University Basic Research and Applied Agricultural Biotechnology

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Summary: I examine the effects of R&D inputs on the subset of life-science outputs which demonstrably has influenced later technology, as evidenced by literature citations in agricultural biotechnology patents. Universities are found to be a principal seedbed for cutting-edge technology development. A university's life-science research budget strongly affects its technology-relevant life-science output as well as graduate education.

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Francis Bacon reputedly was the first to predict science would propel the technological change responsible for much of economic growth. Since Bacon's time, science and technology indeed have come to be inseparable terms, to the extent many of us hardly discriminate between them. Yet science is distinguished by its attention to natural mechanisms and technology by its attention to new goods, the first relating to the second as map to prospector. Science has economic value, that is, primarily insofar as it reduces the cost of discovering useful things. As Narin, Hamilton, and Olivastro have pointed out, science-technology linkages are stronger in the life sciences than in other fields and thus have an especially prominent role in modern agricultural research.

A substantial literature has developed on the relationships between agricultural research expenditures and output (e.g. Huffman and Evenson; Alston, Norton, and Pardey). The strength of these studies lies in their ability to relate observed expenditures to success indicators well downstream toward final beneficiaries. They do not, however, explicitly model the connecting links from basic research to technical change to final use. Two knowledge production function approaches have been taken for tracing such connections, the first focusing on the production of scientific literature as an indicator of basic research output, and the second on the production of patent awards as an indicator of applied technological success.

As an example of the first approach, Pardey used 48-state panel data to relate agricultural experiment stations' expenditures to their scientific publication rates. He found elasticities exceeding unity, implying increasing returns to the scale of agricultural science. Adams and Griliches similarly examined the research performance of U.S. universities in a number of scientific fields during the 1980s. Elasticities of publication with respect to scientific expenditure were just below unity in agriculture, implying slightly decreasing returns. The

second analytical approach, focusing on patent awards, has been more popular. Jaffe (1989) used state-level panel data to regress patent counts against industry and university R&D expenditures. His expenditure elasticities imply that university research strongly influences applied technology although with decreasing returns to scale, a finding reinforced by Acs, Audretsch, and Feldman. More recently, Hall, Jaffe, and Trajtenberg (2001) have matched firms' patent awards to their production and financial inputs, and Foltz, Kim, and Barham have studied patent production in U.S. universities.

I take in the present study a third approach, relating research effort not to basic science or applied technology alone, but to the science that demonstrably has been successful in influencing technology. In this way I am able to link three points on the R&D continuum: input investment, scientific output, and technical discovery. The study exploits the fact that patent applicants are required to cite the scientific literature relevant to their claimed discovery. Such citations therefore represent a connection, verified by U.S. patent examiners, between science and use. Our special interest is in technologies applying molecular or DNA-based methods to agriculture, broadly called agricultural biotechnology (Shoemaker).

A Model of Science and Education Production

A university's knowledge outputs might well be regressed against quantities of building and equipment capital, laboratory materials, and the professor and other employee time devoted to research. Unfortunately, universities typically report program-level efforts as expenditures rather than input quantities. Universities are involved in two graduate life-science activities: research and graduate training. The two are likely to be substantially joint, either because capital goods, professorial time, and research materials are poorly allocable between them or because some

inputs, such as academic positions, are sticky (Adams and Griliches; Leathers). Examples of imperfect allocability abound.

Life-science programs relevant to agricultural biotechnology include the biological sciences (housed typically in the arts and sciences college) and agricultural sciences. Although information about life-science faculty sizes is not centrally available, the National Science Foundation does provide data on graduate enrollments and on the number of post-doctoral researchers working in life-science laboratories. Suppose the analyst suspects universities employ postdoctoral fellows in a way that fails to minimize cost at given output. I would then wish to specify the life-science and graduate-teaching production functions as

(1)
$$S \; = \; S(G, \, \mathbf{B}, \, \mathbf{P}, \, \mathbf{X})$$

(2)
$$G \; = \; G(S, \, \mathbf{B}, \, \mathbf{P}, \, \mathbf{X})$$

where S is life science output, G the number of graduate students enrolled in life science programs, $\mathbf{B} = (B_{agr}, \, B_{bio})$ the vector of agricultural (B_{agr}) and biological (B_{bio}) science budgets, $\mathbf{P} = (P_{agr}, \, P_{bio})$ the corresponding numbers of postdoctoral researchers employed in the agricultural (P_{agr}) and biological (P_{bio}) sciences, and $\mathbf{X}$ a vector of other factors such as university size, location, and reputation. Science and graduate teaching here serve as inputs to one another. Graduate students assist with their professors' research programs, and experience with professors' research is in turn an important element in a graduate student's education. Research and teaching output both depend on budgeted and other inputs.

Each element of budget vector $\mathbf{B}$ is divisible into expenditures on postdoctoral researchers and on other (non-postdoctoral) inputs; that is, for the agricultural sciences, $B_{agr} = W_P P_{agr} + W_N N_{agr}$, and for the biological sciences, $B_{bio} = W_P P_{bio} + W_N N_{bio}$, where non-postdoctoral inputs $\mathbf{N} = (N_{agr}, \, N_{bio})$ consist of such items as faculty salaries,

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research materials, laboratory equipment, and buildings; W_N is their aggregate mean price; and

W_P is mean postdoctoral salary rate. These identities permit us to analyze the impacts of budget

allocation decisions on scientific output and graduate education.

University Budget Allocation Policies

Consider for example the university's scientific research. Holding budgets **B**, graduate

enrollment G, other factors **X**, and prices W_P, W_N fixed, equation (1) may be used to specify the

science output effects of changes in the university's postdoctoral workforce. In the agricultural

sciences, the impact is, by vector addition,

$$(3) \qquad \left. \frac{\partial S}{\partial P_{agr}} \right|_{B^0_{agr}} = \left. \frac{\partial S}{\partial P_{agr}} \right|_{N^0_{agr}} - \frac{W_P}{W_N} \left. \frac{\partial S}{\partial N_{agr}} \right|_{P^0_{agr}} .$$

Similarly, in the biological sciences,

$$(4) \qquad \left. \frac{\partial S}{\partial P_{bio}} \right|_{B^0_{bio}} = \left. \frac{\partial S}{\partial P_{bio}} \right|_{N^0_{bio}} - \frac{W_P}{W_N} \left. \frac{\partial S}{\partial N_{bio}} \right|_{P^0_{bio}} .$$

In each of its two life sciences, the university is modeled here as moving along its

(P, N) isocost line (since total budgets are held fixed) in the direction of the P axis.

