nash equilibria among firms selecting their *g* given their expectation of other firms' choices ($\tilde{g}$). This paper assumes (for this and every other extension wherein a factor demand function is used for an externality-causing input) that equilibria exist to support a continuous inverse factor demand function $w^*(p, g, \tilde{g})$. Changes in *p* or in $\tilde{g}$ will cause the $w^*(g)$ curve to shift. The effect on g^* of increasing output price is positive. The effect of $\tilde{g}$ on g^* can be seen from the implicit function theorem:

$$\frac{\partial g^*}{\partial \tilde{g}} = -\frac{\dfrac{\partial^2 \Pi}{\partial g \partial \tilde{g}}}{\dfrac{\partial^2 \Pi}{\partial g^2}} = -\frac{\dfrac{\partial^2 f}{\partial g \partial G}\dfrac{\partial G}{\partial \tilde{g}} + \dfrac{\partial^2 f}{\partial G^2}\dfrac{\partial G}{\partial \tilde{g}}\dfrac{\partial G}{\partial g} + \dfrac{\partial f}{\partial G}\dfrac{\partial^2 G}{\partial g \partial \tilde{g}}}{\dfrac{d^2 f}{dg^2}} < 0 . \qquad (2)$$

That $\partial g^* / \partial \tilde{g}$ < 0 amounts to a negatively sloped "reaction curve." This feature of factor demands throughout this paper provides some stability to solutions involving a representative firm. As firms use more *g*, their collective increase in use tempers each firm's increase in demand. Finally, the aggregate factor demand for *g* is sensitive to the number of firms using *g*. Increases in $\tilde{g}$ reduce profit, conceivably leading to large drops in $\sum g^*$ as some firms shut down, even though all remaining firms' use more *g*.

In the long run, entry will occur until $p = AC$ for the marginal firm. Equivalently, their marginal product will equal their average product. This basic model is well discussed in the literature. This paper allows for heterogeneous firms and maintains a $p = AC$ long-run equilibrium condition only for marginal firms.

B. Optimum Allocation of *g*

Compare the competitive equilibrium to the socially optimal allocation of resources. A social planner chooses each firm's quantity of *g*, denoted as g_i , to maximize the sum of firms' profits, where each firm's production and profits still depend on other firms' use of *g*. The *i*th first-order condition for the optimal choice of g_i, denoted as g_i^o , captures the external effects of each firm:

$$p\left[\frac{\partial f(g_i, G)}{\partial g_i} + \frac{\partial f(g_i, G)}{\partial G}\frac{\partial G(g_i, \tilde{g})}{\partial g_i}\right] + \sum_{j \neq i} p \frac{\partial f_j(g_j, G)}{\partial G}\frac{\partial G(g_i, \tilde{g})}{\partial g_i} \leq w. \qquad (3)$$

This holds with equality for $g_i^o > 0$. The first part of equation (3) is the usual marginal revenue product (*MRP*) term, and it is followed by the marginal social damage (*MD*) of g_i. Naturally, *MD* is negative. In the *MD* term, the choice of g_i affects the marginal revenue product of *G* for all other firms ($j \neq i$) through its contribution to *G*. The obvious difference between the optimum necessary condition in equation (3) and the competitive one in equation (1) is that the competitive firms do not include the marginal social damage term in their calculus. A Pigouvian tax equal to *MD* would correct this, aligning private and social marginal costs. Entry still occurs until $p = AC$ for the marginal firm, but firms optimally pay for the added costs they inflict on others. When *g* is supplied at its marginal cost, *MC*(*g*), the optimal equilibrium is characterized by:

$$MC = w = MRP + MD. \qquad (4)$$

Allowing competitive firms to use *g* up to the point where $MC = MRP$ leads to overuse of *g*. In this simple model, *G* is also too large ($G^* > G^o$ and $g^* > g^o$).

C. Monopoly

An interesting extension of the model involves monopoly provision of *g*. The monopoly provides *g* for a price *w*; "the firm" or "firms" always refer to actors who use *g* to produce *q*. The downstream market for *q* remains competitive while the upstream market for *g* has a single seller and an externality among users of *g*.

The current investigation begins with two different ways to frame monopoly control of g that yield different results. First, the monopoly might merge with the firms, operating them by giving them g and selling their output. The "merger" monopoly has revenues of $p\sum q$ and costs of $C(\sum g)$. Maximizing the difference by choosing each g_i, the ith first-order condition is:

$$p\left(\frac{\partial f_i}{\partial g_i}+\frac{\partial f_i}{\partial G}\frac{\partial G}{\partial g_i}\right)+\sum_{j\neq i} p\frac{\partial f_j}{\partial G}\frac{\partial G}{\partial g_i}=MC(g), \qquad (5)$$

for all $g_i^* > 0$. Comparing equation (5) to equation (4) reveals that the "merger" monopoly achieves the efficient allocation of resources (assuming throughout that p is fixed).

