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Abstract

Rural Malians who grow dryland crops depend on sorghum as a primary food staple. Despite steady advances in sorghum research, in this risk-prone environment, achieving major gains in national sorghum yields has posed a challenge. We assess the potential economic impact of the first, Guinea-race sorghum hybrids produced and diffused using participatory plant breeding with decentralized, farmer-managed seed systems. We compare this approach to formal plant breeding with a centralized, state-managed seed system, which was the approach pursued prior to 2000. To incorporate risk, we augment the economic surplus model by applying Monte Carlo sampling to simulate distributions of model parameters. A census of sorghum varieties in 58 villages in the high-potential sorghum production zone serves as the adoption baseline. Our findings indicate that research on sorghum hybrids is a sound

investment, but particularly when combined with locally-based mechanisms for disseminating seed. In part, this finding reflects the fact that despite many years of efforts aimed at liberalizing the seed sector in Mali, the sorghum seed system remains largely farmer-based.

I. Introduction

Rural Malians have long depended on sorghum as a staple food crop. Of the five races of sorghum grown south of the Sahara, the Guinea race dominates the Sudanian Savanna, where most of the sorghum in Africa is now produced. Since the droughts that devastated this region in the 1970s-1980s, the Government of Mali (GOM) has sought to raise sorghum productivity through, supports by donor agencies and international research organizations. Sorghum yields reported from 1961 to 2012 by the Cellule de Planification et de Statistiques du Secteur du Développement Rural (CPS-SDR) in Mali, show an average growth rate of 0.49%.

Efforts to improve sorghum in this region relied initially on use of local landraces of the Guinea race, and emphasis was subsequently shifted to introduction of exotic breeding materials which were almost exclusively of Caudatum races. Compared to Caudatum races, local landraces possess multiple traits that contribute to adaptation in the Sudanian Savannah. One such adaptive trait is photo-period sensitivity, which is extremely useful to farmers in risky production environments (Soumaré et al. 2008). The defining traits of the Guinea race, in particular, are the shape of the grain and the fact that the grains turn inside the glumes at maturity, leaving open glumes and lax panicles; these help to mitigate grain damage from insects and mold (Rattunde et al. 2013; Barro-Kondombo et al., 2008; Hausmann et al. 2012).

In 1987, Matlon estimated a regional adoption rate for improved sorghum that did not exceed 5%. In the late 1990s, Yapi et al. (2000) surveyed farmers to measure adoption and assess economic returns to sorghum improvement. These authors differentiated between two categories of varieties: 1) exotic introductions, and 2) "purified" materials from indigenous, Guinea-race varieties. Their study confirmed farmer preferences for germplasm selected from local varieties, but also demonstrated a higher rate of return to investment from approach (2) because of a shorter time lag to adoption.

Since then, Mali's sorghum improvement program has pursued the development of pure Guinea-race hybrids as well as Guinea/Caudatum hybrids and varieties. Working with scientists of the International Crops Research Institute of the Semi-Arid Tropics (ICRISAT), Mali's sorghum breeders have devised research approaches that engage farmers directly in on-farm variety testing and selection. In addition, in order to overcome the state-managed, supply-driven, and unable to respond effectively to farmer demands (Diakité et al. 2008), the national program and ICRISAT have placed greater emphasis on promoting a locally-based system to supply seed.

In 1999, responding to farmers who emphasized that yield was their primary concern, the program initiated the development of hybrid parents based on locally-adapted, Guinea-race germplasm. Researchers sought to test whether hybrids could be created that combine superior yields with the grain and panicle traits preferred by farmers. Assessments of the yield performance of these hybrids showed major advantages relative to superior local landraces across both less and highly productive growing conditions (Rattunde et al. 2013). This experimental proof of concept, combined with the growing interest of farmers and farmer organizations in producing hybrid seed appears to justify the establishment of a full-scale hybrid breeding program for the Sudanian zone of West Africa. However, no systematic economic analysis has yet been conducted to confirm the potential economic impact of such a strategy.

Here, we assess the potential economic impact of the first, Guinea-race sorghum hybrids produced and diffused with the new IER-ICRISAT paradigm. The economic surplus framework serves as our analytical base. To better reflect the stochastic nature of farm production, and for analytical robustness in an ex ante setting, we augment the framework by applying Monte Carlo sampling to simulate probability distributions for model parameters.