Postdoctoral fellows are hired and other inputs retired such that total expenditure in the

respective science remains constant ($W_P \partial P_{agr} = - W_N \partial N_{agr}$, $W_P \partial P_{bio} = - W_N \partial N_{bio}$). If

expenditures are minimal at given output, science production S is unaffected by such reallocation

and (3) and (4) are zero. If (3) or (4) instead are negative (positive), too many (too few)

postdoctoral fellows are employed at given output S. Including **P** together with **B** in (1) and (2)

thus provides a test of allocative efficiency in each university activity.

Besides permitting efficiency tests, (1) – (4) allow us to examine the impacts of alternative budget allocation policies. The effect on science output, for example, of allocating all new agricultural expenditure to non-postdoctoral inputs, that is such that $\partial B_{agr} = W_N \, \partial N_{agr}$, is

$$(5) \qquad \left. \frac{\partial S}{\partial B_{agr}} \right|_{P^0_{agr}} = \frac{1}{W_N} \left. \frac{\partial S}{\partial N_{agr}} \right|_{P^0_{agr}}$$

namely the effect in equation (1) of a *ceteris paribus* change in B_{agr}. The effect instead of allocating all new agricultural expenditures to postdoctoral researchers, such that $\partial B_{agr} = W_P \, \partial P_{agr}$, is by the same reasoning $\partial S / \partial B_{agr} \mid_{N^0_{agr}} = \left(1/W_P\right)\left(\partial S / \partial P_{agr}\right) \mid_{N^0_{agr}}$. Solving (3) for its first right-hand term and substituting into this last expression gives

$$(6) \qquad \left. \frac{\partial S}{\partial B_{agr}} \right|_{N^0_{agr}} = \frac{1}{W_P} \left. \frac{\partial S}{\partial P_{agr}} \right|_{B^0_{agr}} + \frac{1}{W_N} \left. \frac{\partial S}{\partial N_{agr}} \right|_{P^0_{agr}} = \frac{1}{W_P} \left. \frac{\partial S}{\partial P_{agr}} \right|_{B^0_{agr}} + \left. \frac{\partial S}{\partial B_{agr}} \right|_{P^0_{agr}}$$

the sum of the effects in equation (1) of *ceteris paribus* changes in postdoctoral hires P_{agr} and budget size B_{agr}. Impacts of budget policies in the biological sciences are specified by substituting *bio* for *agr* in equations (5) and (6).

Finally, the impact of allocating expenditures in the proportions observed at the representative university is found as the expenditure-weighted average of (5) and (6). This reduces in the case of agricultural programs to

$$(7) \qquad \left. \frac{\partial S}{\partial B_{agr}} \right|_{ave} = \left. \frac{\partial S}{\partial B_{agr}} \right|_{P^0_{agr}} + \frac{P_{agr}}{B_{agr}} \left. \frac{\partial S}{\partial P_{agr}} \right|_{B^0_{agr}}$$

and in the case of biology programs to

$$(8) \qquad \left. \frac{\partial S}{\partial B_{bio}} \right|_{ave} = \left. \frac{\partial S}{\partial B_{bio}} \right|_{P^0_{bio}} + \frac{P_{bio}}{B_{bio}} \left. \frac{\partial S}{\partial P_{bio}} \right|_{B^0_{bio}}.$$

The expenditure-weighted average of (7) and (8) in turn gives the mean marginal impact of total life-science budget on scientific output. An analysis identical to (3) – (8) applies to the effects of resource allocation on graduate training. [1]

Science and Education Production Possibilities

Universities are, though not profit-maximizing in the ordinary sense, under pressure to maximize the services they provide given the budget available. They would therefore wish to maximize the science and graduate training achievable with that budget, as adjusted for any technical or allocative inefficiency abetted by the university's institutional structure or nonmarket missions. Figure 1 depicts one such production possibility frontier (PPF), in which any inefficiencies are ignored and some input allocability is permitted between the two outputs. Beginning at point A, resources are continuously reallocated away from graduate training and toward life-science research. Both outputs initially may rise because, for example, the very fact of establishing a research program can have strong effects on graduate student retention and incentive and thus on education. As more research is entertained, however, it becomes competitive with educational uses of equipment, materials, and faculty time. The PPF slope thus turns negative beyond point C. Further reallocation toward research can impair graduate student recruitment and skill so much that the university becomes less attractive to productive research faculty. Research and education then both decline as shown beyond point C.

Information Spillins, Applied Research, and Fixed Resources

University success depends on factors beyond budgeted inputs, among them the information spilling in from nonmarket sources. I therefore use total industry agricultural research

expenditure as a broad measure of potential spillins and include it as a separate determinant of the university's life science and education output.

A university's facility for absorbing industry resources ought to depend on its own applied research experience, as reflected for example by the quantity of its own biotechnology patents (Foltz, Kim, and Barham; Rausser; Cockburn, Henderson, and Stern). University agricultural biotechnology patent awards are employed here as a measure of this absorptive capacity. [2] By virtue of its absorptive-capacity effect, patentable (i.e. more applied) university research ought to boost basic science output (1) and education output (2). On the other hand, applied research time competes with basic research and teaching time, and in this respect would retard basic research and teaching output.

Finally, university science and education likely are affected by resources that cannot be purchased in any short-run sense and hence would not be well represented by budgeted inputs. Potentially important factors are science program reputation, faculty quality, and university location and size.

Measuring Scientific Output

Universities produce both non-excludable and excludable social benefits. A university's research output can thus be measured at one extreme by the professional influence of its faculty and, at the other, by the economic effects of the research itself. Professional influence is reflected mostly in the quantity and quality of publications (Adams and Griliches; Pardey), and economic influence in consequent yields, profits, or productivity (Evenson; Huffman and Evenson; Huffman and Just). Our own interest centers intermediately between the two, namely on scientists' impacts over downstream biotechnological innovation, a notion Griliches (1994) calls the knowledge externality of basic research. Grupp and Schmoch; Narin, Hamilton, and

Olivastro; and David, Mowery, and Steinmueller observe that citations from patents to scientific literature are concrete evidence of these externalities.

