Royalties and Benefit Sharing Contracts in Bioprospecting*

Rodney B.W. Smith† and Pushpam Kumar‡

February 13, 2002

Abstract

This paper examines the research and development process in the pharmaceutical industry, and the choice of royalty scheme. Facing both cost and production risk, the pharmaceutical firm chooses its production plan and royalty scheme. We examine the effects of royalties on gross and net revenues and show that when faced with only one source of uncertainty the firm will always prefer a royalty on net revenues. However, when both types of uncertainty are present it is possible for the firm to be better off implementing a gross revenue scheme.

JEL Classifications: D81, Q16, Q20

*We are thankful for many helpful suggestions by Kanchan Chopra, Rolf Fare, and Jason Shogren. Pushpam Kumar acknowledges support of the World Bank Capacity Building Project, 2001. Rodney Smith acknowledges support of the Minnesota Agricultural Experiment Station and the Economic Research Service, USDA Cooperative Agreement # USDA/43-3AEL-0-80035.

†1994 Buford Avenue, Department of Applied Economics, University of Minnesota, St. Paul, MN 55108; rsmith@apec.umn.edu

‡Institute of Economic Growth, Environmental Economics Unit, University Enclave, Delhi 110007; pk@ieg.ernet.in.

Royalties and Benefit Sharing in Bioprospecting

Abstract

This paper examines the research and development process in the pharmaceutical industry, and the choice of royalty scheme. Facing both cost and production risk, the pharmaceutical firm chooses its production plan and royalty scheme. We examine the effects of royalties on gross and net revenues and show that when faced with only one source of uncertainty the firm will always prefer a royalty on net revenues. However, when both types of uncertainty are present it is possible for the firm to be better off implementing a gross revenue scheme.

Royalties and Benefit Sharing in Bioprospecting

1 Introduction

The extraction and assaying of organic compounds from plant and animal life has proven instrumental in deriving a number of precious drugs able to cure life threatening diseases. The process of creating biologically based drugs involves several steps and includes: biological extraction, screening, preclinical tests, and clinical trials. If the clinical trial phase is passed successfully, the pharmaceutical firm can then proceed to produce and market what it hopes will be a commercially viable drug. Probably, the most crucial step in the research and development (R&D) process is the first one, biological extraction. Without the plant and animal genetic material, the process of developing the biologically based drug is fraught with problems. The search for genetic material having the potential to create commercially viable drugs is known as *bioprospecting*.

Bioprospecting has enhanced human welfare by providing miraculous drugs that have proved effective in fighting diseases like malaria and HIV. In the past, numerous medicinal plants have yielded effective drugs like Quinine (malaria) from Cinchone, Rauwolfia (hypertension and schizophrenia) from Snakeroot, Vinblastine Vincritine (blood and lymph cancer) from Rosy Periwinkle, and Tubocurine (muscle relaxant) from Curane. While each of these drugs were invented in U.S. or European laboratories, the source of the genetic material underlying their discovery and creation had its origin in the tropics: the Amazon, the Sahara desert and South Asia.

While one finds different types of opinions about the success and commercial viability of bioprospecting, the pharmaceuticals' interest in the process continues (Nature,1998). Currently, more than twenty of the leading pharmaceutical firms in the world are actively involved in bioprospecting. With the initiation of the widely publicized relationship between the U.S. based firm, Merck Inc., and the Costa Rican non-governmental agency (NGO) INBio, the interest in bioprospecting intensified during the 1990s. In fact, since 1996, at least twelve of the 20 largest pharmaceuticals have implemented bioprospecting programs (Asebey,1996). The growing interest of pharmaceuticals in bioprospecting is not difficult to understand considering the current level of dependence that drug discovery has on plant life, micro-organisms and other biota from terrestrial and marine ecosystems. Of the $120 US billion in pharmaceutical sales during the early 1990s, around $43 billion has been attributed to plant-based drugs (de Souza Silva,1996). A single plant species can serve as a tremendous source of profit to a firm. For example, the U.S. based firm Eli Lilly reportedly

generated over $100 million in sales revenue from the drugs vincristine (as Oncovin) and vinblistine (as Velban) – both derived from the Madagascar periwinkle plant. The profit associated with these drugs has been estimated at $88 million (Farnsworth, 1988). Madagascar, the country from which the rosy periwinkle is derived, shared in none of the benefits of such sales. And herein lies the rub. As developing countries and NGOs become more informed about the potential commercial value of their, typically unique, genetic resources, a demand by these entities for a piece-of-the-pie has emerged.

In recent years discussions of bioprospecting tend to center around two issues: (i) the potential magnitude of the benefits of bioprospecting and (ii) the methods by which the pharmaceuticals and genetic resource owners (if any) will share such benefits. At least two reasons explain the interest in the value of genetic resource valuation. The pharmaceutical is interested in the valuation question for obvious reasons: such valuation estimates signal the viability or non-viability of bioprospecting. For biodiversity rich countries, the new directions in benefit sharing in bioprospecting arrangements lend promise to the possibility that their biological resources might serve as an alternative source of income. Environmentalists hope that if genetic resources are shown to have high potential value, the biodiversity rich countries will attempt to manage their genetic resources better – hence giving such countries an incentive to slow down the current rate of deforestation and biodiversity loss in the tropics. The process of valuing plants for pharmaceutical uses attempts to address this issue.

To examine the potential of bioprospecting as a deterrent to rampant deforestation and biodiversity destruction, a series of studies have attempted to place a value on plants and genetic resources with potential medicinal value. Some of the studies conducted in the 1980s and 1990s suggested a aggregate value of medicinal plants (see Principe, 1991; and Mendelsohn and Balick,1995). However, a recent study by Simpson et al. (1996) suggested otherwise. Simpson et al. estimated the value of species on the basis of incremental value-added to the probability of a successful drug discovery. Considering 250,000 species, the incremental value was estimated to be $9000. The Simpson study assumed the likelihood of finding a commercially viable drug was 1:83,333 and the revenue to cost ratio 1:5. The study concluded that a conservation strategy based on bioprospecting would not be viable. Contrary to the Simpson et al. paper, Rausser and Small (2000) argue that if the search in bioprospecting is supplemented with existing knowledge, the odds of finding a commercially viable product is much better than that used in Simpson et al., and concluded that the value of genetic resources for bioprospecting could be substantial and significant.

While the issue of the economic value of medicinal plants and genetic resources will continue

(Kumar, 2001), possibly the more significant aspect of the bioprospecting debate is that of how the benefits of such activities will be shared. With the growing sense of awareness of the financial benefits from bioprospecting, more and more of the biodiversity rich countries are insisting on a share of such benefits. Recent developments in the international law arena strengthen the case for benefit sharing: In a departure from earlier beliefs that genetic resource are the common heritage of the humanity, the United Nations Convention on Biodiversity now explicitly recognizes the sovereignty of nations and their local and indigenous people over the genetic resources within there borders (Article 15&8(j), CBD,1992). Another argument in favor of benefit sharing is that the greater the economic stake by the owner country, the greater the incentive to preserve and share the genetic resources with the prospecting firms. Of course this argument favors property right enforcement and has its roots in the works of Coase (1960). Prospecting firms are acquiescing to the demands for benefits sharing, but admit their reticence in doing so. The reason for their reticence is that the process of bringing a biologically based drug to market is rife with uncertainty concerning R&D and production costs, and subsequent drug market values. Such concerns are understandable, as ten to twenty years might elapse between the collection of genetic material and the marketing of a final product. In many cases the bioprospecting process has met with no results. For example, after 10 years of effort and $170 million, Shaman Pharmaceuticals abandoned their prospecting activities in Nigeria (Moran, 2000).

Presently, the most popular instruments for benefit sharing are royalty payments. Despite the emergence of royalties as the benefit sharing instrument of choice, literature directly addressing the economics of royalties in bioprospecting contracts is sparse. The same can be said for any formal analysis of contracts in bioprospecting. Using a decision theoretic model of the pharmaceutical R&D process, Artuso (1994) argues that a lack of information on the part of locals concerning their plant's chemical potential complicates the problem in designing an appropriate compensation scheme. Artuso (1996) examines the effect of uncertainty (on the part of sample collectors about receiving royalty payments) on prospecting efforts. He breaks the transfer from the firm to locals into two components – a guaranteed payment and a contingent payment (royalty). He concludes that the presence of contingent compensation rights would not only increase the host country's welfare, but would be necessary ingredient of any successful bioprospecting endeavor.

This paper develops a model that captures several of the more important aspects of the pharmaceutical R&D process. Factors that influence the net expected value of a bioprospecting project include: the types of extracts a genetic sample produces; the likelihood of producing a marketable

product or patentable idea; the expected value of the product or idea; and the different problems, and corresponding costs, one might encounter in producing the product/idea. Thus both cost uncertainty and value uncertainty plague the bioprospecting process.