A contribution of this analysis is that it highlights the differences in return to investment between two paradigms of research and development: (1) formal plant breeding with a centralized, state-managed seed system (FPB-S), and (2) participatory plant breeding with decentralized, farmer-managed seed systems (PPB-F). The first paradigm relied primarily on photoperiod-insensitive, introduced germplasm and sought to develop varieties that could be grown over the widest possible geographic area; the second paradigm was initially developed specifically for the Sudan Savannah (700-1100 mm rainfall), and is based on the use of Guinea-race germplasm with its array of adaptive traits. Both paradigms resulted in the release of improved open pollinated varieties (IOPVs) and hybrids, but hybrid varieties reaching farmers' fields resulted only from the PPB-F approach.

We know of no other such comparison in the published literature. Several articles have explored the economic aspects of farmer participatory research (Johnston et al. 2003; Smale et al. 2013; Dalton et al. 2011), but these did not explicitly compare paradigms. Atlin et al. (2001) compare the conditions for achieving genetic gains with participatory plant breeding or formal plant breeding. The authors concluded that participatory plant breeding is most likely to outperform formal plant breeding in low-yield target environments. On a world scale, Mali's is a low-yield environment.

II. Methodology

Below, we present our methodology, including the data source, the components of the analytic framework, the description of scenarios and parameter values that represent the two paradigms.

A. Farm survey

A census of sorghum-growing households was conducted in 58 villages located in the principal sites where IER and ICRISAT have conducted pilot-testing activities from 2009 to 2013. Teams composed of an *animateur* and enumerators implemented the survey instrument in each household, totaling 2,430 family farm enterprises (*exploitations agricoles familiales*, or EAFs). The instrument included: (a) a list of all household members with socio-demographic information; (b) a list of all plots managed by all household members, with the crop planted and farmer estimates of size; and (c) a list of all sorghum varieties grown from 2009 to 2013, with information on seed source, mode of acquisition, changes in area planted over the past five years, and stated reasons for changes. The farm survey conducted for this study was used to measure rates of adoption of sorghum varieties and seed use.

B. Economic surplus framework

The literature based on the use of the economic surplus model to evaluate economic returns to investments in agricultural research is voluminous. Recent examples including the application of the ex ante approach to assess potential returns from investment in agricultural knowledge information systems (AKIS) by Horstkotte-Wesseler et al. (2000), and other examples related to the impacts of biotech crops in developing countries (e.g, Hareau et al. 2006;Falck-Zepeda et al., 2008;Horna et al. 2007; Rudi et al. 2010). In Sub-Saharan Africa, Alene and Coulibaly (2009) applied the ex post approach to assess the impacts of agricultural research on productivity and poverty.

In Mali, Yapi et al. (2000) estimated the economic impacts of sorghum and millet research. As compared to Yapi et al. (2000), who differentiated returns to investment by two categories of research products, we differentiate returns to investment by two paradigms of research and development. In that respect, our approach is similar to Rudi et al. (2010), who compared conventional to marker-assisted breeding in cassava improvement. We also introduce elements of the stochastic, ex ante approaches employed by Falck-Zepeda et al. (2008) and Horna et al. (2007) to analyze biotech crops.

The fundamentals of the economic surplus approach can be simply derived from the formulae shown in Alston et al. (1995). Assuming a closed national economy, as is appropriate in the context of the sorghum sector in Mali, technical change is represented by a parallel shift in the supply curve that results from the adoption of yield-enhancing, sorghum hybrids. The shift in the supply curve generates (a) a change in economic surplus (ΔES), which is composed of (b) a change in consumer surplus (ΔCS) and (c) a change in producer surplus (ΔPS). Producer surplus theoretically measures how much more producers could pay for their inputs and still cover costs. Consumer surplus expresses how much more consumers would be willing to pay to purchase the quantities they consume. Total economic surplus, is equal to producer surplus plus consumer surplus.

Algebraically, the terms are represented by:

$$(1)\ \Delta ES = P_0Q_0K_t(1+0.5Z_t\eta)$$

$$(2)\ \Delta CS = P_0Q_0Zt(1+0.5Z_t\eta)$$

$$(3)\ \Delta PS= (K_t-Z_t)P_0Q_0(1+0.5Z\eta)$$

Conceptually, in these expressions, Kt is the supply shift. Before the supply shift, P0 represents the sorghum price and Q0 represents the quantity produced. The parameter η is the price elasticity of demand. Zt is the relative reduction in price at time t, which is calculated as $Zt = Kt\varepsilon/(\varepsilon+\eta)$, where ε is the price elasticity of supply. Productivity change is represented in terms of the product of cost reduction per ton of output as a proportion of product price (K) and technology adoption at time *t* (A_t). Thus,

$$(4)\ Kt=[((\Delta Y/Y)/\varepsilon - (\Delta C/C))/(1+(\Delta Y/Y))]\times At$$

where ΔY/Y is the average proportional yield increase per hectare; ε is the elasticity of supply ; ΔC/C is the average proportional change in the variable costs per hectare required to achieve the yield increase; and A_t is the rate of adoption of the improved technology at time *t*. Here, the adoption rate is defined as the total area under new technology over total area planted to the crop.