At least two measures of such an externality might be put forth in the present context: (i) the quantity of citations in later agricultural biotechnology patents to a university's scientific articles published in a given year, and (ii) the quantity of the university's scientific articles published that year which later receive at least one patent citation. Because patent examiners require patent applicants to cite the literature instrumental in their discovery, either of these measures would provide an indication of the university's influence over technological discovery (Griliches 1990). A difficulty with measure (i) is that patent citations often continue to be accorded to a paper years after it is published, so that any use of recent publication data requires truncating many of the citations it eventually will receive (Hall, Jaffe, and Trajtenberg 2001). Measure (ii) is less sensitive to this truncation problem and is the approach adopted here. Specifically, let I_{it}^{kj} be unity if a patent document in any year $\tau = t+1, t+2, ..., T$ cites the kth life science publication authored by the jth scientist at the ith university in the tth year, zero otherwise. Measure (ii) of research output is then $S_{it} = \sum_{kj} I_{it}^{kj}$.

Data Development

Our strategy for measuring research output was to use the U.S. Patent Office database, along with patent classifications and key words, to identify patents awarded between January 1985 and August 2000 and which involved the application of molecular or cellular methods to an explicitly stated agricultural application. A total of 1,746 patents were encountered that satisfied those criteria, 40% of which were awarded to U.S. firms, 21% to U.S. universities, and 31% to foreign entities. [3] Literature reference lists on the front pages of the 1,746 patents were examined and references to nonscientific literature eliminated. The Science Citation Index was then utilized to

match each scientific citation to the institutions at which the cited authors worked at time of publication. Finally, citations were sorted by university and year. In this way, I tabulated for each university and year both the number of future patent citations to current publications and the number of current publications that subsequently were cited by at least one patent. [4] CHI Research of Haddon Heights, NJ was employed to assist with the keyword search, clean the reference lists of nonscientific literature, and match author names to home university. [5]

Research outputs were next matched by year to the universities' graduate student enrollments, budgets, postdoctoral employees, patent outputs, program rankings, location, and size. Our primary source of information on graduate enrollments, postdoctoral fellows, and research budgets was the National Science Foundation's WebCASPAR data base. Research budgets represent only expenditures intended to produce research outcomes, although those include most of the resources used to support and train life-science graduate students and tend greatly to exceed expenditures designated specifically as instructional. [6] The most disaggregated level at which budget data can consistently be found are the universities' agricultural and biology programs. [7] However, the National Science Foundation reports faculty sizes at the university rather than program level, so it is infeasible with their data to test the efficiency of budget allocations to agricultural and biology faculty.

Quality ranks of all fields in each of the principal U.S. agriculture and biology programs are available for 1985, 1987, 1989, 1993, 1996, and 1997 from the *Gourman Report*. An aggregate ranking for a given year, university, and program was computed by averaging the rankings of the individual fields in that program. Rankings in years other than the six surveyed were maintained at the most-recent survey year. Universities' BEA regions and public/private status were obtained from the U.S. Department of Education, and the quantity of agricultural

biotechnology patents issued to each university each year were obtained from CHI Research. The WebCASPAR site contains university-level information on size of faculty by rank, average faculty salary, and total graduate and undergraduate enrollment.

In our population of 1,746 agricultural biotechnology patents awarded between 1985 and 2000, 30792 citations were made to 13,325 scientific works published between 1973 and 1997, an average of 2.31 per scientific work. Sixty-one percent (8,099) of the 13,325 cited publications were authored by at least one scientist from a U.S. institution, and 5,619 were authored by at least one U.S. university employee, during this 1973 - 1997 interval. [8] I restrict my attention to the 1985 - 1997 period in order to utilize information on the universities' own patenting, which did not begin until the early 1980s. Only 22% of the 5,619 cited university papers were published between 1973 and 1984, so little information was lost through this restriction. My final data set is a balanced panel consisting of thirteen annual observations on each of 177 universities, collectively producing 4,401 scientific publications that together were cited 9,984 times in agricultural biotechnology patents. [9]

Table 1 provides an annual breakdown of cited publications, citations-received, resource expenditures, and other factors in year of publication. The table underscores secular changes in the demand and supply of biotechnology research, only some of which can be modeled in the present static framework. Demand and supply shifts together may account for part of the post-1995 decline in agricultural biotechnology patent citations, even after (as in both columns 2 and 3) expected truncation bias has been eliminated. Agricultural and life-science budgets each have risen in real terms, and real industry R&D spending in agriculture has trended upward as well. The low incidence of postdoctoral researchers in agriculture reflects the fact that only about one-third of the universities in our sample had an explicitly agricultural program or college.

Econometric Model

Lags between university input and output should be substantial. I examined a variety of temporal patterns in both the science and graduate education equation, including distributed lags as well as finite lags on individual factors. Not surprisingly, lagged inputs did little to explain graduate enrollment. Graduate student numbers would depend largely on the university's current program reputation and on its current training capacity, which in turn depends on current faculty and staff resources. In contrast, much the strongest fit in the science equation was obtained with a geometric distributed lag, suggesting delays between the commitment of university resources and the consequent production of cited science can be quite long. Measures of university size and location were generally nonsignificant, mostly because highly correlated with the other regressors.

The final equations estimated were

(9) $\quad S_{it} = S_{it}[G_{it}, (G_{it})^{0.5}, B_{agr}^{it}, B_{bio}^{it}, P_{agr}^{it}, P_{bio}^{it}, R_{agr}^{it}, R_{bio}^{it}, IRD_t, PAT_{it}, S_{i,t-1}]$

(10) $\quad G_{it} = G_{it}[S_{it}, (S_{it})^{0.5}, B_{agr}^{it}, B_{bio}^{it}, P_{agr}^{it}, P_{bio}^{it}, R_{agr}^{it}, R_{bio}^{it}, IRD_t, PAT_{it}]$

where R_{agr}, R_{bio} are, respectively, the national quality rank of the university's agricultural and biology program;[10] PAT is the number of agricultural biotechnology patents awarded the university that year; IRD is aggregate agricultural R&D expenditure in industry; and budgets B_{agr}, B_{bio} and postdoctoral employees P_{agr}, P_{bio} are as defined above. Square roots of science and graduate education outputs are included to permit PPF curvature.