A second approach has a "gatekeeper" monopoly selling access rights to g to each firm at a price w_i for the ith firm. This problem is fundamentally different for the monopoly owner of g and yields quite different results. As shown above, the monopoly could achieve the optimal equilibrium and maximize total rents by charging $w = MC - MD$. This price, however, leaves profits for the firms. The monopoly captures these rents in the merger approach above, but cannot do so as a gatekeeper. Instead, the monopoly has the incentive to set $MR = MC$ and claim some of those profits for its own. Consider its profit function, $\prod_M = \sum w_i^* g_i - C(\sum g)$. If the monopoly maximizes this by choosing g_i^M, with w_i^* an inverse factor demand function, the ith first-order condition is:

$$w_i + g_i\frac{\partial w_i}{\partial g_i}+\sum_{j\neq i} g_j\frac{\partial w_j}{\partial g_i}=MC(g). \qquad (6)$$

The left-hand side of this equation represents the marginal revenue of g_i, which is the familiar MR terms plus the (negative) marginal revenue effect of g_i on other firms' demand for g. The monopoly equates the MR of g_i to its marginal cost plus the marginal revenue lost from the spillover. This condition differs significantly from equation (5) in how the spillover is treated. Equation (5) explicitly accounts for the marginal damage of g and raises the effective price accordingly. Equation (6) takes it into account partially by raising the price according to how much additional g reduces its value to other firms. The optimal solution compensates for damages regardless of how responsive others' demands are.[1]

Firms' profits need not be zero with a gatekeeper, unlike in the "merger" model where the monopoly captures all profits. The downward sloping demand curves of firms, while not inconsistent with the efficient equilibrium, will distract the limited monopoly away from the optimum. Even a gatekeeper monopoly capable of charging a different price to each firm would deviate from the efficient outcome. Maximizing its own rents is not the same as maximizing the total rents from the resource when the monopoly cannot capture them all. A monopoly able to supplement its choice of w by charging a fixed franchise fee to the firms could achieve the efficient outcome, where $w = MC - MD$ and the franchise fee captures firm profits. In practice, more limited monopolies should not be expected to manage the resource optimally.

D. Monopoly Contracting over α

As another extension, consider the model where the production function is $q = f(g, \alpha, G(g, \tilde{g}))$. Let α be some other input into the production of q. To make this change interesting, consider the possibility that the monopoly is able to costlessly require a particular level of α use by firms. The monopoly will use this as a tool to extract more rent from firms by choosing α and g for each firm. Raising α_i above what is optimal for the firm lowers its profits.[2] The higher α_i, denoted α_i^c, also entails a higher g_i (or else why would the monopoly regulate α?). Firms' factor demands for g will depend on w_i, p, other firms' use of g, and the level of α_i^c

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[1] Consider a simple system, where production is concave in g and decreasing linearly in G (e.g. $q = g^{0.1} - G$). Also, suppose $G = \sum g$. Then $\partial g^* / \partial \tilde{g} = 0$, and the gatekeeper monopoly ignores the externality and acts as a traditional monopoly with $MR = MC$. The merger monopoly sets $w = MC + Np$, for N firms.

[2] When the monopoly is constrained to dictate a single α for the entire industry, some marginal firms may exit as the monopoly equates the MR of α (across all firms) to zero.

set for them. Hence, inverse factor demand will be $w_i^*\left(p, g, \tilde{g}, \alpha_i^c\right)$, and at some level of α_i^c the firm will shut down. Whether or not $\partial w_i^*/\partial \alpha_i^c > 0$ depends on the complementarity in production of inputs g and α. For a monopoly-set level of α_i, denoted $\alpha_i{}^c$, firms' profits will decline.[3] Firms' factor demands for g will depend on w_i, p, other firms' use of g, and the level of α_i^c set for them. Hence, inverse factor demand will be $w_i^*\left(p, g, \tilde{g}, \alpha_i^c\right)$, and at some level of α_i^c the firm will shut down. Whether or not $\partial w_i^*/\partial \alpha_i^c > 0$ depends on the complementarity in production of inputs g and α.

The monopoly ideally sets each firms' g and α to maximize its profit function: $\prod_M = \sum w_i^* g_i - C(\sum g)$. The first-order conditions for its choice of g_i^c and α_i^c are:

$$w_i^* + \sum_j g_j \frac{\partial w_j^*}{\partial g_i} \leq MC(g)$$

$$\sum_j g_j \frac{\partial w_j^*}{\partial \alpha_i} = g_i \frac{\partial w_i^*}{\partial \alpha_i} \leq 0,$$

with equality when $g_i^c > 0$ and $\alpha_i^c > 0$. The first condition is unchanged from the one-input case. The second condition, however, suggests that the monopoly will raise α until the marginal revenue from doing so has been exhausted. Because the factor demand for g does not depend on other firms' use of α, the second condition requires $\partial w_i^*/\partial \alpha_i = 0$ or $g_i = 0$. If g and α are complements, the monopoly will raise $\alpha_i^c > \alpha_i^*$ until the inputs cease to be complements or the firm becomes unprofitable and stops using g altogether, perhaps because α is costly to the firm. If g and α are substitutes, the monopoly lowers $\alpha_i^c < \alpha_i^*$ until the inputs cease to be substitutes or $g_i^c = 0$. The monopoly's choice of α^c effectively shifts the factor demand curves for g outward (relative to allowing α to be chosen competitively), leading to higher w_i, g_i, and $\prod_M$. When the

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[3] When the monopoly is constrained to dictate a single α for the entire industry, some marginal firms may exit as the monopoly equates the *MR* of α (across all firms) to zero.

inputs are substitutes, G is larger than in the competitive case. The effect on G is ambiguous for complementary inputs.

