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An ex ante economic and policy analysis of research on genetic resistance to livestock disease: trypanosomosis in Africa

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Abstract

This paper undertakes an ex ante economic analysis of research on how resistance to trypanosomosis — a dominant livestock disease in Africa — can be maintained and enhanced while retaining and reinforcing characteristics of economic importance to farmers, and on how 'trypanotolerance' can be imparted to susceptible animals while retaining their other important traits. The results indicate that potential benefits to research — historically field-based but increasingly biotechnology-driven — range from two to nine times potential costs and that the internal rate of return on investments can be six times the real interest rate. Field-based research, while exhibiting lower potential benefits on aggregate than does biotechnology research, is also less costly and, because of its more immediate payback, has higher internal rates of return. Returns to biotechnology research hinge on close links with field-based research and on strategic but relatively small incremental human and capital investments. The results also suggest that further research is needed to consistently identify and track the impacts of alternative intellectual property rights (IPRs) options on the levels and distributions of biotechnology research benefits. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Africa; Livestock; Disease; Biotechnology; Intellectual property

1. Introduction

A range of diseases seriously constrains livestock development world-wide (Williams et al., 1995). In Africa, tsetse fly-transmitted trypanosomosis is particularly severe (Jahnke et al., 1988; d'Ieteren, 1993). Annual direct and indirect losses from trypanosomosis have been estimated to be at least billion US$ (bUS$) 1.6 (Swallow, 1998) and as high as bUS$ 5 (Murray and Gray, 1984). Conventional control options are either unavailable (vaccines), expensive (chemotherapy), or difficult to implement effectively (vector suppression). There is, thus, great interest in understanding and exploiting the inherited resistance to trypanosomosis of some livestock species. This resistance — commonly referred to as 'trypanotolerance' — allows animals to survive, reproduce, and remain productive under trypanosomosis risk without the aid of curative or prophylactic drugs (d'Ieteren et al., 1999).

Research on trypanotolerance must accomplish two aims. First, it must identify how disease resistance in trypanotolerant breeds can be maintained and enhanced while retaining and reinforcing other characteristics of economic importance to farmers. Second, it must find ways to confer the trypanotolerance trait to susceptible animals while retaining their other traits of economic importance (d'Ieteren et al., 1999).

Answers to these challenges lie partly in the domain of quantitative field-based research aimed at

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improved utilisation of trypanotolerance in African cattle through selective breeding in pilot schemes. They also lie partly within the realm of biotechnology research in molecular genetics, which aims to determine where precisely in the bovine genome the genes controlling trypanotolerance and other key traits are located (Teale, 1993).

This paper undertakes an ex ante economic analysis of research along these two lines.[1] Section 2 describes field-based and biotechnology research on trypanotolerance and outlines their potential for generating usable outputs. The modelling strategy employed to quantify impacts of that research in Africa is then described and the results of the modelling exercise presented and discussed. Implications for research policy round-out the analysis.

2. Research on trypanotolerance

Quantitative field-based research has yielded basic tools with which the trypanotolerance trait can be identified, quantified, and exploited. Considerable progress has been made in using criteria on trypanotolerance in the field to quantify links between trypanotolerance measurements and a number of economically important production traits (d'Ieteren, 1993). But these conventional field-based approaches to selection and breeding are lengthy and at times inaccurate. Recent advances in DNA technology offer the prospect of progress in understanding typanotolerance in more direct and precise ways.

'Marker-assisted selection' (MAS) of target genes within breeds of tolerant animals, and 'marker-assisted introgression' (MAI) of target genes from tolerant to susceptible breeds are major research thrusts in molecular genetics research on trypanotolerance. Coupled with artificial insemination and embryo transfer technology, MAS and MAI are expected to make possible rapid gains in genetic resistance to trypanosomosis in the cattle population of affected areas of Africa (Teale, 1993).

[1] An international network of institutions is currently undertaking research and outreach activities related to trypanotolerance. Institutions included are the International Livestock Research Institute (ILRI) — which has a prominent role — and several research and development organisations from a number of African countries, Europe, the US, and Australia.