Equations (9) and (10) were fitted alternately with OLS, SUR, a fixed-effects estimator, and a GLS model to correct for heteroskedasticity. The fixed-effects approach searches for unexplained inter-university differences in productivity, and SUR accounts for unobserved

factors affecting both research and graduate training. Heteroskedasticity might arise in the same way as it does between wealthy and poor consumers in a consumption function: prediction errors can feasibly be higher in large universities than in small ones. Because graduate enrollments are large and publication counts are compounded here of fractional rather than whole authorships, count-data estimation approaches are not appropriate (Hausman, Hall, and Griliches).

Results

Single-equation estimates of equation (9) in table 2 and equation (10) in table 3 have R^2s ranging respectively from 0.54 to 0.65 and 0.74 to 0.98, rather high considering the wide variety of sample universities. SUR estimates are close to the OLS ones, and a Lagrange multiplier test of contemporaneous error correlation in the SUR model was rejected at the 95% level (χ^2 statistic 1.16 compared to critical value of 3.84). Although the 177 university-specific dummies in the fixed-effects models cannot jointly be rejected in F-tests, most were statistically nonsignificant and standard errors are nearly all higher in fixed-effects than in OLS estimates. Finally, GLS auxiliary equations used to account for cross-university differences in error variance fitted poorly and little confidence can therefore be given to the GLS estimates. The failure of SUR, fixed-effects, and GLS approaches to improve upon OLS suggest left-out variables had little influence on parameter estimates. The discussion below is based on the OLS model.

The 0.627 coefficient of lagged science output in table 2 suggests lags in university science production are moderate. Corresponding mean delay between university resource commitment and scientific publication is 1.7 years, somewhat less than the approximately 3.0-year mean lag in Pardey's study of agricultural experiment stations but identical to the 1.7-year mean lag that Pakes and Griliches identify for private-sector R&D. Long-run effects are derived

from the short-run ones in table 2 by dividing the latter by (1 - 0.627), although it should be

remembered this represents an average ratio for all of table 2's measured inputs.

Consistent with Adams and Griliches, program quality rank has had a positive *ceteris*

paribus impact on patent-cited research and graduate training. But the effect has been small,

although measured output is restricted here to agbiotech-patent-cited scientific publications.

Information spillins from industry, on the other hand, have had a strong positive effect on

university science production (table 2): a one-percent increase in private-sector agricultural

R&D has, in the short run, induced a 0.50 % increase and, in the long run, a 1.34 % increase in

university patent-cited research. But spillins have had nonsignificant effects on graduate

enrollment numbers (table 3).

Interestingly, a university's applied research effort, as reflected in its agricultural

biotechnology patent awards, has narrowly injured its patent-cited research and graduate

training. Sample-mean elasticities corresponding to parameters -0.647 and -23.45 in tables 2 and

3 are respectively -0.009 and -0.005. The positive or absorptive-capacity effect, that is, of the

university's more applied or patentable research on its more basic research and education

appears to be slightly outweighed by the competition for scarce resources that the more applied

research poses. The negative elasticities may reflect a secular shift in university administrators'

preference for patenting over publishing achievements. More generally, *PAT* effects in tables 2

and 3 are highly tentative because, as table 1 shows, university patenting did not become

important until the later years of our data set.

University Budget Allocation Policies

The significantly positive coefficients of postdoctoral employment P_{agr} and P_{bio} in tables 2 and 3

imply, by (3) and (4), that universities have allocated too little of their budgets to postdoctoral

fellows. Underspending on postdocs likely was related to the shortage in the 1980s and 1990s of

scientists trained in transgenic techniques, as biotech firms competed with universities for this

new and alluring form of human capital. More generally, the misallocation is consistent with

inherent inflexibilities in university governance and hiring, and in the inefficiencies that

commonly arise in multi-objective institutions. University life science budgets themselves are

strongly significant in tables 2 and 3, implying research and education outputs indeed are budget-

constrained. In tables 4 and 5, and following equations (3) – (8), I summarize budget impacts

under alternative allocation policies. Impacts are quoted as elasticities at sample mean.

Scientific returns to budget scale (table 4) are in the short run strongly decreasing unless

the new budgeted money is devoted nearly completely to postdoctoral employees.

A one-percent increase in agricultural budget, for example, boosts patent-cited science output by

8.36 % if the additional money is spent entirely on postdocs, by only 0.08 % if spent on non-

postdoc inputs, and by 0.17 % if allocated in proportion to mean expenditure shares.

Comparable figures for the university's total life science budget are 9.98 %, 0.20 %, and 0.46 %,

the sum of the elasticities in the agricultural and biology programs.

In the long run, however, that is completely allowing for science production lags, returns

to scale are substantially higher. For instance, a one-percent boost in total life science budget

brings a dramatic 26.8 % long-run rise in science output if the money is devoted entirely to

postdoctoral fellows, and a 1.24 % rise if allocated at mean expenditure shares. Allowing, in

other words, even for resource misallocation, long-run returns to scale in university science

production are increasing. Our mean 1.24 % estimate is similar to expenditure elasticities of

experiment station publication rates, ranging from 1.20 to 1.60, reported in Pardey. But it

contrasts with Adams and Griliches' finding of slightly decreasing returns to agricultural budget scale in U.S. universities.

Graduate education returns to budget scale (table 5) reveal patterns close to the short-run science returns in table 4. A one-percent budget rise distributed in historical-mean proportions between agricultural and biological sciences has raised graduate enrollment by 8.7 % if allocated entirely to postdocs, by 0.36 % if allocated to other inputs, and by 0.56 % if spent in proportion to the mean expenditure allocation between postdocs and other inputs. That is, decreasing returns to scale predominate unless the additional monies are allocated almost entirely to postdoctoral fellows. These effects are, nevertheless, high considering that the budgets examined here are earmarked officially for research and exclude specifically classroom expenses. The great importance of postdoctoral fellows to research and training productivity is suggestive of postdocs' strong publication incentives and frequent laboratory interaction with graduate students.