A comparison of these different scenarios is presented in Figure 1 below. The market for g is shown with three different factor demand curves shown. The middle one, $w^*(g)$, represents the competitive demand for g, where $w = MRP$. Imposing a Pigouvian tax on firms shifts their factor demand curve by MD to $w^o(g)$. The third demand curve, $w^c(g)$, represents factor demand when $\alpha^c \neq \alpha^*$, where α^* is the competitively chosen level of α. The marginal revenue curves for w^* and w^c are shown as MR^* and MR^c respectively. The effect of monopoly provision of g can be seen in reducing the quantity of g and raising w. Whether g^* is more or less than g^o, however, depends on the magnitude of the marginal damage and the elasticity of demand. Figure 1 (arbitrarily) shows $g^* < g^o$. The effect of contracting over α is to shift demand and marginal revenue outwards. This necessarily leads to $g^M > g^*$. This might be a movement towards the optimal allocation of g^o, although this is not a necessary result.

[insert Figure1 here]

5. The extended model

This section extends the basic model by including abatement and applies it to bio-engineered seeds in agriculture. These models incorporate abatement by allowing for another factor to affect G. Specifically, the input α abates the harmful effects of G. Let $\tilde{\alpha}$ denote other firms' use of α. Assume the following technological relations hold for $G(g, \alpha, \tilde{g}, \tilde{\alpha})$, for any firms' use of g or α:

$$\frac{\partial G}{\partial g} > 0, \qquad \frac{\partial^2 G}{\partial g^2} > 0,$$

$$\frac{\partial G}{\partial \alpha} < 0, \qquad \frac{\partial^2 G}{\partial \alpha^2} > 0, \text{ and } \qquad \frac{\partial^2 G}{\partial g \partial \alpha} < 0.$$

The stock of G is increased at an increasing rate by g and decreased at decreasing rate by α.

There is also a negative interaction between g and α such that the marginal effect of g on G decreases as α increases.[4]

The firm has the production function $q = f(g, \alpha, G)$. The inputs to the production function are biotech seeds used (g), "care" in the form of refuge zones (α), and the total stock of environmental resistance (G, a detrimental input). Market prices for g and α are w and r, respectively. The price of the output, q, remains p. This model can apply to any firm using a technology that exploits the genetic susceptibility of some pests in the environment, and has the opportunity to undertake costly "care" to reduce their impact on the environmental resistance.

Production technology exhibits these relationships for all firms:

$$\frac{\partial f(g,\alpha,G)}{\partial g} = \frac{\partial f}{\partial g} > 0 \;, \qquad \frac{\partial^2 f(g,\alpha,G)}{\partial g^2} = \frac{\partial^2 f}{\partial g^2} < 0 \,,$$

$$\frac{\partial f(g,\alpha,G)}{\partial \alpha} = \frac{\partial f}{\partial \alpha} > 0 \;, \qquad \frac{\partial^2 f(g,\alpha,G)}{\partial \alpha^2} = \frac{\partial^2 f}{\partial \alpha^2} < 0 \,,$$

$$\frac{\partial f(g,\alpha,G)}{\partial G} = \frac{\partial f}{\partial G} < 0 \;, \qquad \frac{\partial^2 f(g,\alpha,G)}{\partial G^2} = \frac{\partial^2 f}{\partial G^2} < 0 \,,$$

$$\frac{df(g,\alpha,G))}{dg} = \frac{\partial f}{\partial g} + \frac{\partial f}{\partial G}\frac{\partial G}{\partial g} > 0 \,, \qquad \frac{\partial^2 f(g,\alpha,G))}{\partial g \partial G} \leq 0 \,,$$

$$\frac{df(g,\alpha,G)}{d\alpha} = \frac{\partial f}{\partial \alpha} + \frac{\partial f}{\partial G}\frac{\partial G}{\partial \alpha} > 0 \,, \qquad \frac{\partial^2 f(g,\alpha,G))}{\partial \alpha \partial G} \geq 0 \,.$$

The marginal product of biotech seed use is declining in g. The marginal product of refuge zones is also declining. Increasing genetic resistance reduces output at an increasingly harmful rate. The total effects of raising g and α include these direct effects plus their effects through G.[5]

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[4] Only the negative effect of g or the negative interaction between g and α are needed in this model if the other is zero or small. The former condition is one where α actually reduces resistance, which may not be consistent with some biological dynamics. The latter suggests that α mitigates g's contribution to G.

[5] These include the net present value of a firm's own impact on G.

Though conceivable that $df/dg < 0$, it will be assumed to be positive throughout this analysis. Individual farms' use of seeds does more good than harm to that farm's productivity. Increasing resistance makes seeds not more marginally productive, and it makes refuge areas no less marginally productive.[6]

A. Producer Optimization (α endogenous)

The firm's optimization problem is to choose g^* and α^* to maximize profit $\Pi = pf(g,\alpha,G) - C(g,\alpha)$, where $C(g,\alpha) = wg + r\alpha$. Firms choosing $g^* > 0$ and $\alpha^* \geq 0$ satisfy the first-order conditions:

$$\frac{\partial \Pi}{\partial g} = p\left[\frac{\partial f}{\partial g} + \frac{\partial f}{\partial G}\frac{\partial G}{\partial g}\right] - w = 0 \tag{7}$$

$$\frac{\partial \Pi}{\partial \alpha} = p\left[\frac{\partial f}{\partial \alpha} + \frac{\partial f}{\partial G}\frac{\partial G}{\partial \alpha}\right] - r \leq 0. \tag{8}$$

Equation (8) holds with equality for $\alpha^* > 0$. Farmers who select $\alpha^* = 0$ imply that the total marginal revenue product for α is less than r.