To assess the economic value of these changes from the standpoint of an investor, we invoke two standard, summary measures: (1) Net Present Value (NPV), and (2), Internal Rate of Return. Benefits and costs to technology are discounted at a real, social discount rate (*r*) per annum to derive the net present values (NPV) of the investment over the years considered (*t*=1, …..*k*).The aggregate NPV is calculated as:

$$(5)\ NPV=\sum_{k=0}^{\infty}\frac{B_{t+k}-C_{t+k}}{(1+r)};$$

Rather than assume a discount rate, the aggregate internal rate of return (IRR) "endogenizes" the discount rate by calculated as the rate that equates the aggregate net present value (NPV) to zero:

$$(6)\ NPV=\sum_{k=0}^{\infty}\frac{B_{t+k}-C_{t+k}}{(1+IRR)^k}=0$$

At NPV=0, the net present value of cost of the investment is exactly equal to the net present value of the benefit of the investment. If the IRR is greater than 0, then investment in hybrid sorghum is profitable for society; if it is less than 0, then the investment in hybrid research is not profitable to society. Below, we describe another means of incorporating risk.

C. Stochastic simulation

Risk and uncertainty circumscribe the decision-making world of smallholder sorghum growers in the Sudan Savannah of Mali. Heavy rains too late in the season, insects and mold can damage also cause heavy grain losses. Climate change may have exacerbated the variation in timing and distribution of rainfall over the cropping season, making it more difficult even for experienced farmers to choose the optimal input use schedule. Moreover, input market prices could vary over the course of the cropping season, raising overall costs and negatively affecting returns to production. Depending on public policies and the strength of market and nonmarket institutions, production risk and uncertainty may also influence the distribution of returns among consumers and producers.

A limitation of economic surplus models is that they are specified with deterministic values for key parameters. To address this shortcoming, applied researchers often employ sensitivity analysis to test the robustness of their results. In recent studies, researchers have utilized stochastic simulation methods, exploiting the full probability distribution of values. For example, Hareau et al. (2006) used stochastic simulation to evaluate the potential benefits of herbicide-resistant transgenic rice in Uruguay. Falck-Zepeda et al. (2008) used an augmented economic surplus model with probability distributions to account for risk, uncertainty and sparse data to evaluate the potential payoffs and economic risks of adopting transgenic cotton in five West Africa countries using @Risk. Here, we also utilize @risk.

The @Risk software (Palisade Corporation, www.palisade.com/risk/) is a spreadsheet simulation tool that performs risk analyses based on Monte Carlo simulation methods. For example, the software enables us to explore the sensitivity of results to changes in parameters by regressing each output variable on the parameters included in the simulation. We employ triangular distributions for most of our input variables. Triangular distributions have been widely used as a decision-making tool in analyses of risk and uncertainty when data are sparse (Hardaker et al. 2004). The triangular distribution approximates a normal distribution with only three values: minimum, maximum, and mode.

Next, we discuss our parameter assumptions.

D. Parameter values

Scenarios

To operationalize our model, we specify parameter values according to two scenarios that represent two different paradigms that have been pursued by the sorghum improvement programs in Mali and elsewhere in West Africa.

In terms of estimating summary measures of economic impact, key differences between the two paradigms concern the length of the research and development lags before the release of the new product, and the shape of the cost structure, which reflects the transfer of a share of the extension costs to farmers themselves (see, for example, Smale et al. 2003). On the benefits side, there are other types of impacts associated with on-farm selection and locally-based seed supply, such as those related to information and knowledge acquisition by farmers and other agents engaged in the process of technical change (Weltzien et al. 2003).

In their stylized depiction of the temporal distribution of the costs and benefits of agricultural research over time, Figure 1(a), Alston et al. (1995: 30) include five years for the research lag, which they define as the "pretechnology knowledge." This period is followed by a development lag of four years. Once the product has been released, they define another period (of six years) until adoption reaches a maximum of 100% ("the adoption lag").

Later in their volume, Alston et al. (1995: 177-78) state that "conventional breeding programs for cereals usually take six to ten years to develop a new variety" (p. 177); research programs with limited experience will take more time. On the other hand, applied work in developing country environments may need less time if more fundamental research occurs elsewhere and varieties are finished or adapted locally. This was also the case for the caudatum materials brought to the West African Sahel when ICRISAT began working with national sorghum programs. In Figure 1a, we have added a new benefits distribution to the graph to represent that fact that, in many development country settings, the adoption lag is best defined as the time from release to the first year of adoption. In our analysis, we refer to this lag, rather than the time to maximum adoption, as “the adoption lag.”