Marker-assisted techniques have moved from being theoretical concepts to practical appreciation only over the last decade. This has been due in large part to progress in broader initiatives to develop high-density microsatellite linkage maps in a number of vertebrate species. The human and mice genome projects are the most prominent in this regard. Technical innovations and strategies developed in these wider projects are being adapted by geneticists and molecular biologists working on trypanotolerance. The genetic linkage maps emerging from these efforts are being used to develop strategies for MAS and MAI for trypanotolerance. While the ultimate aim is MAS and MAI schemes for domestic livestock species such as cattle and sheep, the breeding cycles of these animals render research lengthy and difficult. Moreover, not only are these livestock species expensive, they are difficult to handle in the large numbers required to achieve statistically significant results. Other mammals are also susceptible to trypanosomosis. Some, like mice, are cheap, small in size, easily maintained, and have fecundity rates and gestation periods that permit production of up to four generations per year. To reduce cost and speed progress, mice are also being used in parallel with the target species.[2]

To date, five 'quantitative trait loci' (QTL) for trypanotolerance in mice have been identified with significant effects on chromosomes 1, 5, and 17 (Iraqi et al., 2001; Kemp et al., 1996, 1997). The resulting 'mouse model' — which is nearing completion — will serve as a guide for efforts to construct comparable models for cattle and other targeted domestic livestock species.

The equipment, methods, and processes available for this work are changing rapidly and fundamentally altering the questions that scientists can explore (Cunningham, 1999). Most critically, they could shorten the lags between key research milestones. But at present, it remains unclear by how much and at what cost relative to potential benefits.

These considerations have important implications for the size and distribution of potential impacts of biotechnological research on trypanotolerance, viewed both in their own right and alongside more conventional quantitative field-based approaches. The modelling strategy developed to quantify the potential

[2] The genetic makeup of mice is also comparatively better understood.

impacts of both lines of research takes these considerations into account.

3. Modelling strategy

Given the differences and uncertainties regarding the nature of the discovery-to-delivery pathways for the outputs of quantitative field-based and biotechnology research on trypanotolerance, the overall objective of the modelling exercise was not to provide definitive estimates of research impacts but rather to establish the likely magnitude of benefits relative to costs under alternative assumptions of research progress. This was achieved by quantifying the implications for aggregate and regional welfare of different scenarios of research duration toward key milestones.

The overall strategy pursued was based on a three-step process. First, research target zones were identified and characterised in the usual fashion (Alston et al., 1995). Second, potentials for technology generation and adoption were specified and, third, potential costs and benefits of research initiatives were quantified.

The focus was on cattle because they are the principal domestic livestock species affected by trypanosomosis for which a significant body of field-based research has been undertaken and for which reliable genetic biotechnologies have been developed or are in prospect. Following Kristjanson et al. (1999), the presence of tsetse flies was taken to define the risk of trypanosomosis in cattle. Data layers for tsetse distribution and cattle density were overlain, showing that approximately one-third of sub-Saharan Africa's 150 million cattle are found in tsetse-infested areas. [3]

Also following Kristjanson et al. (1999), two research target zones were specified, namely eastern and southern Africa, and western and central Africa. [4] The most relevant difference between these two segments of Africa is in the relative importance of trypanotolerant and trypanosusceptible cattle within them. Trypanotolerant cattle are largely absent in tsetse-infested areas in eastern and southern Africa whereas they are prominent — and often the only extant breed — in much of the tsetse-affected areas of western and central Africa (Kruska et al., 1995; Shaw and Hoste, 1987).

Underlying the effort to quantify potentials for technology generation and adoption was the assumption, now standard in the literature, that successful research induces shifts in the aggregate supplies of key outputs (Alston et al., 1995). Successful breeding and selection for trypanotolerance will give rise to productivity gains, due to an increased capacity to control parasite development and limit the onset of anaemia. But given the alternative research thrusts and the uncertainties surrounding the pace of progress within the biotechnology thrust, these gains could appear at sharply different times, with important welfare implications.