Some readers will observe that the model we present captures the essence of a wider set of R&D activities than pharmaceutical R&D. Likewise, the results on the choice of royalty instrument have applications to other problems, e.g., using royalties to coordinate vertical and horizontal contracting activities. However, the motivation for this paper evolved out of an interest in formalizing the bioprospecting process, and hence, we use the bioprospecting story as the backdrop for our discussion. Given both production and cost risk, this paper examines the pharmaceuticals' choice of production/R&D plan and royalty scheme. Section 2 formalizes the notion of a stochastic R&D technology, while sections 3 and 4 focus on the problem of choosing the best production plan. Then section 5 lays out the conditions under which a royalty on gross revenue is preferable to a royalty on net revenues. We show that when faced with only one source of uncertainty the firm will always prefer a royalty on net revenues. However, when both types of uncertainty are present the gross revenue scheme could be optimal.

2 State-Contingent Technology

In what follows we borrow from the state-contingent analysis discussed at length in Chambers and Quiggin (2000). The pharmaceutical firm (or 'firm') wants to design the terms of a contract to offer locals for harvesting biogenetic samples. At the contract design stage, however, actual research and development (R&D) costs are unknown to the firm. Assuming the locals accept the contract, they engage in bioprospecting activities and search for the biogenetic material requested by the firm. The firm chooses its R&D facility and stochastic production (contingency) plan. Finally, nature resolves the cost and production uncertainty and production takes place. The desired output of the R&D process is a set of "success rates" for potential patents/ideas. We discuss this notion in more detail shortly. To summarize the sequence of events we have:

- The pharmaceutical offers contract to locals
- Locals accept or reject the contract
- The firm chooses its R&D facility and contingency plan
- Nature resolves the cost and production uncertainty

- Products/patents sold.

The firm begins by choosing the R&D facility and contingency plan, and the appropriate royalty scheme. The R&D facility is represented by the input vector $\mathbf{x} = (x_1, ..., x_N) \in \mathbb{R}^N_+$. One can think of $\mathbf{x}$ as the vector of labor, equipment, and genetic material used in the R&D process. The firm chooses $\mathbf{x}$ knowing that subsequent costs and production are both random. For instance, the firm might have to go through the screening stage several times before moving to the pre-clinical trial stage. Such an activity might involve extra labor costs and equipment replacement expenses. Each distinct screening, pre-clinical trial pattern can represent a different cost-state. The firm's beliefs concerning the set of possible cost-states is denoted $\Omega^S = \{1, 2, ..., S\}$, with typical element $s \in \Omega^S$.

From samples collected by locals, the firm is interested in developing products with possible medicinal properties, e.g., products having antifungal, antibacterial, antiviral, anti-AIDS, anti-inflammatory characteristics. Denote the set of possible medicinal properties by $\mathcal{M} = \{1, ..., M\}$, with typical element m. An output for the firm is denoted $z^s_m \in [0, 1)$, and is interpreted as the likelihood that a product, or marketable patent, with medicinal property $m \in \mathcal{M}$ is developed, given cost-state s. For simplicity we assume the firm expects to produce only one product for each medicinal property.[1] For cost-state s, the vector of likelihoods is denoted $\mathbf{z}^s = (z^s_1, ..., z^s_M) \in \mathbb{R}^M_+$ and the matrix of state-contingent outputs is represented by $\mathbf{z}^s = \left(\mathbf{z}^1, ..., \mathbf{z}^M\right) \in \mathbb{R}^{M \times S}_+$. With this interpretation, given cost-state s, $\mathbf{z}^s$ is the vector of expected success rates in developing products associated with the set of medicinal properties $\mathcal{M}$.

We refer to the matrix $\mathbf{z} = \left(\mathbf{z}^1, ..., \mathbf{z}^S\right) \in \mathbb{R}^{M \times S}_+$ as the firm's *state-contingent output plan*, or *contingency plan*. The firm's state-contingent technology is represented by the input correspondence

$$X : \mathbb{R}^{M \times S}_+ \to X(\mathbf{z}) \subseteqq \mathbb{R}^N_+,$$

where

$$X(\mathbf{z}) = \left\{ \mathbf{x} \in \mathbb{R}^N_+ : \mathbf{x} \in \mathbb{R}^N_+ \text{ can produce } \mathbf{z} \in \mathbb{R}^{M \times S}_+ \right\}.$$

Here, the technology X maps a contingency plan $\mathbf{z}$ into the set of inputs capable of implementing it. To illustrate the idea behind $X(\mathbf{z})$, assume there are two cost states $s = 1, 2$. Assume further that the firm knows with certainty that cost-state 1 will occur and decides the likelihood vector $\mathbf{z}^{1*}$ is optimal. Likewise, assume the firm knows with certainty that production state-2 will occur

[1] Note that in principle several products could be developed having medicinal property m. In such a case, we simply assume that the sum of likelihoods for these products is strictly less than 1. Likewise, it is possible that one product could have more than one medicinal property.

and decides the likelihood vector $\mathbf{z}^{2*}$ is optimal. Then correspondence X gives all the input vectors capable of producing $\left(\mathbf{z}^{1*}, \mathbf{z}^{2*}\right)$. We will refer to the pair $(\mathbf{x}, \mathbf{z})$ as a state-contingent technology.[2]

Properties of the input set, $X(\mathbf{z})$

X.1 $X(0_{M\times S}) = \mathbb{R}^N_+, \mathbf{0}_N \notin X(\mathbf{z})$ for $\mathbf{z} \geq \mathbf{0}_{M\times S}$ and $\mathbf{z} \neq \mathbf{0}_{M\times S}$;[3]

X.2 $\mathbf{z}' \leq \mathbf{z} \Rightarrow X(\mathbf{z}) \subseteq X(\mathbf{z}')$;

X.3 $\mathbf{x}' \geq \mathbf{x} \in X(\mathbf{z}) \Rightarrow \mathbf{x}' \in X(\mathbf{z})$;

X.4 $\lambda X(\mathbf{z}) + (1-\lambda)X(\mathbf{z}') \subseteq X(\lambda\mathbf{x} + (1-\lambda)\mathbf{x}')$ for $\lambda \in [0,1]$ and all $\mathbf{z}, \mathbf{z}' \in \mathbb{R}^{M\times S}_+$ (convexity of X);

X.5 $X(\mathbf{x})$ is closed for all $\mathbf{z} \in \mathbb{R}^{M\times S}_+$.

The first part of *X.1* says that doing nothing is feasible and the second part says that strictly positive output requires a strictly positive level of at least one input. *X.2* says if an input bundle can produce a state-contingent output plan $\mathbf{z}$ it can always produce a smaller state-contingent output plan. *X.3* says inputs always have positive marginal productivities. *X.4* says that the state-contingent technology is convex, and leads to diminishing marginal productivity of inputs. *X.5* ensures the existence of the revenue-cost function that follows.

3 The Stochastic Revenue-Cost Function

Later it proves convenient to divide inputs into two categories, genetic and non-genetic. We then write the input vector as $\mathbf{x} = (\mathbf{x}_g, \mathbf{x}_h)$ where $\mathbf{x}_g = (x_1, ..., x_G) \in \mathbb{R}^G_+$ is the vector of genetic inputs and $\mathbf{x}_h = (x_{G+1}, ..., x_N) \in \mathbb{R}^{N-G}_+$ is the vector of other inputs. If state s occurs, the firm faces the input price vector $\mathbf{w}^s = (\mathbf{w}_g, \mathbf{w}^s_h)$ where $\mathbf{w}_g = (w_1, ...w_G) \in \mathbb{R}^G_{++}$ is a vector of deterministic unit prices for the genetic material and $\mathbf{w}^s_h = \left(w^s_{G+1}, ..., w^s_N\right)$ is the vector of state-contingent non-genetic input prices. The market for non-genetic inputs is competitive and the firm takes state-contingent input prices as given.

To simplify characterization of the firm/NGO equilibrium and focus attention on the royalty issue, assume the firm wants at least $\bar{x}_g$ of each genetic input. Furthermore, assume any levels of genetic input $x_g \geq \bar{x}_g$ add nothing to the marginal product of R&D activities. The vector $\mathbf{w}_g$

[2] The model we present is a bit different than the standard version in Chambers and Quiggin (2000), in that the pharmaceutical faces state-contingent ex post costs, but no variable ex ante costs. Also in the next section we introduce fixed costs (the genetic inputs), whereas the standard Chambers and Quiggin model does not consider fixed costs.

[3] $\mathbf{0}_N$ is a vector of zeros and $\mathbf{0}_{M\times S}$ is a matrix of zeros.

is fixed by the firm (or a market exists for the products in $\mathbf{x}_g$) and is chosen to ensure locals are willing to deliver at least $\bar{\mathbf{x}}_g = (\bar{x}_1, ..., \bar{x}_G)$ units of the genetic materials. More will be said about $\mathbf{w}_g$ later. Formally, the inputs $\mathbf{x}_g$ are essential inputs, where

X.1E $X(0_{M\times S}) = \mathbb{R}^N_+, (\mathbf{0}_G, \mathbf{x}_h) \notin X(\mathbf{z})$ for $\mathbf{z} \geq \mathbf{0}_{M\times S}$, $\mathbf{x}_h \geq \mathbf{0}_{N-G}$, and $\mathbf{z} \neq \mathbf{0}_{M\times S}$.