Expenditure elasticities in tables 4 and 5 are, except in the postdoc-only scenarios, greater in biological than in agricultural programs, a remarkable fact considering that the scientific publications focused on are those cited in agricultural biotechnology patents. Yet the elasticities should be understood in light of the fact that the representative university's biology program is substantially larger than its agricultural program. Effects of reallocating a dollar from one program to the other are found by comparing the budget and postdoctoral slopes in tables 2 and 3, which are moderately higher in agriculture than in biology. For example, applying equation (6) to table 2 shows that redirecting a million dollars from biology postdocs to agricultural postdocs would in the short run raise a university's agriculturally cited science output by 4.1 publications per year, a quite powerful effect.

Science and Education Production Possibilities

Production possibility frontier segments connecting research and training output are traced in figure 2. The cited-research segment of the figure is generated by holding inputs in table 2 at sample means and varying life science graduate enrollment G from zero to one standard deviation above sample mean. The graduate enrollment segment is generated by holding inputs in table 3 at sample mean and varying cited publications S from zero to one standard deviation above sample mean. Because scientific output and, to a lesser extent, graduate enrollments are strongly right-skewed, the majority of universities lie in the lower portions of the two segments, namely in the vicinity of A or C. Following our earlier discussion, I refer to those on segment AB as research-oriented and those on segment AC as education-oriented.

Figure 2 suggests graduate education in research-oriented universities is a weak substitute for science but that science in education-oriented universities is a weak complement to education. Among research-oriented institutions, boosting graduate enrollment from zero to a hundred reduces patent-cited publication output by only 0.7 per year (an effect which in table 2 indeed has high standard errors). Such weak substitution weakens even further — segment AB becomes flatter — as inputs continue to be reallocated toward education. A relatively strong initial substitution is reasonable because overhead costs incurred in establishing a new graduate program would outweigh any services the new students provide for their professors' research. As the graduate population rises, average training program costs decline and students' research contributions begin at least partly to pay for their educational keep.

Among education-oriented institutions, in contrast, science and education are complements. Boosting annual patent-cited publication output from zero to one raises graduate enrollment by thirteen, underscoring the essential role that the very existence of productive research plays in a successful graduate program. The complementarity weakens — segment CB

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becomes steeper — as inputs are reallocated toward research because the associated sacrifice in student training time begins to outweigh the educational advantages that successful research provides. The kink at point B should not, of course, be taken very seriously. In some universities, a zone of continuous substitutability between research and training would more likely be found. But the absence of many institutions in the vicinity of B suggests most universities instead seek niche markets, where technical relationships between research and graduate education are nonconvex.

Conclusions

The causal relationships one naturally is led to hypothesize between science and technology are difficult to test, primarily because the influence-flows between them are elusive. Most analysts have related R&D expenditures to journal publications as indicators of scientific output, to patent awards as indicators of technical change, or to yields or productivity as indicators of economic benefit. Our own effort instead has been to examine R&D input effects on the production of that life science which demonstrably has influenced later technology, as evidenced by literature citations in agricultural biotechnology patents. The work has involved following the paper trail from patent to scientific article to author, and thence to resource expenditures at the author's university. In the process, I uncover fundamental relationships not only between basic and applied research but also between the university's research and graduate education functions.

I find that a university's life-science research budget strongly affects its graduate education as well as its biotechnology-relevant science. Graduate education returns to research budget scale are decreasing, while research returns to research budget scale are decreasing in the short run but increasing in the long run. Importantly, there is no evidence that life science and graduate training compete strongly with one another. Rather, education in research-oriented

universities serves as a weak substitute for life science, while life science in education-oriented universities serves as a weak complement to education. Universities appear in general to seek out niche markets in graduate training and research, and nonconvexities in such situations are to be expected. On average, scale returns in biology budgets are higher than in agricultural budgets, although agricultural expenditures are slightly more effective in generating agriculturally cited science than are biology budgets. Universities hire too few postdoctoral fellows, especially in agricultural programs. Program quality ranking has its own influence on program success, and there is preliminary evidence of a feedback effect from applied research effort to basic research output.

Efforts to relate knowledge outputs to inputs exploit either the temporal, geographic, institutional, or citation linkages between them. Each approach has its strengths and weaknesses and I must tbe content with a gradual accretion of evidence from a variety of analytic methods. The present study has pursued a combination of approaches, using university institutional links to connect resource input to science output, and patent citation links to connect science output to successful technical change. Results strongly support the hypothesis that universities serve as a principal seedbed for cutting-edge technology, and hence provide an additional argument for public funding of university research.

Table 1. Life Science and Graduate Training Outputs and Inputs: Annual University Totals

Article Publication Year	Adjusted Number of Ag-Biotech-Cited Publications	Adjusted Number of Ag Biotech Citations	Number of Life-Science Graduate Students	Agricultural Sciences Budget	Biological Sciences Budget	Number of Postdocs in Agricultural Sciences	Number of Postdocs in Biological Sciences	Aggregate Industry Agricultural Biotechnology R&D	Number of University Agricultural Biotechnology Patents
1985	283	894	46,728	125.7	217.7	367	8,358	294.1	2
1986	343	942	47,259	132.8	231.9	404	8,869	308.2	2
1987	420	1067	47,259	132.8	249.6	436	9,355	293.7	0
1988	485	1331	47,967	134.5	267.3	455	9,639	320.6	2
1989	660	1607	48,852	141.6	279.7	504	10,349	329.7	4
1990	786	1954	49,914	143.4	292.1	511	10,862	343.5	4
1991	855	1715	51,330	150.5	300.9	553	11,385	353.9	5
1992	1007	2009	53,454	150.5	313.3	619	12,019	349.2	11
1993	1095	2058	54,870	152.2	325.7	686	12,495	368.2	11
1994	1053	2034	56,286	159.3	332.8	689	13,118	370.4	11
1995	1263	2176	56,286	168.2	338.1	672	13,344	396.0	12
1996	1335	1907	55,578	175.2	336.3	656	13,531	396.1	28
1997	1091	1375	54,339	173.5	350.5	679	13,417	429.7	53
Means	821	1621	51,551	148.7	295.6	563	11,416	350.3	11

Agricultural and biological science budgets and aggregate private R&D expenditures are reported in tens of millions of 1996 dollars.