To account for these factors, Table 1 shows key parameters that define the potential for technology generation and adoption under four scenarios. Scenario I captures the discovery-to-delivery profile and potential productivity impacts of quantitative field-based research on trypanotolerance. Scenario II describes potentials for technology generation and adoption from biotechnology research assuming a continuation of the current rate of progress in this research — i.e. using existing methods. This is taken as the 'pessimistic' view of biotechnology research. In the 'moderately optimistic' scenario III, the assumed profile reflects accelerated progress in biotechnology research due to the exploitation of innovations in related branches of research (Cunningham, 1999). Scenario IV models a 'highly optimistic' view of biotechnology research by assuming an even more rapid movement from discovery to delivery and uptake of biotechnology research outputs, again due to exploitation and application of advances in related branches of biotechnology research.

[3] The Kristjanson et al. (1999) computation was a major advance in that it allowed, for the first time, a unified spatially explicit representation of livestock populations — and thus, meat and milk production — in Africa's tsetse-affected areas. However, the data available both then and now do not permit livestock populations to be linked to several other factors that define disease risk (i.e. in addition to presence of tsetse flies) — e.g. trypanosome species, topography, natural vegetation types, livestock breeds, livestock and human population distributions and densities, conditions in factor and product markets, and agricultural production systems. Assessments of potential returns to research — such as that in this paper — would be greatly enriched by such information.

[4] Note, however, that the rationale for this specification differs somewhat in the current analysis from that used by Kristjanson et al. (1999), which is based largely on assumptions about meat and milk trade (p. 85).

Table 1
Model parameters

Parameter	Scenario I (field-based)	Scenario II (pessimistic biotechnology)	Scenario III (moderately optimistic biotechnology)	Scenario IV (highly optimistic biotechnology)
Years to mice QTL[a] map	Not applicable	7	5	5
Years (cumulative) to cattle QTL map	Not applicable	30	12	7
Years (cumulative) to maximum adoption	1	45	25	10
Maximum adoption rate (%)	10	50	50	50
Maximum ENPG[b]: E & S[c]	0.48	23.66	23.66	23.66
Maximum ENPG[b]: W & C[d]	1.82	16.02	16.02	16.02
Most likely ENPG: E & S	0.06	2.77	2.77	2.77
Most likely ENPG: W & C	0.21	1.87	1.87	1.87
Minimum ENPG: E & S	0.00	0.00	0.00	0.00
Minimum ENPG: W & C	0.00	0.00	0.00	0.00
Dissemination threshold[e]: E & S	0.18	8.80	8.80	8.80
Dissemination threshold[e]: W & C	0.68	5.95	5.95	5.95
Probability of dissemination: E & S	0.45	0.45	0.45	0.45
Probability of dissemination: W & C	0.45	0.45	0.45	0.45
Conditional ENPG: E & S	0.27	13.15	13.15	13.15
Conditional ENPG: W & C	1.01	8.90	8.90	8.90

[a] QTL: quantitative trait loci.
[b] ENPG: expected net productivity gain.
[c] E & S: eastern and southern Africa.
[d] W & C: western and central Africa.
[e] Dissemination thresholds are computed as simple averages of the minimum, most likely, and maximum ENPGs.

There are two major differences among the three biotechnology scenarios: first, regarding the number of years to generate the QTL maps for mice and cattle and, second, regarding the number of years to achieve maximum adoption by farmers of animals possessing the trypanotolerance trait identified via MAS and MAI, which, as described earlier, would be introduced into herds via such methods as artificial insemination and embryo transfer.

In scenario II 'pessimistic', the assumption is that the QTL map for mice will have no relevance for cattle. Researchers will, thus, have to focus only on the search for the cattle QTL map, which could require an additional 20–25 years of work. Maximum adoption will not occur for yet another 15 years.

In scenario III 'moderately optimistic', the assumption is that the mice QTL map will have significant but incomplete relevance for cattle. Researchers will need another 5–10 years to complete the cattle QTL map. Maximum adoption will be achieved only slightly more rapidly than in scenario II — i.e. after 13 years.

Table 2
Data on prices, quantities, and elasticities[a]

Parameter	Eastern and southern Africa		Western and central Africa	
	Meat	Milk	Meat	Milk
Supply elasticity	1.4	1.0	1.7	1.0
Demand elasticity	1.8	0.5	1.8	0.5
Price (US$/tonne)	1384	248	2019	404
Quantity (tonne)	374000	2113000	398000	759000

[a] Source: Kristjanson et al. (1999) (p. 87).