The value of the patent or product addressing medicinal property m depends on future market conditions and, *ex ante*, is assumed stochastic. Index future market conditions by $t \in \Omega^T = \{1, 2, ..., T\}$, and represent the value of the patent/product m given future market condition (price-state) t by $p^t_m \in \mathbb{R}_{++}$. Given cost-state s, the firm is concerned with the state-contingent revenue vector

$$\mathbf{r}^s = \mathbf{z}^s\mathbf{p} = \begin{bmatrix} r^{s1} = \sum_{m=1}^M p^1_m z^s_m \\ r^{s2} = \sum_{m=1}^M p^2_m z^s_m \\ \vdots \\ r^{sT} = \sum_{m=1}^M p^T_m z^s_m \end{bmatrix} \in \mathbb{R}^T_+,$$

where $\mathbf{p} = \left(\mathbf{p}^1, , , .\mathbf{p}^T\right) \in \mathbb{R}^{M\times T}_{++}$ is the matrix of state-contingent expected values for ideas $m = 1, ..., M$, with $\mathbf{p}^t = \left(p^t_1, ..., p^t_M\right)$. The variable r^{st} is the expected revenue generated when cost-state s and price-state t occurs.

Given input price vector $\mathbf{w}^s$ and essential genetic vector $\bar{\mathbf{x}}_g$, the minimum cost of producing the contingency plan $\mathbf{z}$ is represented by the stochastic cost function

$$\begin{aligned} c\left(\mathbf{w}^s, \mathbf{z}, \bar{\mathbf{x}}_g\right) &= \min_{\mathbf{x}_h} \left\{\mathbf{w}^s_h \cdot \mathbf{x}_h + \mathbf{w}_g \cdot \bar{\mathbf{x}}_g : (\mathbf{x}_h, \bar{\mathbf{x}}_g) \in X(\mathbf{z})\right\} \\ &= \bar{C}_g + \min_{\mathbf{x}_h} \left\{\mathbf{w}^s_h \cdot \mathbf{x}_h : (\mathbf{x}_h, \bar{\mathbf{x}}_g) \in X(\mathbf{z})\right\}, \end{aligned}$$

where $\bar{C}_g = \mathbf{w}_g \cdot \bar{\mathbf{x}}_g$ is the "fixed" cost of the genetic material. The stochastic revenue-cost function is defined as

$$\begin{aligned} c\left(\mathbf{w}^s, \mathbf{r}, \mathbf{p}, \bar{\mathbf{x}}_g\right) &= \min_{\mathbf{x}_h, \mathbf{z}} \left\{\mathbf{w}^s_h \cdot \mathbf{x}_h + \bar{C}_g : (\mathbf{x}_h, \bar{\mathbf{x}}_g) \in X(\mathbf{z}), r^{st} \leq \sum_{m=1}^M p^t_m z^s_m, \quad t \in \Omega^T, s \in \Omega^S\right\} \\ &\quad \min_{\mathbf{z}} \left\{c\left(\mathbf{w}^s, \mathbf{z}, \bar{\mathbf{x}}_g\right) : r^{st} \leq \sum_{m=1}^M p^t_m z^s_m, \quad t \in \Omega^T, s \in \Omega^S\right\}, \end{aligned}$$

if there exists a feasible input vector capable of producing the state contingent output $\mathbf{r}$, and ∞ otherwise. Here $\mathbf{r} = \left(\mathbf{r}^1, ..., \mathbf{r}^S\right) \in \mathbb{R}^{S\times T}_+$. For notational convenience, define $C(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \equiv c\left(\mathbf{w}^s, \mathbf{r}, \mathbf{p}, \bar{\mathbf{x}}_g\right)$. The basic properties of the revenue-cost function are detailed in Chambers and Quiggin, chapter 4.

4 Pharmaceutical and NGO/Local Preferences

Let $\pi = \left(\pi^1, ..., \pi^S\right) \in \Pi \subseteq \mathbb{R}^S_{++}$, represent the producers' beliefs concerning cost-states, where

$$\Pi = \left\{ \pi : \pi \in \mathbb{R}^S_{++} \text{ and } \sum_{s=1}^{S} \pi^s = 1 \right\},$$

and let $\theta = \left(\theta^1, ..., \theta^T\right) \in \Theta \subseteq \mathbb{R}^T_{++}$, represents the producers' beliefs concerning price-states, where

$$\Theta = \left\{ \theta : \theta \in \mathbb{R}^T_{++} \text{ and } \sum_{t=1}^{T} \theta^t = 1 \right\}.$$

Here Π is the set of all possible beliefs held by the firm regarding the potential costs and Θ is the set of all possible beliefs regarding possible price scenarios.

Define the vector of net returns given cost-state s by

$$\mathbf{y}^s = \mathbf{r}^s - \left(\mathbf{w}^s \cdot \mathbf{x}\right) \mathbf{1}_T$$

where $\mathbf{1}_T$ is the T-dimensional unit vector.[4] Preferences will be represented by a continuous and increasing function $W : \mathbb{R}^{S \times T} \to \mathbb{R}$, of the state-contingent net returns $\mathbf{y} = \left(\mathbf{y}^1, ..., \mathbf{y}^S\right) \in \mathbb{R}^{S \times T}$. Producer preferences, then can be expressed in terms of the revenue-cost function

$$\mathbf{y}^s = \mathbf{r}^s - C\left(\mathbf{w}^s, \mathbf{r}, \mathbf{p}\right) \mathbf{1}_T.$$

Assume that locals share the same beliefs (π, θ) as the firm and are risk neutral with respect to those beliefs. Let $e\left(\cdot\right) > 0$ denote the deterministic effort-cost to locals of harvesting the vector of genetic material $\mathbf{x}_g$. The effort-cost function satisfies $e', e'' > 0$. With no royalties, the per-unit compensation to the NGO for the harvested material is the deterministic price vector $\mathbf{w}_g$. Then net profit to the locals is given by

$$\mathbf{w}_g \cdot \mathbf{x}_g - e\left(\mathbf{x}_g\right).$$

The firm chooses the price vector $\mathbf{w}_g$ to ensure the NGO collects the vector of genetic inputs $\bar{\mathbf{x}}_g$. This is ensured if, for each genetic input $g = 1, ..., G$, the following necessary condition is satisfied

$$w_g = \frac{\partial}{\partial g} e\left(\mathbf{x}_g\right)\Big|_{\mathbf{x}_g = \bar{\mathbf{x}}_g}.$$

[4] This would be written as

$$\mathbf{y}^s = \begin{bmatrix} y^{s1} \\ y^{s2} \\ \vdots \\ y^{sT} \end{bmatrix} = \begin{bmatrix} r^{s1} \\ r^{s2} \\ \vdots \\ r^{sT} \end{bmatrix} - \left(\mathbf{w}^s \cdot \mathbf{x}\right) \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} = \mathbf{r}^s - \left(\mathbf{w}^s \cdot \mathbf{x}\right) \mathbf{1}_T.$$

5 The No Royalty Case

We first examine the benchmark case wherein the firm does not pay royalties. Such a case would be consistent with situations where the firm simply pays the NGO a per-unit, or flat, fee for the genetic materials gathered.

5.1 Risk-neutral Production Equilibria

Say a risk-neutral producer's beliefs are given by the vectors π and θ. Then the producer maximizes expected utility

$$W(\mathbf{y}) = \sum_{t=1}^{T}\sum_{s=1}^{S} \theta^t \pi^s \left[r^{st} - C\left(\mathbf{w}^s, \mathbf{r}, \mathbf{p}\right)\right].$$

The first order condition on $\mathbf{r}$ can be written by the complementary slackness conditions: for all $(s,t) \in \Omega^S \times \Omega^T$,

$$\frac{\partial W}{\partial r^{st}}(\mathbf{y}) = \theta^t \pi^s - \sum_{j=1}^{T}\sum_{k=1}^{S} \theta^j \pi^k C_{r^{st}}\left(\mathbf{w}^k, \mathbf{r}, \mathbf{p}\right) = \theta^t \pi^s - \sum_{k=1}^{S} \pi^k C_{r^{st}}\left(\mathbf{w}^k, \mathbf{r}, \mathbf{p}\right) \leq \mathbf{0}, \quad r^{st} \geq 0$$

where $C_{r^{st}}(\cdot) = \frac{\partial C(\mathbf{w}^s, \mathbf{r}, \mathbf{p})}{\partial r^{st}}$. The expected marginal cost of increasing revenue in state (s,t) is at least as large as subjective probability of that state. Graphically, equilibrium is where a hyperplane is just tangent to producers isocost curve. The slope of the hyperplane is given by ratio of subjective probabilities. Hence, the isocost curve is determined by the equilibrium level of revenue-cost. Here, instead of determining directly, the optimal mix of outputs – as in the typical non-stochastic case – the producer determines the optimal mix of state-contingent revenues.

Summing the first order conditions over production-states gives the *arbitrage condition*

$$\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{S} \pi^k C_{r^{st}}\left(\mathbf{w}^k, \mathbf{r}, \mathbf{p}\right) \geq \sum_{t=1}^{T}\sum_{s=1}^{S} \theta^t \pi^s = 1. \tag{1}$$

Here, $\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{S} \pi^k C_{r^{st}}(\cdot)$ is the expected marginal cost of increasing all state-contingent revenues by the same small amount in each production-state – the marginal cost of a sure increase in revenue of one unit. If $\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{S} \pi^k C_{r^{st}}(\cdot) < 1$, then the producer could increase profit with probability 1 by increasing or decreasing all revenues equally. A state-contingent revenue matrix is potentially optimal for some producer only if the arbitrage condition holds.