- *Competitive firms equate their marginal revenue product to factor price for each input.*

B. Producer Optimization (α exogenous)

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[6] This assumption can be motivated from an ecological viewpoint. Suppose a certain number of pests invade a farm with biotech-seeded land and refuges. As more pests become resistant, the productivity of an additional biotech seed decreases because the pests that land on it are more likely to resist its biological defenses. The productivity of an additional refuge area, however, is unlikely to decrease with resistance, because resistant pests have no advantage in the refuge. If anything, more pests might spillover from the refuges when resistance increases, because the resistant pests do not compete with the vulnerable pests on the rest of the farm.

Now consider firms that face a floor for α. Although they could opt for a higher α^*, continue to assume that at least locally the marginal profit of α is nonpositive. The firm's choice essentially becomes over g with α as a parameter. The profit function can be rewritten as:

$$\Pi = pf(g, G; \alpha) - wg - r\alpha .$$

The first-order condition, in choosing g^c where $\alpha = \alpha^c$, is:

$$\frac{\partial \Pi}{\partial g} = p\left[\frac{\partial f}{\partial g} + \frac{\partial f}{\partial G}\frac{\partial G}{\partial g}\right] - w \le 0 , \qquad (9)$$

with equality for $g^c > 0$. The firm continues to choose g^c such that its marginal revenue product equals its price, given that α^c is unprofitably high.[7]

- *When one input is fixed, firms still producing equate marginal revenue product to factor price for the other input.*

C. Comparative Statics for the Firm

Before proceeding, recall the functional assumptions made to this point. Production is concave in inputs g and α. The input G is detrimental to production, and G is a function of g and α. G rises increasingly in g and falls decreasingly in α. The second-order conditions for maximizing a profit function where α is endogenously determined are:

$$\frac{\partial^2 \Pi}{\partial g^2} =< 0 , \ \frac{\partial^2 \Pi}{\partial \alpha^2} < 0 , \text{ and}$$

$$\frac{\partial^2 \Pi}{\partial g^2}\frac{\partial^2 \Pi}{\partial \alpha^2} - \left(\frac{\partial^2 \Pi}{\partial g \partial \alpha}\right)^2 > 0 , \text{ where}$$

$$\frac{\partial^2 \Pi}{\partial g \partial \alpha} = p\left[\frac{\partial^2 f}{\partial g \partial \alpha} + \frac{\partial^2 f}{\partial g \partial G}\frac{\partial G}{\partial \alpha} + \frac{\partial^2 f}{\partial \alpha \partial G}\frac{\partial G}{\partial g} + \frac{\partial^2 f}{\partial G^2}\frac{\partial G}{\partial \alpha}\frac{\partial G}{\partial g} + \frac{\partial f}{\partial G}\frac{\partial^2 G}{\partial g \partial \alpha}\right]. \qquad (10)$$

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[7] A comparable analysis could be made for α being set below the competitive value. $\alpha^c > \alpha^*$ is used here to highlight the difference from the competitive equilibrium where often $\alpha^* = 0$.

The first term in equation (10) could be positive or negative. The remaining terms are all positive. It seems likely that $\partial^2\Pi / \partial g \partial \alpha > 0$, and it is necessary true when $\partial^2 f / \partial g \partial \alpha \geq 0$.

Let $g^* = g^*(w, p, r, \tilde{g}, \tilde{\alpha})$ and $\alpha^* = \alpha^*(r, p, w, \tilde{g}, \tilde{\alpha})$ be factor demand functions fulfilling the first-order conditions in equations (7) and (8). The effects of price changes are:

$$\frac{\partial g^*}{\partial w} = \frac{\frac{\partial^2\Pi}{\partial g \partial \alpha}\frac{\partial^2\Pi}{\partial \alpha \partial w} - \frac{\partial^2\Pi}{\partial \alpha^2}\frac{\partial^2\Pi}{\partial g \partial w}}{\frac{\partial^2\Pi}{\partial g^2}\frac{\partial^2\Pi}{\partial \alpha^2} - \left(\frac{\partial^2\Pi}{\partial g \partial \alpha}\right)^2} = \frac{\frac{\partial^2\Pi}{\partial \alpha^2}}{\frac{\partial^2\Pi}{\partial g^2}\frac{\partial^2\Pi}{\partial \alpha^2} - \left(\frac{\partial^2\Pi}{\partial g \partial \alpha}\right)^2} < 0 \tag{11}$$

$$\frac{\partial \alpha^*}{\partial w} = \frac{\frac{\partial^2\Pi}{\partial g \partial \alpha}\frac{\partial^2\Pi}{\partial g \partial w} - \frac{\partial^2\Pi}{\partial g^2}\frac{\partial^2\Pi}{\partial \alpha \partial w}}{\frac{\partial^2\Pi}{\partial g^2}\frac{\partial^2\Pi}{\partial \alpha^2} - \left(\frac{\partial^2\Pi}{\partial g \partial \alpha}\right)^2} = \frac{-\frac{\partial^2\Pi}{\partial g \partial \alpha}}{\frac{\partial^2\Pi}{\partial g^2}\frac{\partial^2\Pi}{\partial \alpha^2} - \left(\frac{\partial^2\Pi}{\partial g \partial \alpha}\right)^2} \tag{12}$$

By the negative definiteness of the profit function, the denominators are positive and the numerators determine the sign of each price change. The own-price effects are necessarily negative. When inputs are complements and $\partial^2\Pi / \partial g \partial \alpha > 0$, the cross-price effects are negative.