In scenario IV 'highly optimistic', the QTL map for mice has a 100% fit for cattle — i.e. there is a one-to-one correspondence between trypanotolerance genes in mice and cattle. The task for researchers will, thus, be one of minor verification and refinement, which will require less than 2 years of additional work. Maximum adoption in this case will be reached soon thereafter — i.e. 3 years. [5]

Distinct maximum, most likely and minimum productivity gains for both quantitative field-based and biotechnology research were assumed for eastern and southern Africa as well as western and central Africa. Yield gains reported for tolerant and susceptible animals were converted to region-specific estimates by weighing them by the shares of each kind of animal in each region (see Appendix for details of method used).

Data on the adoption of livestock biotechnology in Africa are not available. But there is direct evidence on the of rates of adoption of the trypanotolerance trait by farmers. Between 1977 and 1985, numbers of trypanotolerant cattle in tsetse-infested areas in 18 countries in central and western Africa previously unpopulated with cattle grew by 10% per year (Shaw and Hoste, 1987). By 1985, they accounted for 50% of the total cattle population (ILCA, 1992). Based on these findings, a maximum adoption rate of 50% was assumed under all four scenarios, with each tracking a logistic profile. [6]

Potential benefits from research activities in the four scenarios were quantified using a closed economy economic surplus model. The closed economy assumption was based on data that indicate that in 1997 total trade (imports plus exports) equalled just 1.9 and 0.7% of total meat and milk production, respectively, in both regions of Africa (FAOSTAT, 1999).

Base price and quantity data were taken from Kristjanson et al. (1999) and are shown in Table 2. The prices are weighed averages of 1997 farm-gate prices of meat and milk for each region. Regional meat and milk production figures were obtained by multiplying average 1989–1993 production by the percentage of animals found in tsetse-infested areas in each region. Elasticities of supply and demand for meat and milk taken from Kristjanson et al. (1999), are based on several regional empirical studies.

Research costs were assumed to include human and capital expenditures and estimated based on relevant investments by ILRI, which is a global leader in research on trypanotolerance and accounts for an estimated 65% of global research expenditures. Noting that ILRI devotes one-third of a full-time equivalent (FTE) senior scientist to field-based research on improved utilisation of trypanotolerant African cattle through selection and breeding in pilot schemes at a rate of US$ 360,000 per FTE, a similar rate is assumed for scenario I. Following Kristjanson et al. (1999) (p. 89), an annual growth rate of 3% was assumed for these costs. Initial capital costs of US$ 770,000 are those associated with establishing source herds.

Human resource costs under scenarios II, III, and IV were based on ILRIs commitment of three FTEs to research on the molecular genetics of trypanotolerance, again at a rate of US$ 360,000 per FTE and assuming an annual growth rate of 3%. Capital costs were based

[5] These three scenarios of progress in biotechnology research on trypanotolerance are not arbitrary guesses, but rather are based on recent developments in the molecular genetics of trypanotolerance. Specifically, the assessment is based on progress in work being undertaken by ILRI and its partners and in which one of the co-authors, Fuad Iraqi, is deeply involved (Iraqi and Teale, 1998; Iraqi et al., 2001; Kemp et al., 1997). At current rates of progress, trypanotolerance genes in mice are expected to be identified within 5–10 years. Verifying the relevance of these genes in cattle and sheep and identifying others could take another 20–25 years, again at current rates of progress. But the nature of biotechnology is such that current rates of progress are unlikely to hold for long. For instance, for many years parentage verification was based on blood-group typing. As mentioned above, this is now being replaced by typing based on microsatellite characterisation. Within a few years, conversion to the DNA methodology will be all but complete, with significant savings from the greater precision attained. Costs will fall further as such methods as in vitro fertilisation, cloning, and transgenesis are refined, and as automated methods such as DNA chip technology or mass spectrometry make manual gel-based methods obsolete. Further economies of a more direct sort are possible using hair rather than blood in sampling (Cunningham, 1999). These developments could cut the period to identifying the QTL map for trypanotolerance in mice by one-third and in cattle by two-thirds.