Call the set of revenue vectors satisfying (1) the *efficient set.* Denote the efficient set by $\Xi(\mathbf{w}, \mathbf{p})$, where $\mathbf{w} = \left(\mathbf{w}^1, ..., \mathbf{w}^S\right)$ and

$$\Xi(\mathbf{w}, \mathbf{p}) = \left\{ \mathbf{r} : \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{k=1}^{S} \pi^k C_{r^{st}}\left(\mathbf{w}^k, \mathbf{r}, \mathbf{p}\right) \geq 1 \right\}.$$

The boundary of $\Xi(\mathbf{w}, \mathbf{p})$ is called the *efficient frontier* and is represented by

$$\Xi_o\left(\mathbf{w}^1, ..., \mathbf{w}^S, \mathbf{p}\right) = \left\{ \mathbf{r} : \sum_{t=1}^{T} \sum_{s=1}^{S} \sum_{k=1}^{S} \pi^k C_{r^{st}}\left(\mathbf{w}^k, \mathbf{r}, \mathbf{p}\right) = 1 \right\}.$$

The efficient set is the collection of state-contingent revenues that are potentially expected-profit maximizing.

5.2 Risk-averse / Schur-concave Production Equilibria

The producer is *risk-averse with respect to the subjective beliefs* (π, θ) if

$$W(\bar{y}\mathbf{1}_{S\times T}) \geq W(\mathbf{y}), \quad \forall\ \mathbf{y},$$

where $\bar{y}\mathbf{1}_{S\times T}$ is the state-contingent output vector with $\bar{y} = \sum_{t=1}^{T}\sum_{s=1}^{S} \theta^t \pi^s y^{st}$ occurring in every state of nature. Let $\preceq_{\boldsymbol{\pi\theta}}$ denote a partial preference ordering of risky outcomes having a common mean and defined over the vector of beliefs (π, θ). This partial ordering is defined by

$$\mathbf{y} \preceq_{\boldsymbol{\pi\theta}} \mathbf{y}'.$$

and is read: $\mathbf{y}$ and $\mathbf{y}'$ have the same mean and $\mathbf{y}$ is less risky than $\mathbf{y}'$ (in a Rothschild-Stiglitz way). Here, the partial ordering is interpreted as saying $\mathbf{y}$ is "better than" $\mathbf{y}'$.

The function $W : \mathbb{R}^{S\times T} \to \mathbb{R}$ is *generalized Schur-concave* for (π, θ) if $\mathbf{y} \preceq_{\pi\theta} \mathbf{y}' \Longrightarrow W(\mathbf{y}) \geq W(\mathbf{y}')$. Schur–concavity doesn't impose additive separability across states, and hence does not rely on any independence axioms. The mean-variance model is a special case of Schur–concavity.

The producer with generalized Schur-concave preferences chooses state-contingent revenues to maximize

$$W(\mathbf{y}) = W\left(\mathbf{r}^1 - C\left(\mathbf{w}^1, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T, \mathbf{r}^2 - C\left(\mathbf{w}^2, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T, ..., \mathbf{r}^S - C\left(\mathbf{w}^S, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T\right).$$

Assuming preferences are smoothly differentiable in state-contingent revenues, the first order conditions on r^{st} are

$$W_{y^{st}}(\mathbf{y}) - \sum_{s=1}^{S} C_{r^{st}}(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \sum_{k=1}^{T} W_{y^{sk}}(\mathbf{y}) \leq 0, \quad r^{st} \geq 0, \quad \forall\ (s,t) \in \Omega^S \times \Omega^T, \tag{2}$$

with complementary slackness.

The arbitrage condition is derived by summing these first order conditions over t to get

$$\sum_{t=1}^{T}\sum_{s=1}^{S} W_{y^{st}}(\mathbf{y}) \leq \sum_{t=1}^{T}\sum_{s=1}^{S}\left[\sum_{s=1}^{S} C_{r^{st}}(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \sum_{k=1}^{T} W_{y^{sk}}(\mathbf{y})\right]$$

or

$$1 \leq \sum_{t=1}^{T}\sum_{s=1}^{S}\left[\sum_{s=1}^{S} C_{r^{st}}\left(\mathbf{w}^{s},\mathbf{r},\mathbf{p}\right)\frac{\sum_{k=1}^{T} W_{y^{sk}}\left(\mathbf{y}\right)}{\sum_{\hat{t}=1}^{T}\sum_{\hat{s}=1}^{S} W_{y^{\hat{s}\hat{t}}}\left(\mathbf{y}\right)}\right]. \tag{3}$$

In other words, a producer with generalized Schur–concave preferences also chooses a revenue vector in the efficient set.

Chambers and Quiggin show the following:

Lemma 1 *If $W : \mathbb{R}^{S\times T} \rightarrow \mathbb{R}$ is generalized Schur-concave and once continuously differentiable everywhere on its domain, then*

$$\left(\frac{W_{y^{st}}\left(\mathbf{y}\right)}{\pi^{s}\theta^{t}} - \frac{W_{y^{jk}}\left(\mathbf{y}\right)}{\pi^{j}\theta^{k}}\right)\left(y^{st} - y^{jk}\right) \leq 0, \quad \text{for all } s,j \in \Omega^{S} \text{ and } t,k \in \Omega^{T}.$$

In the appendix we show the following

Corollary 1 *The equilibrium choice of r satisfies*

$$\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\mathbf{r},\mathbf{p}\right)\left(r^{st} - \sum_{\hat{s}=1}^{S}\sum_{\hat{t}=1}^{T}\theta^{\hat{t}}\pi^{\hat{s}}r^{\hat{s}\hat{t}}\right) \leq 0. \tag{4}$$

Here, the choice of r^{st} is such that a small radial expansion of r^{st} would lead to an increase in expected profit. The risk-averter operates on a smaller scale than a risk-neutral producer in that the averter can radially expand the optimal state-contingent revenue vector and increase profit. The risk-averter trades off expected return in an effort to provide self insurance against cost and production risk.

6 Production with Royalties

We now examine the pharmaceutical's problem of deciding whether to implement a royalty on gross revenues or one on net revenues. Assume the NGO is risk neutral. If the royalty rate on gross revenues by β and the cost/production-state (s,t) occurs, the NGO receives βr^{st} in royalties. Then given beliefs θ and π, the NGO's expected net rent from bioprospecting is:

$$v\left(\bar{\beta},\bar{C}_{g},\bar{\mathbf{x}}_{g}\right) \equiv \bar{C}_{g} + \sum_{t=1}^{T}\bar{\beta}\theta^{t}r^{t} - e\left(\bar{\mathbf{x}}_{g}\right) = \bar{V},$$

where $\bar{V}$ is the locals' reservation value. Here, we assume there must exist at least one probability vector (θ,π) for which the NGO is risk neutral and the producer is risk-averse. As an aside, although we assume locals are risk neutral, all of the results that follow still obtain under risk aversion. Recall

that this analysis is primarily concerned with choosing among one of two affine, royalty schemes. It is relatively simple to see that if both agents were risk averse and shared common beliefs, then if the pharmaceutical prefers a royalty on gross revenues, the locals will. Both will prefer the scheme that generates the smaller risk. They would likely differ, however, on the level of the up-front payment. Admittedly, this paper simplifies things by assuming the up-front payment is set equal to $\bar{C}_g$ and the royalty level is set to ensure the expected net revenue received by locals is equal to the exogenous level $\bar{V}$.

6.1 Production with non-negative state-contingent profits

We begin by first considering the case where $r^{st} - C(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \geq 0$ for all $(s,t) \in \Omega^S \times \Omega^T$. (We relax this assumption shortly.) Assume the firm pays a royalty rate of $\bar{\beta}$ on gross revenues. In such a case firm preferences are given by

$$W(\mathbf{y}) = W\left(\left(1-\bar{\beta}\right)\mathbf{r}^1 - C\left(\mathbf{w}^1, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T, ..., \left(1-\bar{\beta}\right)\mathbf{r}^S - C\left(\mathbf{w}^S, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T\right).$$

With smoothly differentiable preferences, the first order conditions for an interior solution on r^{st} are

$$\left(1-\bar{\beta}\right)W_{y^{st}}(\mathbf{y}) - \sum_{s=1}^{S} C_{r^{st}}(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \sum_{k=1}^{T} W_{y^{sk}}(\mathbf{y}) = 0, \quad \forall\ (s,t) \in \Omega^S \times \Omega^T. \tag{5}$$

Summing (5) over t shows that with gross revenue royalties, the arbitrage condition is

$$\left(1-\bar{\beta}\right)\sum_{t=1}^{T}\sum_{s=1}^{S} W_{y^{st}}(\mathbf{y}) = \sum_{t=1}^{T}\sum_{s=1}^{S}\left[\sum_{s=1}^{S} C_{r^{st}}(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \sum_{k=1}^{T} W_{y^{sk}}(\mathbf{y})\right],$$

or

$$1-\bar{\beta} = \sum_{t=1}^{T}\sum_{s=1}^{S}\left[\sum_{s=1}^{S} C_{r^{st}}(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \frac{\sum_{k=1}^{T} W_{y^{sk}}(\mathbf{y})}{\sum_{\hat{t}=1}^{T}\sum_{\hat{s}=1}^{S} W_{y^{\hat{s}\hat{t}}}(\mathbf{y})}\right]. \tag{6}$$

In other words, we get the standard result that with gross revenue royalties the firm never operates on the efficient frontier (see, e.g., Bousquet et al., 1998). Hence, making the NGO partial residual claimant of revenues only introduces a production distortion.