The effects of price changes for the case where α is exogenous can be found more easily. The concavity of the profit function in g determines the responsiveness of the firm to changes in w. The effect of α on the choice of g^* can be found as:

$$\frac{\partial g^*}{\partial \alpha} = -\frac{\frac{\partial^2\Pi}{\partial g \partial \alpha}}{\frac{\partial^2\Pi}{\partial g^2}}. \tag{13}$$

The sign of $\partial g^*/\partial \alpha$ depends on the complementarity of inputs. When α negatively affects the total marginal product of g, the firm will decrease its use of g when α is raised. Factor demand for g also depends on parameters $\tilde{g}$ and $\tilde{\alpha}$. In a fashion similar to equation (13), the sign of $\partial g^* / \partial \tilde{\alpha}$ is determined by:

$$\frac{\partial^2 \Pi}{\partial g \partial \tilde{\alpha}} = p\left[\frac{\partial^2 f}{\partial g \partial G}\frac{\partial G}{\partial \tilde{\alpha}} + \frac{\partial^2 f}{\partial G^2}\frac{\partial G}{\partial \tilde{\alpha}}\frac{\partial G}{\partial g} + \frac{\partial f}{\partial G}\frac{\partial^2 G}{\partial g \partial \tilde{\alpha}}\right] > 0 \qquad (14)$$

As expected, equation (14) shows g and $\tilde{\alpha}$ are complements, regardless of whether g and α are complements. An approach similar to equation (2) shows that g and $\tilde{g}$ are substitutes.

- *When* g *and* α *are complementary inputs, raising the floor on* α *leads to higher seed use. Others' use of care complements seed use, and their use of seeds is a substitute.*

D. Externality

The model presents externalities in the use of both *g and* α. With superscripts identifying the source of the externality, the marginal damages caused by a representative firm are:

$$MD^g = p\sum \frac{\partial f}{\partial G}\frac{\partial G}{\partial g} < 0$$

$$MD^\alpha = p\sum \frac{\partial f}{\partial G}\frac{\partial G}{\partial \alpha} > 0,$$

where summations range over all other firms. The MD^g term, as before in equation (4), reflects the damage caused by the choice of g. The MD^α term reflects the benefit to other firms caused by the choice of α. A two-part Pigouvian tax corrects this externality. One part taxes g according to MD^g and another subsidizes α based on MD^α. Marginal damages of g and α are proportional to $\partial G/\partial g$ and $\partial G/\partial \alpha$, respectively. Conditions characterizing optimal use of g and α (denoted g^o and α^o) for the representative firm are:

$$p\left[\frac{\partial f}{\partial g} + \frac{\partial f}{\partial G}\frac{\partial G}{\partial g}\right] = w - MD^g, \qquad (15)$$

$$p\left[\frac{\partial f}{\partial \alpha}+\frac{\partial f}{\partial G}\frac{\partial G}{\partial \alpha}\right]=r-MD^{\alpha}\,. \tag{16}$$

These conditions resemble the competitive equilibrium except for the inclusion of the *MD* terms. With these taxes, firms internalize their marginal damages. They effectively raise the price of *g* and lower the price of α. Comparing the optimal equilibrium to the competitive one requires tracing the effects of simultaneous price changes. The presence of externalities encourages firms to use too much *g* and too little α and create too much *G* when inputs are substitutes ($\partial^2\Pi / \partial g \partial \alpha < 0$). When they are complements, the difference between the optimum and competitive equilibria depends on magnitude of marginal damages and price elasticities.

- *The marginal damage, or Pigou tax, is the sum of marginal losses to other firms' revenue.*

E. Supply of *g*

Consider an upstream factor supply market for biotech seeds. Let the total market supply of biotech seeds be $\sum g$. Furthermore, assume that $w_i^*\left(g, p, r, \tilde{g}, \tilde{\alpha}\right)$ is the inverse factor demand for the *i*th firm. From equation (11), the factor demand curves for *g* slope downward. Suppose that a representative supplier in the factor market for *g* has the cost function *C*=*C*(*g*) and marginal costs equal to *MC* = *MC*(*g*), which are nondecreasing in *g*. The representative supplier chooses *g* to maximize $\Pi = wg - C(g)$. For a competitive, price-taking supplier of $g > 0$, given factor price w^*, the first-order condition is:

$$w^* = MC(g)\,.$$

The market price is determined by the intersection of the supplier's *MC* and the inverse aggregate factor demand w^*.