[6] This adoption rate is high by most standards, but can be justified on two grounds. First, if the trypanotolerance trait is identified and conferred on susceptible animals or enhanced in partially tolerant animals, it will have major welfare impacts. Most critically, these impacts will be direct and clearly recognisable to farmers — i.e. reduced mortality and morbidity in animals, translating into increased productivity in livestock and cropping systems. Second, even where such gains have been relatively small and incremental, farmers in tsetse-infested areas have adopted improved animals with alacrity (Shaw and Hoste, 1987).

Table 3
Potential welfare impacts of research across regions under alternative scenarios of technology development and release (million US$, percent of total benefits in brackets)

	Scenario I (field-based)	Scenario II (pessimistic biotechnology)	Scenario III (moderately optimistic biotechnology)	Scenario IV (highly optimistic biotechnology)
Producer benefits	14.17 (43)	29.19 (43)	122.10 (43)	215.06 (43)
Consumer benefits	18.06 (57)	38.69 (57)	159.36 (57)	280.68 (57)
E & S Africa				
Producer benefits	3.22 (10)	18.28 (27)	75.83 (27)	133.57 (27)
Consumer benefits	4.29 (13)	24.41 (36)	101.22 (36)	178.28 (36)
Total E & S	7.51 (23)	42.69 (63)	177.05 (63)	311.85 (63)
W & C Africa				
Producer benefits	10.95 (34)	11.16 (16)	46.27 (16)	81.49 (16)
Consumer benefits	13.77 (43)	14.03 (21)	58.15 (21)	102.40 (21)
Total W & C	24.72 (77)	25.19 (37)	104.42 (37)	183.89 (37)
Total benefits	32.23 (100)	67.88 (100)	281.46 (100)	495.74 (100)
Total costs	6.38	52.49	53.81	53.81
Benefit:cost ratio (BCR)	5.05	1.29	5.23	9.21
Internal rate of return (IIR)	32	2	12	31

on ILRIs projected capital investments in this work, assuming that this constitutes 65% of global capital allocation to molecular genetics research on trypanotolerance. This amounted to an initial capital outlay of million US$ (mUS$) 1.23 under all three scenarios II, III, and IV. In scenarios III and IV, an additional cost of US$ 230,800 every 3 years was included to capture the cost of up-grading and purchasing new equipment so that scientists can keep pace with, and take advantage of, developments in related fields in molecular genetics.

The model was solved over a 50 years horizon assuming a 5% real interest rate, which has been used in a number of ex ante analyses of research impact in Africa (e.g. Kristjanson et al., 1999; Mills, 1998a,b).

4. Results

Table 3 shows the distribution of estimated welfare impacts between producers and consumers, and across the two research target zones, under the four scenarios of technology development, release, and uptake. In scenario I (quantitative field-based), benefits are five times costs (the benefit:cost ratio, BCR = 5.05), and at 32%, the internal rate of return (IRR) is well above the assumed real interest rate of 5%. In scenario II (pessimistic biotechnology), research benefits barely cover costs (BCR = 1.29) and the IRR of 2% is lower than the assumed real interest rate. In scenario III (moderately optimistic biotechnology), the BCR of 5.23 is comparable to that of field-based research, but the IRR of 12%, while more than double the real interest rate, is considerably lower. In scenario IV (highly optimistic biotechnology), the BCR equals 9.21, almost double that for both field-based research and moderately optimistic biotechnology, and the IRR of 31% matches that of field-based research. Although total costs under scenarios III and IV are mUS$ 1.32 higher than they are under scenario II, by significantly shortening the period to expected release of research output, this additional investment adds over mUS$ 213 to discounted benefits under scenario III and mUS$ 427 under scenario IV.