Table 2. Agricultural Biotechnology-Cited Life Science Research in U.S. Universities: Parameter Estimates

Variable	OLS		GLS		Fixed Effects		SUR	
	Estimate	t	Estimate	t	Estimate	t	Estimate	t
Intercept	- 0.670	- 0.49	0.032	0.04	- 7.436	- 1.96	-0.315	- 0.23
Graduate Enrollment (G)	0.002	0.90	0.003	1.83	- 0.008	- 1.15	0.001	0.39
$G^{0.5}$	- 0.099	- 1.42	- 0.089	- 2.40	- 0.052	- 0.24	-0.098	- 1.40
Agr Budget (B_{agr})	0.436	3.28	0.193	1.65	0.901	2.60	0.490	3.68
Bio Budget (B_{bio})	0.323	3.07	0.185	2.26	0.108	4.20E-01	0.370	3.48
Agr Postdocs (P_{agr})	0.137	4.91	0.203	5.72	0.135	3.37	0.145	5.20
Bio Postdocs (P_{bio})	0.013	5.72	0.017	7.76	0.035	5.73	0.013	5.97
Agr Sci. Rank (R_{agr})	- 0.001	-0.20	0.004	0.87	0.001	0.05	-0.003	- 0.54
Bio Sci. Rank (R_{bio})	- 0.008	- 1.86	- 0.007	- 2.67	- 0.016	- 1.77	-0.008	- 1.92
Industrial R&D (IRD)	0.007	2.13	0.003	1.86	0.016	4.30	0.007	2.11
University Patents (PAT)	- 0.647	- 1.77	1.040	1.43	- 0.803	- 2.01	-0.673	- 1.84
Lagged Science ($S_{i,t-1}$)	0.627	28.65	0.531	24.37	0.420	16.41	0.627	28.63
R^2	0.63		0.54		0.65			

Dependent variable: S_{it}, number of life science publications cited in agricultural biotechnology patents, by university and year, 1985-1997 (observations through August 2000). Sample size: 2,301. Data used in these regressions are on a per-university basis but otherwise expressed in the same units as in table 1.

Table 3. Life Science Graduate Training in U.S. Universities: Parameter Estimates

Variable	OLS		GLS		Fixed Effects		SUR	
	Estimate	t	Estimate	t	Estimate	t	Estimate	t
Intercept	313.38	11.62	206.51	9.27	174.36	7.75	311.28	11.54
Science (S)	- 2.76	- 3.93	- 3.84	- 3.88	- 0.98	- 3.82	- 3.09	-4.40
$S^{0.5}$	15.63	3.79	16.60	3.72	3.65	2.33	15.52	3.77
Agr Budget (B_{agr})	48.10	18.42	52.30	17.63	- 4.98	- 2.13	48.00	18.52
Bio Budget (B_{bio})	39.30	19.05	40.10	16.50	9.50	5.54	39.00	19.13
Agr Postdocs (P_{agr})	7.68	14.38	7.26	9.68	1.22	4.61	7.80	14.60
Bio Postdocs (P_{bio})	0.50	11.52	0.78	15.55	0.52	13.37	0.51	11.80
Agr Rank (R_{agr})	- 1.69	- 15.92	- 1.41	- 13.13	0.18	1.48	- 1.69	15.93
Bio Rank (R_{bio})	- 0.15	- 1.71	0.14	1.55	- 0.17	- 2.81	- 0.16	-1.78
Indus. R&D (IRD)	- 0.03	- 0.51	0.06	1.53	0.32	13.73	- 0.02	-0.38
Univ. Patents (PAT)	- 23.45	- 3.12	- 21.97	- 2.61	- 14.85	- 5.61	- 22.83	-3.04
R^2	0.81		0.74		0.98			

Dependent variable: G_{it} , current graduate enrollment in life science programs, by university and year 1985-1997 (observations through August 2000). Sample size: 2,301. Data used in these regressions are on a per-university basis but otherwise expressed in the same units as in table 1.

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Table 4. Budget Impacts on Agricultural Biotechnology-Cited Life Science Research in U.S. Universities: Elasticities at Sample Means

Short Run

	Agricultural Sciences	Biological Sciences	Total Life Science
Marginal Dollar Allocated …			
Entirely to Postdoctoral Fellows	8.362	1.618	9.980
To All But Postdoctoral Fellows	0.079	0.116	0.195
In Proportion to Mean Expenditure Share	0.173	0.290	0.463

Long Run

	Agricultural Sciences	Biological Sciences	Total Life Science
Marginal Dollar Allocated …			
Entirely to Postdoctoral Fellows	22.418	4.338	26.756
To All But Postdoctoral Fellows	0.213	0.310	0.523
In Proportion to Mean Expenditure Share	0.464	0.778	1.242

Postdoctoral salary is assumed to be $30,000 per year in 1996 dollars.

Table 5. Budget Impacts on Life Science Graduate Training in U.S. Universities: Elasticities at Sample Means

	Agricultural Sciences	Biological Sciences	Total Life Science
Marginal Dollar Allocated ...			
Entirely to Postdoctoral Fellows	7.548	1.178	8.726
To All But Postdoctoral Fellows	0.139	0.225	0.364
In Proportion to Mean Expenditure Share	0.223	0.336	0.559

Post-doctoral salary is assumed to be $30,000 per year in 1996 dollars.