Perhaps even more important for applied research on improved cereal varieties is that the adoption ceiling may never reach 100%. For example, the adoption potential of most varieties in rainfed agriculture will never be 100% of crop area because they were bred for specific environments and farming objectives. Moreover, for the Mali sorghum-growing context, full adoption by a single variety or by any variety type (hybrids only) at any one point in time is not expected to be welfare-improving for smallholder growers and thus would not constitute a desirable goal for national policy (Bazile et al. 2008). The declining benefits stream depicted by Alston et al. (1995:30), shown in Figure 1a, reflects their recognition that varieties will become obsolete and farmers will replace them.

The actual scenario for Guinea-race sorghum hybrids is depicted in Figure 1b, based on the cost series supplied by ICRISAT for the hybrid program from 2000-2013 and the maintenance costs for the plant breeding program supplied by IER. Here, we have assumed that the research system generates recurring constant costs to which targeted, specific investments, such as development of cytoplasmic male-female parents in the new hybrid program, and related expenditures, constitute additional expenditures. To represent the recurring costs, we referred to those reported by Yapi et al. (2000) based on interviews with the principal researchers of the national program (see annexes).

In Scenario A, we assume a research and development lag that is very close to the ideal type shown in Figure 1a. Yet, the adoption lag is shorter than would be expected in the situation described for cereal improvement in most developing countries, and shorter than was the case in the early years of Mali’s sorghum improvement program. The research costs considered in this scenario include the financing of the McKnight Foundation from 2000 to 2013, added to the maintenance research costs of the national program as reported by Yapi et al. (2000), inflated to current (nominal) values at the rate of 2011-2012 (0.03%). We assume that farmer’s themselves undertake their own cost-benefit calculation when deciding whether or not to participate. In Scenario A, the time lag until adoption begins is only 1 year at minimum, and maximum adoption occurs in 10 years. Benefits and costs are simulated over a period of 20 years considering the reduced time lag between validation of sorghum hybrids and diffusion.

Scenario B represents the state-managed approach pursued in the initial years of the program, updated; in some sense, a “counterfactual” for Scenario A. To generate this cost series, we have taken the maintenance cost series compiled by Yapi et al. (2000) inflated to current values (as above), adding to these the same total investment for the hybrid program but distributed over a longer period (25 years) to represent a different paradigm with the same investment constraint. Globally, cost series assembled in Yapi et al. (2000) show a similar shape to that observed in Figure 1a. However, we expect the time lag to adoption begins to be considerably longer—at least 5 years—with the maximum attained 15 years after official release of the hybrid. As portrayed by Yapi et al. (2000), costs are initially lower, rising to a maximum and then gradually diminishing.

Parameter values

Table 1 presents the definitions of parameters and the values assigned to them to simulate the economic impacts of recently released, sorghum hybrids. To project impacts, we compare two scenarios. Scenario A (PPB-F), is the current main approach to sorghum improvement in Mali. Scenario B, is the counterfactual and previous main approach, (FPB-S). Other than total areas, total investments, and total years of simulation, for which one parameter value or time series of values is assigned per scenario, each parameter is associated with a triangular distribution of three (minimum, maximum, mode) values per scenario.

Contextually, we assume a closed economy where sorghum is not officially traded in international markets. We also assume that demand and supply are relatively inelastic. Despite the evolution of grain markets in urban areas (e.g., Bessler and Kergna 2002), supply chains for seed and grain are not vertically-integrated as is the case for rice, cotton, and some horticultural crops.

Area. The area targeted by the FPB-S in Mali included all the sorghum-growing areas in the country, estimated at1.25 M ha in 2013. In contrast, the area targeted by pilot research on Guinea-race, sorghum hybrids using the PPB-F approach is the Sudanian Savanna, which lies within the rainfall isohyets of 800 to 1200 mm, and covers an estimated 348,000 ha (ICRISAT 2015).

Yield increase (%). Based on farmer field trials, Rattunde et al. (2013) found that the Guinea-race sorghum hybrids yielded 17 to 47% over the local check, with the top three hybrids averaging 30%. For the PPB-F Scenario, applied to the Sudanian Savanna target area, we followed Rattunde et al. (2013) with a minimum of 17%, mode of 30%, and maximum of 47% when farmers grow Guinea-race sorghum hybrids as compare to local varieties. For the FPB-S Scenario, we followed Yapi et al. (2000), assuming a minimum of 5%, mode of 20%, maximum of 30% when modeling the national sorghum area (with the exclusion of the Sudanian Savanna because it did not pertain).