Consumers capture larger shares of benefits than do producers in all four scenarios and in both regions.[7] Gains from field-based research accrue largely to

[7] Note that there is no difference across the three scenarios of biotechnology research in either this distribution or in that between regions because of the computation method employed — i.e. all parameters are constant across the three scenarios except for the research and adoption profile (Table 3).

farmers in the western and central region where potential productivity gains from this type of research are largest (Table 1). The converse is true for biotechnology research. Furthermore, potential productivity gains for across-breed MAI are higher than are they are for within-breed MAS. MAI is most relevant in eastern and southern Africa, where susceptible breeds predominate. Thus, while the total value of meat and milk production in western and central Africa is 85% higher than in eastern and southern Africa (Table 3), producers in the eastern and southern region capture almost two-thirds of total gains under the three biotechnology scenarios.

5. Implications for research policy

At first glance, since resources devoted to field-based research on trypanotolerance generate significantly lower potential benefits on aggregate than do those from biotechnology research — even under the most pessimistic scenario of progress in biotechnology research — one might conclude that overall priority should be given to biotechnology. But such a conclusion would be incorrect for several reasons.

A key recognition is that farmers are conservative in their breed preferences, particularly those farmers rearing multi-purpose animals in mixed crop-livestock production systems, as in much of Africa. Outputs of biotechnology research must match farmers' needs. These needs are reflected in selections of animals based on traits for which heritability is known, not all of which will be linked to trypanotolerance. The relevance of biotechnology research, and, most important, the likelihood that farmers will actually adopt the outputs of that research and realise the potential gains, thus, hinges on close links with field-based work. The latter, it should be noted, has as a high an IRR as biotechnology research under the most optimistic scenario of progress.

The outputs of MAS and MAI schemes will have to be multiplied and delivered in the real world — i.e. outside the experimental environment within which most current work is being undertaken. Specifically, 'source' or 'reference' herds will need to be maintained, and the embryos and nuclei emerging from MAS and MAI within these herds appropriately stored and effectively delivered to farmers. Ideally, such herds should be held in the village settings within which farmers make their decisions.

But historically — even in livestock experiment stations where environmental factors are easily controlled — work on the improvement of African livestock has often produced disappointing results. In particular, delivering superior animals to local breeders has met with major institutional hurdles (Cunningham, 1999; Planchenault and Traore, 1993).

These considerations raise enormous challenges in delivering outputs of research on trypanotolerance to farmers. Three broad options exist: private delivery using markets; provision by public agricultural research and extension systems largely outside markets; and mixed private–public provision using farmer organisations. Each option has advantages and drawbacks relative to the others.

Most research on trypanotolerance has been funded by the public sector, with a view to alleviating poverty in small-scale agriculture. The likely requirement of profit-driven private sector involvement in the future delivery of trypanotolerance innovations raises complex issues in intellectual property rights (IPRs) over these innovations and greatly complicates the picture. Moschini and Lapan (1997) demonstrate that when there is scope and incentive to acquire IPR over technological innovations, research benefits are likely to differ significantly — in both size and distribution — depending on where these rights reside. Specifically, they show that if private firms hold these rights, the conventional assumption of competitive pricing of technologies is inappropriate because these firms will extract monopoly rents. Unfortunately, the data required to examine this issue rigorously within the current analysis do not exist; the technologies in question have yet to be developed. However, the question is crucial to fully interpreting the results reported in Table 3 and warrants explicit consideration.

Moschini and Lapan (1997) (p. 1240) show that when private firms hold IPR over innovations, total benefits can fall by up to 60%, depending on assumptions about relative supply and demand elasticities. Falck-Zepeda et al. (2001) report rent transfers of 30.5% of producer surplus from farmers to input suppliers who hold intellectual property rights over a genetically-improved agricultural technology. In Table 4, these findings are used to explore the implications of two distinct regimes of ownership rights over,

Table 4
The size and distribution of benefits assuming alternative ownership rights and delivery pathways for biotechnology (million US$)

Ownership and delivery regime	Input supplier surplus	Producer surplus	Consumer surplus	BCR
Private ownership & delivery	33.52[a]	76.32	143.42	4.71[b]
Public ownership & delivery	0	122.10	159.36	5.23

[a] Assumes that private input suppliers capture 30.5% of producer surplus (Falck-Zepeda et al., 2001).
[b] Assumes that total benefits decline by 10% (Moschini and Lapan, 1997).

and delivery of, research outputs (i.e. the embryos and nuclei emerging from MAS and MAI schemes, or the methods and processes used to produce them) specifically, based on the results for scenario III reported in Table 3, complete private ownership and delivery of innovations on the one hand, and complete public ownership and delivery or the other, are contrasted. The figures shown in Table 4 are intended to be illustrative and not definitive.