Suppose instead that a monopoly supplies the seed market. It provides a quantity g_i to each firm for price w_i to maximize $\prod_M = \sum wg - C(\sum g)$. In the case where $g_i > 0$, the *i*th first-order conditions is:

$$w_i^*(g,\tilde{g},\tilde{\alpha}) + \sum_j g_j \frac{\partial w_j^*(g,\tilde{g},\tilde{\alpha})}{\partial g_i} = MC(g).$$

This condition for monopoly pricing parallels that of equation (6). The monopoly prices *g* to extract the most rent possible from the resource. From equation (2), the effect of *g* on the marginal revenue from sales to all firms is negative, so the monopoly raises *w* over its marginal cost. Equations (11) and (12) show the effects of increasing *w* on g^* and α^*. Monopoly mark-up of *w* causes g^* to decrease. For complementary inputs, the monopoly equilibrium exhibits less α than the competitive equilibrium. For substitutes, α will increase, and *G* will unambiguously decrease.

How this compares to the optimal outcome, however, depends on comparing equations (15) and (16) where $w = MC(g)$ with equations (7) and (8) where *w* includes the monopoly mark-up. Whether the monopoly mark-up inflates α and the effective price of *g* more than the Pigouvian taxes do will determine how g^* and α^* compare to g^o to α^o. As noted earlier, this depends on whether on the margins *g* causes more damage to firms than it elicits in substitution away from *g*. The crux of the difference between the monopoly and competition, to put it another way, is the difference between the externality's effect on others' output and its effect on others' marginal productivity. If the former effect is larger, the marginal damage will be larger. If resistance predominantly makes seeds less productive then the monopoly markup will be larger.

- *A monopoly raises* w *based on each firm's impact on others' marginal productivity, not their damage to others' output.*

F. Monopoly Contracting over α

The monopoly might be able to extract more rent by requiring each firm to use α at a certain level, α_i^c. For a fixed α_i^c, the firm's factor demand function for g is $g_i^c\left(p, w, r, \alpha_i^c, \tilde{g}, \tilde{\alpha}\right)$ implicitly defined by equation (9). Using the inverse factor demand function for g_i^c, $w_i^c(g_i, \alpha_i^c, \cdot\,)$, the monopoly maximizes profits $\prod_M = \sum(w^c g) - C(\sum g)$ by choosing g and α^c for each firm. The first-order conditions arise for the ith firm in the g market:

$$w_i^c\left(g_i, \alpha_i^c, \cdot\right) + \sum_j g_j \frac{\partial w_j^c\left(g_i, \alpha_i^c, \cdot\right)}{\partial g_i} = MC(g)$$

$$\sum_j g_j \frac{\partial w_j^c\left(g_i, \alpha_i^c, \cdot\right)}{\partial \alpha_i} \leq 0,$$

with equality when $\alpha^c > 0$. The first condition represents the $MR = MC$ condition for the monopoly, where each firm's w is inflated over MC by the amount of g_i's effect on the marginal revenue from all firms. The second condition, $MR = MC$ for α, shows how the monopoly will raise α until doing so no longer increases its (net) revenues from sales of g to *all* firms. Raising α_i^c alters that firm's demand for g according to equation (13). Raising α_i^c increases demand for g by other firms because g and $\tilde{\alpha}$ are always complements. As α_i^c climbs higher, firms' will approach their shut-down point and some may exit, until the necessary condition that the net MR of raising α_i^c be zero is satisfied. More g and more α lead to ambiguous effects on G. Resistance under monopoly could be above or below the optimum.

Finally, briefly consider the case where the monopoly is unable to discriminate between its consumers. Assume $w^*\left(\sum g, p, r, \tilde{\alpha}\right)$ is the inverse aggregate factor demand. If it can only charge a single $w = w^*$ for all users, then its first-order conditions become the following.

(a) Where α is competitively determined and $\prod_M = w^*\sum g - C(\sum g)$, we have:

$$w^*\left(\sum g\right)+\frac{\partial w^*\left(\sum g\right)}{\partial g}\sum g = MC(g)\,.$$

(b) Where the monopoly sets one $\alpha = \alpha^c$ for all firms and $\prod_M = w^*(\alpha^c, \cdot)\sum g - C(\sum g)$, we have:

$$w^c\left(\sum g, \alpha^c, \cdot\right)+\frac{\partial w^c\left(\sum g, \alpha^c, \cdot\right)}{\partial g}\sum g = MC(g)$$

$$\frac{\partial w^c\left(\sum g, \alpha^c, \cdot\right)}{\partial \alpha}\sum g = 0\,.$$

- *Contracting over care allows the monopoly to shift out the demand for seeds, extract more rents from firms, and increase seed use* and *care.*

G. Efficiency

Consider the effects on efficiency in the factor market of removing Pigouvian taxes, providing g via a monopoly, and then having that monopoly contract over α. Let superscripts {o, $*$, M, c} represent the optimal, competitive, simple monopoly, and monopoly-contracting-over-α cases, respectively. Removing the Pigouvian taxes where $\partial^2\Pi / \partial g \partial \alpha > 0$ leads to increased g and decreased α by all firms: $g^* > g^o$ and $\alpha^* \le \alpha^o$. Therefore, $G^* > G^o$. Where $\partial^2\Pi / \partial g \partial \alpha < 0$, on the other hand, the total changes in g and α depend on their substitutability and the magnitudes of MD^g and MD^α.