We now consider the effect of a royalty on net revenue $\mathbf{r}^s - C(\mathbf{w}^s, \mathbf{r}, \mathbf{p})\mathbf{1}_T$, $s = 1, ..., S$. With a payment of $\hat{\beta}$ over net revenues, firm preferences are given by

$$W(\mathbf{y}) = W\left(\left(1-\beta\right)\left[\mathbf{r}^1 - C\left(\mathbf{w}^1, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T\right], ..., \left(1-\beta\right)\left[\mathbf{r}^S - C\left(\mathbf{w}^S, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T\right]\right).$$

With smoothly differentiable preferences, the first order conditions for an interior solution on r^{st} are

$$\left(1-\beta\right)\left[W_{y^{st}}(\mathbf{y}) - \sum_{s=1}^{S} C_{r^{st}}(\mathbf{w}^s, \mathbf{r}, \mathbf{p}) \sum_{k=1}^{T} W_{y^{sk}}(\mathbf{y})\right] = 0, \quad \forall\ (s,t) \in \Omega^S \times \Omega^T. \tag{7}$$

Straightforward algebraic manipulations reveal that when royalties are based on net revenues, the firm operates along the efficient frontier. That gross revenue royalties introduce a production distortion whereas net revenue royalties do not should be no surprise, as the two respective royalties are essentially ad valorem and net profit taxes. Ad valorem taxes introduce a production distortion, while net profit taxes do not.

6.2 Gross or net revenue royalties?

We now examine the question of whether the expected utility maximizing firm should implement a gross revenue royalty or net revenue royalty.

With the net revenue scheme if $r^{st} < C^s = C(\mathbf{w}^s, \mathbf{r}, \mathbf{p})$, then $(1-\beta)\left(r^{st} - C^s\right) < 0$. In such a case the locals would be paying the firm a royalty. This outcome, however, is untenable. Even if willing, the NGO is unlikely to be able to credibly honor such an arrangement. Such realities require that we make some slight changes in the royalty scheme. One obvious strategy is to make the royalty rate zero in those states where expected revenues r^{st} are too small. For a given feasible state-contingent production plan $\mathbf{r}_o$, divide the set of state-contingent profits into two groups,

$$\Omega_+ = \left\{(s,t) : \left(1-\bar{\beta}\right) r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) \geq 0 \text{ and } \left(1-\hat{\beta}\right)\left(r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p})\right) > 0\right\}$$

and

$$\Omega_- = \left\{(s,t) : \left(1-\bar{\beta}\right) r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) < 0 \text{ or } \left(1-\hat{\beta}\right)\left(r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p})\right) < 0\right\}.$$

The set Ω_+ is the set of states within which profits are nonnegative for both royalty schemes and Ω_- is the set of states within which profits are strictly negative for at least one of the two royalty schemes. In the appendix we show that a meaningful comparison of the gross and net royalty scheme only requires examination of the state-contingent profits in the set Ω_+. The expected profit conditional on the profit being nonnegative is

$$\begin{aligned}
\mu_\gamma &= \frac{1}{J}\sum_{(s,t)\,\in\,\Omega_+}\sum \pi^s\theta^t\left[\left(1-\bar{\beta}\right) r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p})\right] = \left(1-\bar{\beta}\right)\bar{r} - \bar{C} \\
\mu_\nu &= \frac{1}{J}\sum_{(s,t)\,\in\,\Omega_+}\sum \pi^s\theta^t\left(1-\hat{\beta}\right)\left(r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p})\right) = \left(1-\hat{\beta}\right)\left(\bar{r} - \bar{C}\right)
\end{aligned}$$

where $J = \sum\limits_{(s,t)\,\in\,\Omega_+}\sum \pi^s\theta^t$, and $\bar{r} = \frac{1}{J}\sum\limits_{(s,t)}\sum_{\in\,\Omega_+} \pi^s\theta^t r_o^{st}, \bar{C} = \frac{1}{J}\sum\limits_{(s,t)}\sum_{\in\,\Omega_+} \pi^s\theta^t C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p})$. We say $\hat{\beta}$ and $\bar{\beta}$ are *equivalent royalty rates for* $\mathbf{r}_o$ if

$$\mu_\gamma = \left(1-\bar{\beta}\right)\bar{r} - \bar{C} = \left(1-\hat{\beta}\right)\left(\bar{r} - \bar{C}\right) = \mu_\nu,$$

i.e., if they yield the same expected value/profit. We say the pair of royalty rates $\hat{\beta}$ and $\bar{\beta}$ are *feasible for* $\mathbf{r}_o$ if $0 \leq \bar{\beta} < \left(\bar{r} - \bar{C}\right)/\bar{r}$. The royalties are feasible if both $\bar{\beta}$ and $\hat{\beta}$ are nonnegative and less than one.

Lemma 2 *Assume the royalty rates $\bar{\beta}$ and $\hat{\beta}$ are feasible and equivalent royalty rates for the state-contingent production plan $\mathbf{r} \in \mathbb{R}_+^{S\times T}$. Assume the producer has mean-variance preferences. (i) If the producer faces only production risk or only cost risk, then she (weakly) prefers the net revenue royalty to the gross revenue royalty; (ii) If the variance of state-contingent costs is equal to the variance of state-contingent revenues, then the producer will (weakly) prefer to implement $\mathbf{r}$ with the net revenue royalty.*

Proof: See appendix.

Given net and gross revenue royalty rates that are equivalent, the firm that faces only cost uncertainty will prefer the net revenue scheme to the gross revenue scheme. This is because the variation (variance) in state-contingent profits is higher for the gross revenue scheme. The same is true for a firm facing only production uncertainty. Likewise, if the variance of revenues is equal to the variance of production costs, the firm will prefer the net revenue scheme. Again, this follows from the fact that in such a case the variance of profits using the net returns scheme is smaller than that for the gross returns scheme. An immediate result of lemma 2 is that if the pharmaceutical faces only one type of risk, the "preferred" royalty will be one based on net revenues. The optimal linear royalty scheme will be a net revenue royalty.

Lemma 2 shows that if the variance of costs and revenues are the same, the firm will prefer the net revenue scheme. The next lemma gives the rules for choosing the gross revenue, or net revenue scheme when both production and cost uncertainty exists. Denote the standard deviation of revenues associated with nonnegative profit states by σ_r and denote the standard deviation of costs associated with nonnegative profit states by σ_C.

Lemma 3 *Assume the royalty rates $\bar{\beta}$ and $\hat{\beta}$ are feasible and equivalent royalty rates for the state-contingent production plan $\mathbf{r} \in \mathbb{R}_+^{S\times T}$. Assume the producer has mean-variance preferences. (i) If $\sigma_r < \sigma_C$ then the firm will implement $\mathbf{r}$ with the net revenue royalty scheme. (ii) If $\sigma_r > \sigma_C$, and*

$$\frac{\sigma_r\left(2-\hat{\beta}-\bar{\beta}\right)}{2-\hat{\beta}} \leq \sigma_C \leq \frac{\sigma_r\left(\hat{\beta}-\bar{\beta}\right)}{\hat{\beta}}, \tag{8}$$

then the firm will implement the net revenue scheme. Otherwise it implements $\mathbf{r}$ with the gross revenue royalty scheme.

Proof: See appendix.

Lemma 3 says that if the variation in revenues is large enough, for a given stochastic revenue vector $\mathbf{r}$, the firm should implement a gross revenue scheme. Hence, if a firm has very little uncertainty regarding R&D costs, it is quite possible that the gross revenue scheme will be the best course of action to follow. Given that pharmaceutical firms prefer using net profit royalties, it is likely that they are more concerned with cost uncertainty than the variation in expected revenues. Or, if concerned with the variation in expected revenues, the covariance effect is not large enough to induce the firm to choose the gross revenue scheme and its associated production distortions.