Suppose property rights and responsibility for delivery reside with the private sector, and that private firms extract monopoly rents as demonstrated by Falck-Zepeda et al. (2001). Suppose further that under these conditions total benefits fall by 10% compared with the case of pure public ownership and delivery, which is well within the range reported by Moschini and Lapan (1997) (p. 1240). The results under scenario III would change as follows: the BCR and consumer benefits would by 11%, but producer surplus by almost 60%. Diffusion of research results, already assumed to be slow, would likely be even slower. There may be no system of private ownership of research results that would justify private investment in this technology.

Under public ownership of intellectual property rights and public delivery of innovations, gains from research can be assumed to be passed on to producers and consumers and the level and distribution of gains reported in Table 3 hold. This amounts to a 'defensive patent strategy' in which protected innovations are in effect licensed out at zero cost to farmers. However, even here problems arise. The institutional constraints facing public delivery of agricultural technologies in many African countries mentioned above suggest that pure public ownership of rights and pure public delivery of technologies are unlikely to be feasible and sustainable.

A third option, midway between pure private and pure public ownership of intellectual property rights, might be for the public sector to pursue a 'market segmentation strategy' in which innovations are licensed out at zero cost for marginal farmers while larger farmers who are more able to pay for the technologies are charged some fee.[8] Alternatively, private companies could be contracted to undertake the delivery of innovations for which the public sector has ownership but for which the private sector can charge market-determined rates. Under any scenario, institutional capacity to manage the implications of IPR for research activities is crucial to the distribution of the gains from biotechnological research on trypanotolerance.

6. Summary

Under conditions of increasingly tight research budgets, pressures to demonstrate relevance, cost-effectiveness, and the impacts of particular research thrusts are mounting (Alston et al., 1995). Few efforts have been made to complete such analyses for research on livestock disease resistance and none at all for research on trypanotolerance in Africa, whether it be field-oriented or biotechnology-based. This paper seeks to fill that gap by undertaking an ex ante assessment of the potential impacts of these two research thrusts on trypanotolerance in Africa.

By increasing knowledge of mammalian genetic structure and contributing to fast and convenient measurement of that structure, biotechnology is opening new scope for understanding livestock diseases such

[8] Determining fair and sustainable fees for the latter group would be a crucial empirical question requiring considerable detailed research. Further, how precisely intellectual property would be protected is far from clear. For instance, in the US, cattle genetic improvements are protected largely by trade marks. The extent to which such an option is feasible in much of Africa is unclear.

as trypanosomosis. However, because of the costs of undertaking biotechnology-based research on livestock, the uncertainty of the economic benefits, and the lack of knowledge of genes that produce useful modifications, usable results may not emerge for many years. The current analysis indicates that relevant and economically justifiable research on trypanosomosis in Africa depends on close links between field-based and biotechnology research as well as scientists abilities to keep pace with, and take advantage of, related developments in molecular genetics. Maintaining current levels of human resource allocations and making strategic but relatively small capital investments would ensure that capacity. The results also suggest that further research is needed to consistently identify and track the impacts of alternative intellectual property rights regimes, their implications for delivery options, and thereby their effects on the levels and distributions of research benefits.

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Appendix A. Modelling the productivity gains

Following Alston et al. (1995) — and employing methods recently applied by Kamau et al. (1997), Mills (1998a,b), Mills and Karanja (1997), and Omamo et al. (2000) — K_{it}, the zone-specific research-induced supply shift for commodity i in period t was calculated as follows:

$$K_{it} = \Pr(k_i > k_i^{\mathrm{a}}) E[k_i | k_i > k_i^{\mathrm{a}}] \frac{A_{it} P_{i0}}{\varepsilon_i}$$

where k_i is the probability of net productivity gains, k_i^{a} a dissemination threshold, A_{it} the expected adoption rate for the period, P_{i0} the initial unit price of the commodity, and ε_i is the supply elasticity for the zone. $\Pr(k_i > k_i^{\mathrm{a}})$ represented the probability that the net productivity gain will exceed the dissemination threshold. $E[k_i | k_i > k_i^{\mathrm{a}}]$ is the expected net productivity gain conditional upon the dissemination threshold being exceeded.