The case of $\partial^2\Pi / \partial g \partial \alpha > 0$ has important efficiency implications for monopoly factor supply. The monopoly exerts its power, and seed use and care will decline ($w^M > w^*$, $g^M < g^*$, $\alpha^M < \alpha^*$). The effect of monopoly on G is ambiguous. If $\alpha^* = \alpha^M = 0$, then $G^M < G^*$. Though the externality encourages overuse of g and monopoly pricing reduces this, it is possible that the monopoly over-corrects for the externality. Also, the monopoly captures more of the resource rents at the expense of the firms. If possible, the monopoly might require increased abatement in order to boost sales of g. This leads to $\alpha^c > \alpha^M$, $g^c > g^M$, and $w^c > w^M$.

Figure 2 illustrates one possible series of these changes for the factor market. Following the same approach as in Figure 1, let w^o, w^*, and w^c be the inverse factor demands for g under Pigouvian taxes, under no taxes, and under a $\alpha^c > \alpha^M$ set by the monopoly. Marginal revenue curves are given for the two monopoly cases (MR^M and MR^c). If the effect of the Pigouvian taxes is to move the demand for g down to w^o, the market will clear at $g^o < g^*$. Instead, if the monopoly controls g, the use of g will decline, possibly to a point below g^o as shown in Figure 2. The monopoly gains considerable rents, while the firms lose surplus. Moreover, a monopoly that achieves g^o will still not be optimal if α remains sub-optimal. When demand for g and $\tilde{\alpha}$ are positively related, the monopoly that raises α^c shifts the demand for g outwards, and increases output (and w and profits). The increase in g might move the equilibrium closer to g^o, though this outcome is not necessary. The possibility of raising α leaves the monopoly with still more profits, possibly at the expense of firms.

[insert Figure2 here]

This model provides a framework easily applied to genetic resistance resources. When a genetically engineered crop becomes available, farmers often implement it with $\alpha = 0$. If the externalities were corrected, the equilibrium would shift to $\alpha > 0$. Under monopoly provision of g, expect w to rise and g and G to fall. The amount of care remains bounded at zero. Whether resistance predominantly affects seeds' marginal productivity or yields should serve as a qualitative indicator of whether the monopoly mark-up exceeds the marginal damages. Allowing the monopoly to require a higher α should bring windfall gains to the monopoly, higher w and g, and possibly some exit from the industry. In some cases (especially those with large monopoly mark-ups and large "damages" from under-using α), efficiency gains can be made. This story should be subjected to empirical tests.

The downstream market for *q* may also figure prominently in welfare analysis, especially when the final product (e.g. cotton, corn) provides substantial consumer surplus. The effects of upstream market structure on the marginal costs for *q* are not investigated formally in this paper. Nonetheless, Figure 3 can illustrate the downstream implications of market structure. Suppose that correcting the externalities lowers the marginal costs of *q* from the competitive case; $MC^* > MC^o$. Suppose that monopoly pricing of *w* raises the marginal costs of *q*, despite any cost-savings of lower *G*. Finally, suppose that mandating a higher α leads to lower marginal costs as the input mix approaches the optimum.[8] Figure 3 depicts $MC^M > MC^* > MC^o$ and $MC^M > MC^c$. An arrow is included for MC^c, because although it is to the right of the MC^M curve, this case might not have lower marginal costs than the competitive one. If it does, then the welfare gains in the downstream market from having a monopoly contract over α are evident. As a policy matter, a monopoly contracting over α might be preferred to requiring the factor market to price at marginal cost. It is also worth noting that the downward sloping demand curve in Figure 3 has not been incorporated into the preceding analyses that fixed *p*. Such a demand curve would entice the monopoly to further restrict *g* and raise the price of *q*.

[insert Figure3 here.]

6. Household Production

A similar model, building off of Grossman's (1972) model of household production of health services, can be applied to the health care side of the genetic pool commons. The appeal of the preceding analysis is its applicability to a broad family of genetic resistance problems where

[8] Future research will investigate these conjectures. The monopoly seeking to maximize demand for *g* has incentives to expand the downstream market for *q* by their selection of α^c. Choosing α^c closer to the optimal might accomplish this by lowering *MC*.

production involves an impure public good and costly abatement options are available. Whereas in Grossman's model, the household produces healthy days using inputs such as medical services and healthy time, additional inputs are specified: g and G. Like earlier, g represents the use of antibiotics and G is a measure of antimicrobial resistance. Optimization of the household production would follow in a similar way as the firm's optimized their output of q. Market structure may similarly play an important role to the extent that a monopoly controls the supply of antibiotics to the household. This could be the case where a dominant pharmaceutical firm supplies the medicine protected by patents. Alternatively, a large-scale health maintenance organization (HMO) may possess sufficient market power to affect abatement behavior by dictating prescription guidelines to its physicians or requiring more diagnostic tests. An HMO may internalize the effects of the resistance spillover much like hospitals may be expected to do likewise. Further work is needed to fully elaborate this model.

7. Conclusion

Many aspects of a simple model of production externalities have been explored. The basic externalities model is applied to a stock of genetic resistance that is contributed to by users of a particular input, such as biotech seeds. The model also investigates the implication of another costly input, a form of abatement affecting the stock of resistance. Abatement behavior represents an important, and often overlooked, aspect of resistance management.[9] Other firms' abatement levels are complements in production to a firm's use of seeds, just as others' use of seeds makes each firm's own use of seeds less valuable. This relationship across firms can make higher levels of abatement consistent with greater factor demand for seeds, irrespective of abatement and seeds being substitutes within a firm. With prices not reflecting the social cost of seed use (or the social benefit of abatement), too much resistance can be expected in equilibrium.