Research
Output

C

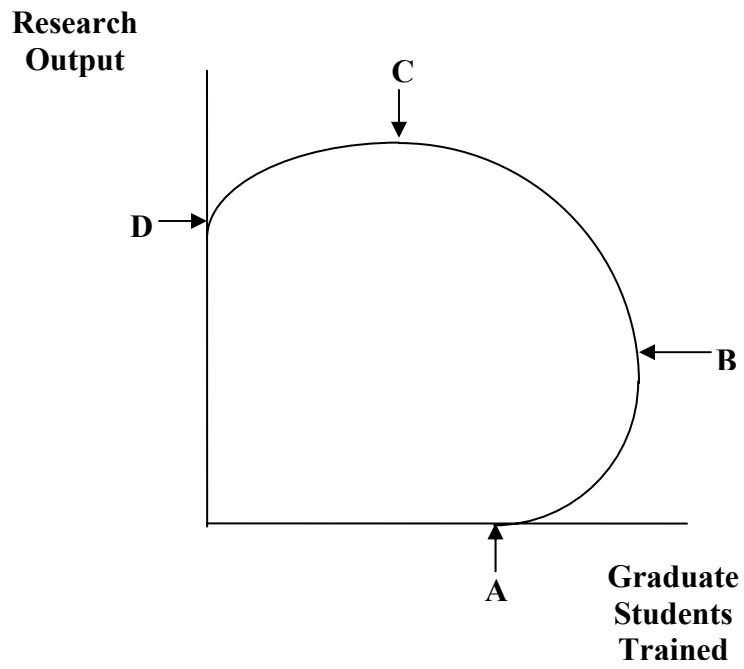D →

B

A

Graduate
Students
Trained

Figure 1. Research-education tradeoffs in universities: illustrative production possibility frontier
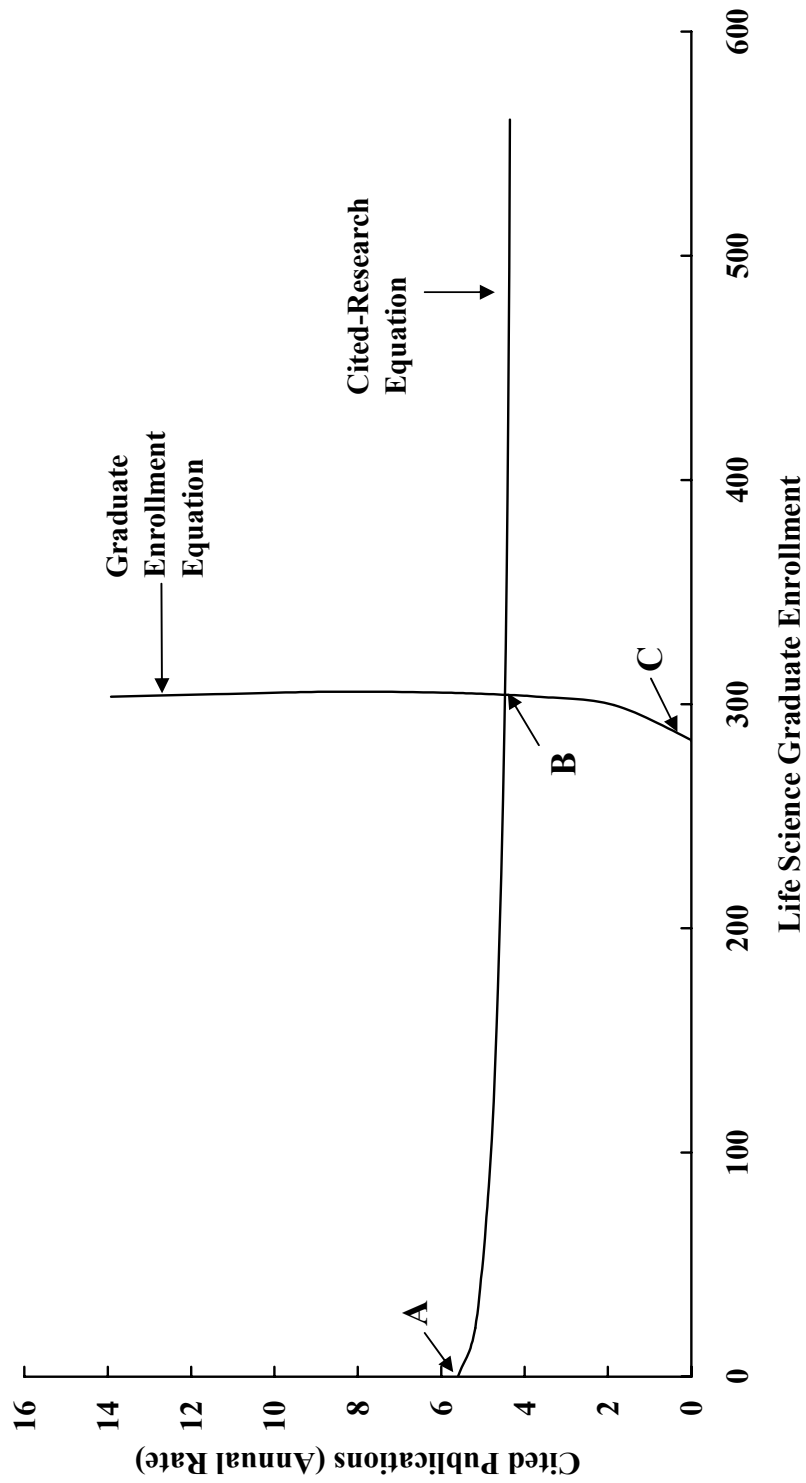
Figure2. Cited life science research and graduate training in U.S. universities: estimated production possibility frontier

Footnotes

[1]   Effects (3) – (8) are determined simultaneously if budget allocations in agriculture enhance or degrade the marginal returns to investment in biology or vice versa, as would be modeled by interaction terms in (1) of the form $S = S(B_{agr} B_{bio} , P_{agr} P_{bio} , ...)$.

[2]   Universities' agricultural biotechnology patenting rates initially were specified as an endogenous variable along with research and graduate training. However, little success was achieved in predicting it satisfactorily. Patenting has only recently become a university objective, and even then only in a minority of universities (Ervin et al.).

[3]   Three percent were assigned to nonprofit institutes, 3% to agencies of the federal government, and 4% left unassigned.

[4]   Alternative methods are available for dealing with multiple authorship (Narin). Under the "whole count" approach, a full credit is assigned to each author's university. In the "fractional count" approach, employed in this study, universities are assigned a fraction of a credit in proportion to the number of their employees in the author list. To correct for any truncation bias in the quantity of a university's cited articles, I followed Hall, Jaffe, and Trajtenberg (2001) by dividing into the jth observation the percentage of citations that already have been accorded to a cited article of the jth vintage, as estimated from the histogram of citations to articles published in the mid-1980s.

[5]   CHI Research has specialized since the late 1970s in the use of patent data as indicators of innovative activity. Some references on a patent's front page are to nonscientific literature such as congressional hearings. To check whether a cited work has significant scientific content, CHI first employs an expert to determine whether the work involved original science, then verifies that the work is available in standard research libraries.

[6]   "Instruction" budgets commonly refer only to classroom teaching and advising time. Life science R&D expenditures in the WebCASPAR data base include: "(a) all funds expended for activities specifically organized to produce research outcomes and commissioned by an agency external to the institution or separately budgeted by an organizational unit within the institution; (b) research equipment purchased under research project awards from current fund accounts; and (c) research funds for which an outside organization, educational or other, is a subrecipient" (National Science Foundation).