Careful reading of lemma 3 reveals that nothing is said about which linear royalty scheme is optimal. Say the stochastic vector $\mathbf{r}_\gamma^* = \left(\mathbf{r}_\gamma^{1*}, ..., \mathbf{r}_\gamma^{S*}\right) \in \mathbb{R}^S$ satisfies

$$\mathbf{r}_\gamma^* \in \arg\max_{\mathbf{r}} \left\{ W\left(\bar{\beta}\mathbf{r}^1 - C\left(\mathbf{w}^1, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T, ..., \bar{\beta}\mathbf{r}^S - C\left(\mathbf{w}^S, \mathbf{r}, \mathbf{p}\right)\mathbf{1}_T\right)\right\},$$

and $\sigma_r < \sigma_C$. Then by lemma 3, if for $\mathbf{r}_\gamma^*$ there exists a net revenue royalty rate $\hat{\beta}$ that is feasible, then for the firm with mean-variance preferences

$$\begin{aligned} & W\left(\bar{\beta}\mathbf{r}_\gamma^{1*} - C\left(\mathbf{w}^1, \mathbf{r}_\gamma^*, \mathbf{p}\right)\mathbf{1}_T, ..., \bar{\beta}\mathbf{r}_\gamma^{S*} - C\left(\mathbf{w}^S, \mathbf{r}_\gamma^*, \mathbf{p}\right)\mathbf{1}_T\right) \\ \leq \; & W\left(\left(1-\hat{\beta}\right)\left(\mathbf{r}_\gamma^{1*} - C\left(\mathbf{w}^1, \mathbf{r}_\gamma^*, \mathbf{p}\right)\right)\mathbf{1}_T, ..., \left(1-\hat{\beta}\right)\left(\mathbf{r}_\gamma^{S*} - C\left(\mathbf{w}^S, \mathbf{r}_\gamma^*, \mathbf{p}\right)\right)\mathbf{1}_T\right). \end{aligned}$$

Hence, the worse the firm could do would be to choose $\mathbf{r}_\gamma^*$. It follows that, relative to the gross revenue royalty, the net revenue scheme is "optimal"/preferred. Similar arguments show that $\sigma_r > \sigma_C$, and condition (8) holds, then the gross revenue scheme will be optimal.

Remark Let $\mathbf{y}_\gamma$ and $\mathbf{y}_\nu$ be the stochastic net revenue streams associated with the gross and net revenue royalties respectively. If, in addition to having $\sigma_r < \sigma_C$, we have $\mathbf{y}_\nu \preceq_{\boldsymbol{\pi\theta}} \mathbf{y}_\gamma$, then Lemmas 2 and 3 hold for generalized Schur-concave preferences.

Kate and Laird (1999) conducted interviews with leading pharmaceutical firms linking the rate of royalty with different influencing factors. Table 1 provides typical royalty rates for different levels of research. Although the response of firms were elicited to gauge the impact of different factors influencing the rate of royalty all firms surveyed preferred implementing royalties on net sales instead of gross sales.

7 Conclusion

Royalty payments to locals (groups of indigenous people, NGOs or any collective body) from pharmaceutical firms has become the instrument of choice for sharing the expected benefits of

bioprospecting. Using an axiomatic framework of production under uncertainty, this paper lays out the essential steps a firm might consider in making its choice of royalty instrument, and has shown that a risk averse firm will typically weakly prefer royalties on net revenues to royalties on gross revenues. This is indeed the case when there is only one type of uncertainty. However, when both cost and price/value risks are present, a blind adherence to the net revenue rule is not advocated.

The initial habit of offering royalties on gross revenue royalties might have been a reflection of inexperience in using royalties in bioprospecting agreements. However, recent trends show that firms are beginning to implement royalty schemes that are based on net revenues/sales instead of gross revenues. Some of the recently concluded bioprospecting contracts between International Cooperative Biodiversity Group (ICBG) and various local organizations suggest there is indeed a trend in favor of using net revenue royalty schemes. Whether based on gross or net revenues, from the firm's perspective the most attractive property of a royalty scheme is its ability to act as a risk sharing device. There is evidence that a few firms are beginning to implement "differential" royalties, e.g., royalties indexed to costs. Differential royalties have the advantage that in addition to risk shifting, they can provide genetic harvesters with incentives to exercise more care in screening genetic samples.

Although the model presented here assumes locals are risk neutral, all of the results still hold obtain under risk aversion. This is true because the analysis is concerned with choosing among one of two classes of royalty schemes: gross or net revenues. Risk aversion on the part of locals becomes an issue, however, when the up-front payment level is endogenized. Admittedly, this paper simplifies things by assuming the up-front payment is set equal to the cost of extracting the genetic resource and the royalty level is set to ensure the locals' expected net revenue is equal to an exogenous reservation level. Endogenizing the reservation value, e.g., via a bargaining model, etc., and determining the optimal level of up-front payment under risk aversion is a topic for future research.

Although the backdrop for our model is the pharmaceutical R&D process, the model captures the essence of a wider set of R&D activities than pharmaceutical R&D, and could serve as a point of departure in modeling the choice of plant size and scope under production, cost, and price uncertainty. The same is true for our results on the choice of royalty instrument.

8 Appendix

Proof of corollary 1: The risk-neutral producer chooses state-contingent revenues such that

$$\frac{\sum_{s=1}^{S}\pi^{s}C_{r^{st}}\left(\mathbf{w}^{s},\mathbf{r},\mathbf{p}\right)}{\pi^{s}\theta^{t}}=\frac{\sum_{s=1}^{S}\pi^{s}C_{r^{jk}}\left(\mathbf{w}^{s},\mathbf{r},\mathbf{p}\right)}{\pi^{j}\theta^{k}},$$

while the risk-averter's FOC (2) and lemma 1 reveal state-contingent revenues satisfy

$$\left(\frac{\sum_{s=1}^{S}\pi^{s}C_{r^{st}}\left(\mathbf{w}^{s},\mathbf{r},\mathbf{p}\right)}{\pi^{s}\theta^{t}}-\frac{\sum_{s=1}^{S}\pi^{s}C_{k}\left(\mathbf{w}^{s},\mathbf{r},\mathbf{p}\right)}{\pi^{j}\theta^{k}}\right)\left(r^{st}-r^{jk}\right)\leq 0.$$

Multiplying each first order condition by r^{st} and summing gives

$$\sum_{s=1}^{S}\sum_{t=1}^{T}\theta^{t}\pi^{s}r^{st}-\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\mathbf{r},\mathbf{p}\right)r^{st}=0. \tag{9}$$

Add and subtract $\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\cdot\right)\sum_{s=1}^{S}\sum_{t=1}^{T}\theta^{t}\pi^{s}r^{st}$ to (9) and rearrange terms:

$$\begin{aligned}&\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\mathbf{r},\mathbf{p}\right)r^{st}-\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\cdot\right)\sum_{s=1}^{S}\sum_{t=1}^{T}\theta^{t}\pi^{s}r^{st}\\ =\;&\sum_{s=1}^{S}\sum_{t=1}^{T}\theta^{t}\pi^{s}r^{st}\left[1-\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\cdot\right)\right]\leq 0.\end{aligned}$$

The above expression reveals that

$$\sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{k=1}^{S}\pi^{k}C_{r^{st}}\left(\mathbf{w}^{k},\mathbf{r},\mathbf{p}\right)\left(r^{st}-\sum_{\hat{s}=1}^{S}\sum_{\hat{t}=1}^{T}\theta^{\hat{t}}\pi^{\hat{s}}r^{\hat{s}\hat{t}}\right)\leq 0.$$

■

Before proving lemma 2, we make the following observation.

Observation 1: When faced with two stochastic production plans yielding the same expected profit, an agent with Schur-concave preferences will prefer the production plan with the smaller risk. Here we focus on mean-variance preferences and interpret risk as the variance in profits. Given the two sets of state-contingent profits $\Omega_{+}\left(\mathbf{r}\right)$ and $\Omega_{-}\left(\mathbf{r}\right)$, the mean profits associated with the truncated net and gross revenue royalty schemes are given by

$$\begin{aligned}\tilde{\mu}_{\gamma}&=\sum_{(s,t)\in\,\Omega_{+}(\mathbf{r})}\sum\pi^{s}\theta^{t}\left[r^{st}-\bar{\beta}r^{st}-C^{s}\right]+\sum_{(s,t)\in\,\Omega_{-}(\mathbf{r})}\sum\pi^{s}\theta^{t}\left[r^{st}-C^{s}\right]\\&=\bar{\tilde{r}}-\overline{\tilde{C}}-\bar{\beta}H_{r}\end{aligned}$$

and

$$\begin{aligned}\tilde{\mu}_{\gamma}&=\sum_{(s,t)\in\,\Omega_{+}(\mathbf{r})}\sum\pi^{s}\theta^{t}\left(1-\hat{\beta}\right)\left[r^{st}-C^{s}\right]+\sum_{(s,t)\in\Omega_{-}}\sum\pi^{s}\theta^{t}\left[r^{st}-C^{s}\right]\\&=\bar{\tilde{r}}-\overline{\tilde{C}}-\hat{\beta}\left(H_{r}-H_{C}\right),\end{aligned}$$

where $\overline{\tilde{r}} = \sum \sum_{(s,t)\in\Omega_+(\mathbf{r})} \pi^s \theta^t r^{st}$, $\overline{\tilde{C}} = \sum \sum_{(s,t)\in\Omega_+(\mathbf{r})} \pi^s \theta^t C^s$, $H_r = \sum \sum_{(s,t)\in\Omega_+(\mathbf{r})} \pi^s \theta^t r_o^{st}$ and $H_C = \sum \sum_{(s,t)\in\Omega_+(\mathbf{r})} \pi^s \theta^t C^s$. In this case, given $\bar{\beta}$ and $\mathbf{r}$, choose $\hat{\beta}$ so that $\bar{\beta}$ and $\hat{\beta}$ are equivalent:

$$\begin{aligned} \overline{\tilde{r}} - \overline{\tilde{C}} - \bar{\beta} H_r &= \overline{\tilde{r}} - \overline{\tilde{C}} - \hat{\beta}\left(H_r - H_C\right) \\ \bar{\beta} H_r &= \hat{\beta}\left(H_r - H_C\right). \end{aligned}$$