Minimum, most likely and maximum potential net productivity gains achieved by research were assumed to form a triangular distribution. Two parameters were calculated based on this distribution: first, the probability of exceeding the net yield gain threshold for the technology to be released for dissemination — commonly referred to as the "probability of research success" (Alston et al., 1995, p. 477); and, second, the expected net yield gain conditional on the dissemination threshold being exceeded. The results of these calculations are presented in Table 1.

The strategy used to model these productivity gains reflected precisely the fundamental aims of research on trypanotolerance — i.e. how resistance to trypanosomosis can be maintained and enhanced in tolerant animals while retaining and reinforcing characteristics of economic importance to farmers, and how it can be imparted to susceptible animals while retaining their other important traits. Potential gains in meat and milk output under the field-based research thrust were obtained directly from field data (ILCA/ILRAD, 1986, 1988; Planchenault and Traore, 1993). To identify potential meat and milk yield gains under the biotechnology research thrust, estimates of whole-herd productivity — as captured by a herd productivity index covering meat and milk production — emerging from long-term field research on cattle produced under contrasting conditions of disease risk in various tsetse-affected parts of Africa were used (ILCA/ILRAD, 1986, 1988).

For *field-based research*, maximum, most likely and minimum gross yield gains for tolerant animals of 3.11, 0.36, and 0% were obtained directly from data reported by Planchenault and Traore (1993) (p. 37). For susceptible animals, equivalent figures were 0.59, 0.07, and 0%, respectively (ILCA/ILRAD, 1988, p. 249). The net productivity gains for the field-based option shown in Table 1 were obtained by reducing the gross productivity gains by farmers adoption costs, taken here to be 19.1%, which is the cost of

introducing a desired bull into a herd, based on the representative herd structure reported in Kristjanson et al. (1999) (p. 84).

For *biotechnology research*, potential gains to MAI and MAS were considered separately. Estimates of maximum, most likely and minimum gross productivity gains for MAI were taken from ILCA/ILRAD (1988) (p. 249). The maximum gain possible was taken to be that corresponding to the difference between the productivity index value of a susceptible animal produced under high disease risk but with chemoprophylaxis (137.5) and that of a similar animal produced under conditions of no disease risk and no chemoprophylaxis (172.5). The estimate of most likely gain was given by the difference between the index value of a susceptible animal produced under high disease risk with chemoprophylaxis (137.5) and the productivity of a tolerant animal produced under similar conditions with no chemoprophylaxis (141.6). The minimum yield gain was taken to be zero — i.e. the susceptible animal would be able to survive under high risk but with no discernible yield gain. The resulting maximum, most likely and minimum net yield gains were 25.45, 2.98, and 0%, respectively. They were assumed to apply throughout eastern and southern Africa, where susceptible cattle predominate and thus where MAI is likely to be the key intervention. An estimated maximum gross productivity gain for MAS of 13.0% was obtained from results of quantitative phenotyping of trypanotolerant cattle reported from Trail et al. (1994) (pp. 189–190). Most likely and minimum gross productivity gains for MAS of 1.52 and 0% were generated using the relationship between comparable estimates for MAI. To estimate the gain applicable for western and central Africa — which comprises both trypanotolerant and susceptible cattle — a weighed average of the gross productivity gains from MAS and MAI was computed, where the weights were the shares of tolerant cattle (66%) and susceptible cattle (34%) in the region (source: Kruska et al., 1995; Shaw and Hoste, 1987). Net productivity gains for both MAI and MAS were obtained by reducing the gross productivity gains by 7.05%, which is the cost of embryo transfer as a share of the value of herd meat and milk offtake, assuming a cost of US$ 100 per transfer (Cunningham, 1999, p. 3), 6.8 transfers per herd, a total value of meat and milk offtake of US$ 1489 per metric tonne, and, again, the representative herd structure reported in Kristjanson et al. (1999) (p. 84).

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