[7]   Medical science budgets were examined as well, but dropped after pretesting suggested they were nonsignificantly related to agbiotech-cited research.

[8]   Cited papers published from 1998 through 2000 were excluded because CHI Research had not yet cleaned these citations of nonscientific literature.

[9]   The identities of the 177 universities are available on request from the authors.

[10]   The number one is assigned to the top-ranked program, two to the second-ranked program, and so forth. The *Gourman Report* provides no rankings to programs below the top 35 or 40. I assigned each of these unranked programs the rank of 115, namely the mean of the rankings they would have received had a rank been assigned to them.

References

Acs, Z., D. Audretsch, and M. Feldman. "Real Effects of Academic Research: Comment." *American Economic Review* 82(1992):363-67.

Adams, J. "Fundamental Stocks of Knowledge and Productivity Growth." *Journal of Political Economy* 98(1990):673-702.

Adams, J., and Z. Griliches. "Research Productivity in a System of Universities." NBER Working Paper No. 5833, 1996.

Alston, J. M., G.W. Norton, and P.G. Pardey. *Science Under Scarcity*. Ithaca: Cornell University Press, 1995.

Buccola, S.T., and Y. Xia. "The Rate of Progress in Agricultural Biotechnology." *Review of Agricultural Economics* 26 (2004): 3 - 18.

Cockburn, I., R. Henderson, and S. Stern, "Balancing Incentives: The Tension Between Basic and Applied Research." NBER Working Paper No. 6882, 1999.

David, P., D. Mowery, and W. Steinmueller. "Analyzing the Economic Payoffs from Basic Research." *Economic Innovation and New Technology* 2(1992):73-90.

Ervin, D., T. Lomax, S. Buccola, K. Kim, E. Minor, H. Yang, L. Glenna, E. Jaeger, D. Biscotti, W. Armbruster, K. Clancy, W. Lacy, R. Welsh, and Y. Xia. "University-Industry Relationships and the Public Good: Framing the Issues in Agricultural Biotechnology." Proceedings of an Expert Workshop, Research Triangle Park, N.C., November 19 - 20, 2002 (www.agri-biotech.pdx.edu).

Evenson, R. "Spillover Benefits of Agricultural Research: Evidence from U.S. Experience." *American Journal of Agricultural Economics* 71(1989):447-52.

Foltz, J.D., K. Kim, and B. Barham. "A Dynamic Analysis of University Agricultural

    Biotechnology Patent Production." *American Journal of Agricultural Economics*

    85(2003):187-97.

Gourman, J. *The Gourman Report: A Rating of Graduate and Professional Programs in*

    American and International Universities, 2nd to 7th editions. Los Angeles: National

    Education Standards, various years.

Graff, G., A. Heiman, and D. Zilberman. "University Research and Offices of Technology

    Transfer." *California Management Review* 45 (Fall 2002):88-115.

Griliches, Z. "Patent Statistics as Economic Indicators: A Survey." *Journal of Economic*

    Literature 28(1990):1661-707.

_____. "Productivity, R&D, and the Data Constraint." *Amer. Econ. Rev. 84* (1994):

    1 - 23.

Grupp, H., and U. Schmoch. "Perception of Scientification as Measured by Referencing

    Between Patents and Papers." H. Grupp, ed., *Dynamics of Science-Based*

    Innovation. Berlin: Springer-Verlag, 1992.

Hall, B., A. Jaffe, and M. Trajtenberg. "Market Value and Patent Citations: A First Look."

    NBER Working Paper No. 7741, 2000.

_____. "The NBER Patent Citations Data File: Lessons, Insights, and Methodological

    Tools." NBER Working Paper No. 8498, 2001.

Hausman, J., B. Hall, and Z. Griliches. "Econometric Models for Count Data with an

    Application to the Patents-R&D Relationship." *Econometrica* 52 (1984):

    909-38.

Huffman, W.E., and R.E. Evenson. "Contributions of Public and Private Science and Technology to U.S. Agricultural Productivity." *American Journal of Agricultural Economics* 74(1992):751-56.

Huffman, W.E., and R.E. Just. "Funding, Structure, and Management of Public Agricultural Research in the United States." *American Journal of Agricultural Economics* 76(1994): 744-59.

Jaffe, A. "Real Effects of Academic Research." *American Economic Review* 79(1989):984-99.

_____. "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value." *American Economic Review* 76(1986):984-99.

Leathers, H.D. "Allocatable Fixed Inputs as a Cause of Joint Production: A Cost Function Approach." *American Journal of Agricultural Economics* 73(1991):1083-90.

Narin, F., K.S. Hamilton, and D. Olivastro. "The Increasing Linkage Between U.S. Technology and Public Science." *Research Policy* 26(1997):317-30.

Narin, F., CHI Research, Inc., Haddon Heights, New Jersey, personal communication.

National Science Foundation. *WebCASPAR: Your Virtual Bookshelf of Statistics on Academic Science and Engineering*, http://caspar.nsf.gov.

Pakes, A., and Z. Griliches. "Patents and R&D at the Firm Level." *Economic Letters* 5(1980):377-81.

Pardey, P.G. "The Agricultural Knowledge Production Function: An Empirical Look." *Review of Economics and Statistics* 71(1989):453-61.

Pardey, P.G., and B. Craig. "Causal Relationships Between Public Sector Agricultural

    Research Expenditures and Output." *American Journal of Agricultural Economics*

    71(1989):9-19.

Rausser, G. "Private/Public Research: Knowledge Assets and Future Scenarios." *American*

    Journal of Agricultural Economics 81 (1999):1011-27.

Rosenberg, N., and R.P. Nelson. "American Universities and Technological Advance in

    Industry." *Research Policy* 23 (1994):323-48.

Shoemaker, R., ed. *Economic Issues in Agricultural Biotechnology*. Agricultural

    Information Bulletin No. 762, Economic Research Service, USDA, 2001.

Zucker, L.G., M.R. Darby, and M.B. Brewer. "Intellectual Human Capital and the Birth of

    U.S. Biotechnology Enterprises." *American Economic Review* 88(1998):290-306.