The variance of the respective truncated net and gross revenue royalty schemes is given by

$$\tilde{\sigma}_\gamma^2 = \sum_{(s,t)\in\,\Omega_+(\mathbf{r})} \sum \pi^s \theta^t \left[\left(1-\bar{\beta}\right) r^{st} - C^s - \tilde{\mu}_\gamma\right]^2 + \sum_{(s,t)\in\,\Omega_-(\mathbf{r})} \sum \pi^s \theta^t \left[r^{st} - C^s - \tilde{\mu}_\gamma\right]^2 \tag{10}$$

$$\tilde{\sigma}_\nu^2 = \sum_{(s,t)\in\,\Omega_+(\mathbf{r})} \sum \pi^s \theta^t \left\{\left(1-\hat{\beta}\right)\left[r^{st} - C^s - \tilde{\mu}_\nu\right]\right\}^2 + \sum_{(s,t)\in\,\Omega_-(\mathbf{r})} \sum \pi^s \theta^t \left[r^{st} - C^s - \tilde{\mu}_\nu\right]^2, \tag{11}$$

where $C^s = C\left(\mathbf{w}^s, \mathbf{r}, \mathbf{p}\right)$.

Obviously, the relative magnitude of (10) and (11) depend only on the expressions containing $\bar{\beta}$ and $\hat{\beta}$. It follows that a comparison of $\tilde{\sigma}_\gamma^2$ and $\tilde{\sigma}_\nu^2$ can be accomplished by focusing only on the set Ω_+. ■

Lemma 2: *Assume the royalty rates $\bar{\beta}$ and $\hat{\beta}$ are feasible and equivalent royalty rates for the state-contingent production plan $r \in R_+^{S\times T}$. Assume the producer has mean-variance preferences. (i) If the producer faces only production risk or only cost risk, then she (weakly) prefers the net revenue royalty to the gross revenue royalty; (ii) If the variance of state-contingent costs is equal to the variance of state-contingent revenues, then the producer will (weakly) prefer to implement r with the net revenue royalty.*

Proof. Given observation 1, it proves convenient to focus attention on the mean and variance of the stochastic matrix of nonnegative profits generated by the net royalty and gross royalty schemes. Given $\mathbf{r}_o$ and the corresponding values $\mu_\gamma = \mu_\nu, J, \bar{r}$, and $\bar{C}$, the variance conditioned on profit being nonnegative is given by

$$\begin{aligned} \sigma_\gamma^2 &= \frac{1}{J} \sum_{(s,t)\,\in\,\Omega_+} \sum \pi^s \theta^t \left[\left(1-\bar{\beta}\right) r_o^{st} - C^s - \mu_\gamma\right]^2 \\ &= \left(1-\bar{\beta}\right)^2 \sigma_r^2 + \sigma_C^2 - 2\left(1-\bar{\beta}\right)\sigma_r \sigma_C. \end{aligned} \tag{12}$$

and

$$\begin{aligned} \sigma_\nu^2 &= \frac{1}{J} \sum_{(s,t)\,\in\,\Omega_+} \sum \pi^s \theta^t \left[\left(1-\bar{\beta}\right)\left(r_o^{st} - C^s\right) - \mu_\gamma^H\right] \\ &= \left(1-\hat{\beta}\right)^2 \sigma_r^2 + \left(1-\hat{\beta}\right)^2 \sigma_C^2 - 2\left(1-\hat{\beta}\right)^2 \sigma_r \sigma_C. \end{aligned} \tag{13}$$

To compare the two variances subtract (13) from (12)

$$\sigma_\gamma^2 - \sigma_\nu^2 = \left[\left(1-\bar{\beta}\right)^2 - \left(1-\hat{\beta}\right)^2\right]\sigma_r^2 + \left[1-\left(1-\hat{\beta}\right)^2\right]\sigma_C^2 + 2\left[\left(1-\hat{\beta}\right)^2 - \left(1-\bar{\beta}\right)\right]\sigma_r\sigma_C. \quad (14)$$

The coefficients for σ_r^2 and σ_C^2 are strictly positive. To show part i) observe that if there are only production risks, then $\sigma_r^2 = 0$ and $\left[1-\left(1-\hat{\beta}\right)^2\right]\sigma_C^2 > 0$, implying $\sigma_\gamma^2 > \sigma_\nu^2$. If there are no cost risks, then $\sigma_C^2 = 0$ and $\left[\left(1-\bar{\beta}\right)^2 - \left(1-\hat{\beta}\right)^2\right]\sigma_r^2 > 0$, again implying $\sigma_\gamma^2 > \sigma_\nu^2$. By definition, with $\mu_\gamma = \mu_\nu$ and $\sigma_\gamma^2 > \sigma_\nu^2$, the producer with mean-variance preferences will weakly prefer to implement $\mathbf{r}$ with the net revenue royalty scheme.

Now assume $\mathbf{r}_o$ maximizes the firm's utility with the gross revenue royalty. Then we know the firm (weakly) prefers the set of stochastic returns $\mathbf{y}_\nu(\mathbf{r}_o) = \left(\mathbf{y}_\nu^1(\mathbf{r}_o), ..., \mathbf{y}_\nu^S(\mathbf{r}_o)\right)$ to $\mathbf{y}_\gamma(\mathbf{r}_o) = \left(\mathbf{y}_\gamma^1(\mathbf{r}_o), ..., \mathbf{y}_\gamma^S(\mathbf{r}_o)\right)$. Here $\mathbf{y}_\nu^s(\mathbf{r}_o) = \left(y_\nu^{s1}(\mathbf{r}_o), ..., y_\nu^{sT}(\mathbf{r}_o)\right)$ is the state-contingent matrix of net profits generated by $\mathbf{r}_o$ when using the net revenue royalty scheme, with

$$y_\nu^{st}(\mathbf{r}_o) = \begin{cases} \left(1-\bar{\beta}\right)r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) & \text{if } \left(1-\bar{\beta}\right)r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) \geq 0 \text{ and } \left(1-\hat{\beta}\right)\left(r_o^{st} - C^s\right) > 0 \\ r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) & \text{otherwise} \end{cases}.$$

The vector $\mathbf{y}_\gamma^s(\mathbf{r}_o) = \left(y_\gamma^{s1}(\mathbf{r}_o), ..., y_\gamma^{sT}(\mathbf{r}_o)\right)$ is the state-contingent matrix of net profits generated by $\mathbf{r}_o$ using the gross revenue royalty scheme, with

$$y_\gamma^{st}(\mathbf{r}_o) = \begin{cases} \left(1-\bar{\beta}\right)\left(r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p})\right) & \text{if } \left(1-\bar{\beta}\right)r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) \geq 0 \text{ and } \left(1-\hat{\beta}\right)\left(r_o^{st} - C^s\right) > 0 \\ r_o^{st} - C(\mathbf{w}^s, \mathbf{r}_o, \mathbf{p}) & \text{otherwise} \end{cases}.$$

Clearly, even though $\mathbf{y}_\gamma$ maximizes the firm's utility when implementing the gross revenue royalty, it does not necessarily maximize its utility when implementing the net revenue royalty. Consider another state-contingent revenue matrix $\mathbf{r}_o$ such that

$$r_* \in \arg\max_{\mathbf{r}} \left\{ W(\mathbf{y}_\nu(\mathbf{r})) : \sum_{(s,t)\,\in\,\Omega_+}\sum \pi^s\theta^t\left(1-\hat{\beta}\right)\left(r^{st} - C(\mathbf{w}^s, \mathbf{r}, \mathbf{p})\right) \geq \left(1-\hat{\beta}\right)\left(\bar{r} - \bar{C}\right) \right\},$$

i.e., choose a state-contingent revenue plan such that profits are no no smaller than that associated with the the plan $\mathbf{y}_\nu(\mathbf{r}_o)$. Since the firm can do no worse than choosing $\mathbf{r}_o$, it follows that with mean-variance preferences the net royalty scheme will be at least weakly preferred to the corresponding gross revenue scheme. To show part ii) simply observe that if $\sigma_r^2 = \sigma_C^2$ then

$$\sigma_\gamma^2 - \sigma_\nu^2 = \bar{\beta}^2 > 0.$$

Again, it follows that with mean-variance preferences the net royalty scheme will be at least weakly preferred to the corresponding gross revenue scheme. ■

Lemma 3: *Assume the royalty rates $\bar{\beta}$ and $\hat{\beta}$ are feasible and equivalent royalty rates for the state-contingent production plan $r \in R_+^{S\times T}$. Assume the producer has mean-variance preferences. (i) If $\sigma_r < \sigma_C$ then the firm will implement the net revenue royalty scheme. (ii) If $\sigma_r > \sigma_C$, and*

$$\frac{\sigma_r\left(2-\hat{\beta}-\bar{\beta}\right)}{2-\hat{\beta}} \leq \sigma_C \leq \frac{\sigma_r\left(\hat{\beta}-\bar{\beta}\right)}{\hat{\beta}},$$

then the firm will implement the net revenue scheme. Otherwise it implements r with the gross revenue royalty scheme.