[9] In different contexts, this abatement behavior can take many different forms like refuge areas, careful pesticide application, diagnostic screening for bacterial infections, "finishing off" a prescription, etc.

This paper extends this model to discuss monopoly ownership of the critical input (e.g. seeds). Despite essentially controlling access to the common pool resistance resource, a monopoly lacking perfect price discriminating ability will inefficiently steward the resource. A monopoly incapable of capturing all of the resource rents raises the seed price above its marginal cost of production. In doing so, seed use declines relative to the competitive equilibrium. If the optimal use of seeds is less than the competitive level, then monopoly pricing may shift the equilibrium closer to the optimal quantity of seeds. For a fixed level of abatement, the comparison between the optimal and the monopoly prices of seeds is straightforward. Comparing the monopoly markup to the Pigouvian tax involves comparing $\sum_j g_j \frac{\partial w_j^*(g,\tilde{g},\tilde{\alpha})}{\partial g_i}$ and $p\sum_{j\neq i}\frac{\partial f_j}{\partial G}\frac{\partial G}{\partial g_i}$. The monopoly markup depends on the price elasticity of factor demand for all firms with respect to a firm's use of seeds, whereas the Pigouvian tax depends on the firm's marginal damage to other firm's output. This result suggests that the efficiency gains to monopoly pricing depend in part on how the resistance spillover affects other firms' marginal productivity and their output. The monopoly deviates from optimal pricing as the resistance externality operates predominantly through the marginal productivity of seeds and not through output, or vice versa.

Incorporating abatement complicates matters, but also reflects an important feature of resistance externalities. Users of the resistance resource can undertake costly abatement, whereas the monopoly supplier typically cannot. Given the opportunity (including some enforcement mechanism), the monopoly will choose to require a level of abatement above the competitive level in order to spur demand for their revenue-generating product, the seeds. This higher level of abatement, however, depends only on the cost of enforcement and the complementarity of abatement and seed use – it does not necessarily relate to optimal resource use. The deadweight loss from the monopoly pricing of seeds may in fact be exacerbated when the firm can require inefficiently costly levels of abatement. If the monopoly markup exceeds the marginal damage caused by seed use, however, there remains the possibility that allowing the monopoly to contract over the level abatement can lead to welfare gains in the seed market. The different market structures examined here also have an effect on the downstream market (for corn or medical services), where considerable consumer surplus may be at stake.

This analysis applies readily to the behavior of a dominant biotechnology supplier to farms. This paper's results imply that monopoly suppliers may conserve resistance resources better than a competitive market, especially when the marginal resistance externality is large. In addition, this paper emphasizes abatement as an important aspect of resistance management. If the marginal resistance damage is small relative to the monopoly's mark-up, requiring more abatement may reduce the deadweight losses. Moreover, the monopoly has an interest, albeit limited, in supporting such a requirement. Monsanto, Inc., for example, regularly contracts over "refuge areas" in farms using their seeds, so as to mitigate the development of genetic resistance. In 2000, the EPA and Monsanto required all users of Bt corn seeds to plant 20% of their acreage with non-Bt corn in an attempt to provide refuges for non-resistant insects to dilute any genetic advantage resistance may confer. This model suggests how such a policy ($\alpha^c = 0.25g$) might be in the interests of Monsanto and also represent efficiency gains.

Several important elements have been neglected in the present treatment, most especially the dynamic nature of the problem. Future research may integrate the temporal nature of decision-making. Preliminary indications suggest that this static model sufficiently captures the important elements of the actors' choice of the use of seeds and abatement. Yet managing genetic resources requires more than merely optimally using the current stock. Changing technologies and improving the stock are crucial tasks. Historically, genetic resistance has often been more effectively addressed by inventing new inputs to keep one step ahead of advancing adaptation than by using existing inputs more efficiently. R&D into new technologies such as biotech crops and antibiotics yields welfare gains not considered here. One obvious connection between developing new technologies and managing them once they are implemented is monopolies. Monopoly control over new technologies may do more than allow for some regulation of externalities – it provides the rents that encourage R&D investment in the first place (Aledort and others 2000).

The model is ripe for extensions into other areas with genetic common-pool resources. This basic framework points to policies likely to remedy the overuse of certain resources. Changing incentives via property rights and regulation of abatement behavior hold some promise. Research in antibiotic use suggests that "better educated" producers and consumers are unlikely to provide much help (Gonzales and others 1999). Given the enormity and complexity of resistance externalities, first-best policy solutions do not appear feasible. Changes in institutional design (e.g. monopolizing certain inputs, producer-regulated abatement) may offer the best avenue for resource conservation. The next step is to find and assess empirical evidence in light of this framework.

This paper attempts to lay the groundwork for a rigorous economic treatment of one aspect of production in agriculture that is growing in salience. This appears due in part to genetic commons' immunity to technical solutions and conventional economic solutions (privatization, merger, or state control). Formal analysis of different management possibilities merits attention. This paper begins that process.

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