Proof: First, consider the case where $\sigma_C > \sigma_r$. Define $\Delta = \sigma_C - \sigma_r$, or $\sigma_C = \sigma_r + \Delta$. Then equation (14) can be written as

$$\sigma_\gamma^2 - \sigma_\nu^2 = \left[\left(1-\bar{\beta}\right)^2 - \left(1-\hat{\beta}\right)^2\right]\sigma_r^2 + \left[1-\left(1-\hat{\beta}\right)^2\right](\sigma_r+\Delta)^2 + 2\left[\left(1-\hat{\beta}\right)^2 - \left(1-\bar{\beta}\right)\right]\sigma_r(\sigma_r+\Delta).$$

Rearranging terms and simplifying gives

$$\sigma_\gamma^2 - \sigma_\nu^2 = \bar{\beta}^2\sigma_r^2 + \left(2\hat{\beta}-\hat{\beta}^2\right)\Delta^2 + 2\bar{\beta}\Delta\sigma_r, \tag{15}$$

which is a quadratic equation in σ_r and Δ. Simple calculations show the roots of (15) to be

$$\Delta_1 = -\frac{\bar{\beta}\sigma_r}{2-\hat{\beta}} \text{ and } \Delta_2 = -\frac{\bar{\beta}\sigma_r}{\hat{\beta}}.$$

Both roots are negative implying that $\sigma_\gamma^2 - \sigma_\nu^2 > 0$ as long as $-\frac{\bar{\beta}\sigma_r}{\hat{\beta}} < \Delta < -\frac{\bar{\beta}\sigma_r}{2-\hat{\beta}}$. This only holds if $\sigma_r > \sigma_C$. It follows that if $\sigma_C > \sigma_r$, then $\sigma_\gamma^2 - \sigma_\nu^2 > 0$. This establishes part (i). To establish part (ii) observe that if $\sigma_r \geq \sigma_C$, equation (14) can be written as

$$\sigma_\gamma^2 - \sigma_\nu^2 = \left[\left(1-\bar{\beta}\right)^2 - \left(1-\hat{\beta}\right)^2\right]\sigma_r^2 + \left[1-\left(1-\hat{\beta}\right)^2\right](\sigma_r-\Delta)^2 + 2\left[\left(1-\hat{\beta}\right)^2 - \left(1-\bar{\beta}\right)\right]\sigma_r(\sigma_r-\Delta).$$

Rearranging terms and simplifying gives

$$\sigma_\gamma^2 - \sigma_\nu^2 = \bar{\beta}^2\sigma_r^2 - \left(2\hat{\beta}-\hat{\beta}^2\right)\Delta^2 + 2\bar{\beta}\Delta\sigma_r, \tag{16}$$

which is a quadratic equation in σ_r and Δ. The roots of (16) are

$$\Delta_1 = \frac{\bar{\beta}\sigma_r}{2-\hat{\beta}} \text{ and } \Delta_2 = \frac{\bar{\beta}\sigma_r}{\hat{\beta}}.$$

If $0 < \Delta < \frac{\bar{\beta}\sigma_r}{2-\hat{\beta}}$ or $\frac{\bar{\beta}\sigma_r}{\hat{\beta}} < \Delta$, then $\sigma_\gamma^2 - \sigma_\nu^2 > 0$. Rearranging terms yields that if

$$\frac{\sigma_r\left(2-\hat{\beta}-\bar{\beta}\right)}{2-\hat{\beta}} \leq \sigma_C \leq \frac{\sigma_r\left(\hat{\beta}-\bar{\beta}\right)}{\hat{\beta}},$$

then $\sigma_\gamma^2 - \sigma_\nu^2 \geq 0$ and the firm with mean-variance preferences will implement the net revenue scheme. Otherwise, if σ_C is not in the interval $\left[\frac{\sigma_r(2-\hat{\beta}-\bar{\beta})}{2-\hat{\beta}}, \frac{\sigma_r(\hat{\beta}-\bar{\beta})}{\hat{\beta}}\right]$, then it will choose to implement the gross revenue scheme. ■

'Raw' material or early research: 0.5-2%
Raw material (e.g. dried plants, soil samples) and basic extracts (organic or aqueous) : 0.5-2%
Extracts (organic or aqueous): 0.5-2%
Value added data: 1-4%
Ethnobotanical information: 1-4%
Material supplied with some results from screening: 2-3%
Identified bioactive compound (with known structure and test tube activity): 1-4%
Clinical data: 2-15%
Animal model data supplied with identified bioactive compound: 2-6%
Clinical data supplied with identified bioactive compound: 5-15%

Table 1. The Market Rate: Average Range of Royalties on Net Sales

References

[1] Artuso, A. (1994) *An Economic and policy Analysis of Biochemical Prospecting (Pharmaceuticals)*,Ph.D. Thesis, Cornell University.

[2] Artuso, A (1996) "Economic Analysis of Contractual Arrangements for Biochemical Prospecting in Discovery of New Pharmaceuticals." In Biodiversity, Biotechnology and Sustainable Development in Health and Agriculture: Emerging Connections by the Pan American Health Organization, Washington DC.

[3] Asebey, E.J. (1996) "Indigenous Knowledge and Intellectual Property: Towards Equitable Compensation." In Biodiversity, Biotechnology and Sustainable Development in Health and Agriculture: Emerging Connections by the Pan American Health Organization, Washington DC.

[4] Bousquet, Alain et al., (1998) "Risk Sharing in Licensing," *International Journal of Industrial Organization*, 16(5): 535-54.

[5] Chambers, R.G. and J. Quiggin. (2000) Uncertainty, Production, Choice & Agency: The State-Contingent Approach, Cambridge University Press

[6] Coase, R.H. (1988) *The Firm, the Market and the Law*, The University of Chicago Press.

[7] De Souza Silva, J. (1996) "From Medicinal Plants to Natural Pharmaceuticals: The Marketing of Nature." In Biodiversity, Biotechnology and Sustainable Development in Health and Agriculture: Emerging Connections by the Pan American Health Organization, Washington DC.

[8] Farnsworth, N.R. and D.D. Soejarto (1985) "Potential Consequences of Plant extinction in the United States on the current and future availability of prospecting drugs," *Economic Botany* 39(3).

[9] Farnsworth, N.R. (1988) "Screening for New Medicines." In E.O. Wilson *Biodiversity*, National Academy Press.

[10] Grifo, F.T. and D.R. Downes, (1996) "Agreements to Collect Biodiversity for Pharmaceutical Research: Major Issues and Proposed Principles." In Brush, S.B. and Stabinsky, D. (Ed)

(1996) *Valuing Local Knowledge, Indigenous People and Intellectual Property Rights*, Island Press, Washington DC.

[11] Kate, K. and S.A. Laird (1999) The Commercial Use of Biodiversity, Earthscan, London pp. 66-68.

[12] Kloppenberg, J. and S. Rodrigues, (1992) "Conservationists or Corsairs?" *Seedling* 9.

[13] Kumar, P. (2001) "Valuation of Medicinal Plants for Pharmaceutical Uses: Review of Literature and Issues," Discussion Paper 33, Institute of Economic Growth, Delhi.

[14] Laird, S.A. (1993) "Contracts for Biodiversity Prospecting" in Reid. W.V. et el *Biodiversity Prospecting: Using Genetic Resources for Sustainable Development*, WRI.

[15] Mendelsohn, R. and M.J. Ballick, (1995), "The Value of Undiscovered Pharmaceutical in Tropical Forests," *Economic Botany* 49(2).

[16] Moran, K. (2001), *Lessons from Bioprospecting in India and Nigeria*, http://www.cs.org/publications/CSQ/244/moran.html.

[17] Nature vol 392, April 1998 "When rhetoric hits reality in debate on Bioprospecting."

[18] Principe, P. (1991), "Valuing the Biodiversity of Medicinal Plants" in Akerele, O. et al (eds.) *The Conservation of Medicinal Plants*, Cambridge University Press.

[19] Principe, P. (1996) "Monetizing the Pharmaceutical Benefits of Plants." In Balick, M.J.et al (ed.) *Medicinal Resources of the Tropical Forest*, Columbia University Press, NY.

[20] Reid. W.V. et el (eds.) (1993) BiodiversityProspecting: Using Genetic Resources for Sustainable Development, WRI.

[21] Rausser, G.C. and A.A. Small, (2000) "Valuing Research Leads: Bioprospecting and the Conservation of Genetic Resources," *Journal of Political Economy*108.

[22] Simpson, D.R. R.A. Sedjo, and J.W. Reid, (1996) "Valuing Biodiversity for use in Pharmaceutical Research," *Journal of Political Economy* 78.

[23] United Nations (1992) "United Nations Convention on Biological Diversity," cited in Reid. W.V. et al *Biodiversity Prospecting: Using Genetic Resources for Sustainable Development*, WRI.