Adoption rate (%): In a synthesis of existing studies, Kelly et al. (2015) reported that estimates of the percent of sorghum area planted to improved varieties ranged from 13% (nationally representative surveys) to 18% (estimate based on seed production data) to 30% (geographically targeted studies, such as Yapi et al. 2000). Our village census data, which cover the 2009-2013 period in 58 villages of the Sudanian Savanna, show an overall average adoption rate for improved varieties of 26% in 2013, with about 3% of area in the newly released, Guinea-race hybrids.

Considering Scenario B, as our minimum, we utilize the 5% reported by Matlon in 1987; the maximum adoption rate (33%) is based on expert opinion reported by Ndjeunga et al. (2012) as the national adoption rate. We use a mode of 20%, since the higher estimates of Yapi et al. (2000) and this study are consistent (nearly 30% in each study), but geographically-targeted.

In Scenario A, we use as the minimum the 3% we observed in the village census. For the maximum, we draw from the example of pearl millet hybrids in India. In 2006, hybrids covered more than 60% of the area sown to pearl millet (Pray and Nagarajan 2010); historically, the highest adoption rates for high-yielding millet, most of which was hybrid, were recorded for Gujarat and Maharashtra (99% and 94%, respectively, in 1994, according to Deb, Bantilan and Rai 2005). For a maximum, we posit 80%; for a mode, 50%.

Number of years until adoption begins: In our Scenario A, where seed systems are more decentralized, we assume a one year lag as a minimum time until the first adopters begin, but also allow time for awareness and learning (mode of 3 years), with a maximum of 5 years. For Scenario B, following Yapi et al., 2000, and reflecting the more centralized, state-managed seed system, we assume a minimum of 5 years, a mode of 8, and a maximum of 10 years.

The number of years to maximum adoption level: The number of years until adoption of a technology attains its maximum depends on numerous factors, including the strength of policies and institutions that supply seed and promote its use. Yapi et al. (2000) found a period of 10 years in Mali, while Alene and Coulibaly (2009) found a period of 8 years across Sub-Saharan Africa. Thus, we assume the minimum of 5 years, a mode of 8, and a maximum of 10 years for Scenario A, with a minimum of 8, mode of 10, and maximum of 15 in Scenario B.

Total time period of cost and benefit streams: In Scenario B, costs and benefits are simulated over a period of 25 years, as in the ex post analysis conducted by Yapi et al. (2000), which reflected a more state-managed, centralized breeding program than is the case in Scenario A. In Scenario A, we predict that after 20 years the best-performing hybrids will be produced by farmers will be guided by their benefit-maximizing objectives to switch from existing to newer hybrids.

Cost Advantage of hybrids (CFA/kg): Rattunde et al. (2013) found that with a maximum yield of 3 MT/ha, the production cost per kg of grain was 62% less for a sorghum hybrid relative to the best local variety. With a yield of 1500 MT/ha, the cost advantage of the sorghum hybrid was 24%, and in the worst case of 1 MT/ha, -16%. We employ these values for the triangular distribution in Scenario A.

A parallel analysis was conducted for IOPVs. With a maximum yield of 1.3 MT/ha, the cost advantage of IOPVs relative to the best local variety was 18%. The mean yield of 0.7 MT/ha generated a reduced cost of 10%, and the minimum yield of only 350 kg/ha was associated with a -3% cost advantage. For Scenario B, which corresponds to the period analyzed by Yapi et al. (2002), we apply these estimates as the triangular distribution.

Discount rate (%): Several studies addressing public investment used a minimum discount rate of 5% in their analysis (Alene and Coulibaly, 2009). For this analysis the maximum discount rate is fixed at 15%, considering the potential for private investment in sorghum hybrids, with a mode of 10%. A World Bank study for nine Latin America countries, Lopez (2008) used a range of 5-7% for 20 to 25 years projects. We use a triangular distribution of 5%, 10%, and 15% for both scenarios.

Price of sorghum (CFA/ton): Price is assigned a normal distribution with mean $334 per ton and a standard deviation of 45.9 per ton, based on time series data from the *Observatoire du Marché Agricole* (OMA) during the period 2000 – 2012. The same source provides a maximum price of $600 per ton and a minimum price of $200 per ton with a mode of $300 per ton during the period. Crop price distributions do not change by scenario.

Price elasticity of supply: Masters et al. (2003) and Alston et al. (1995) suggest that in ex ante analyses when data are scarce, the supply elasticity can be set at 1. Noting that acreage elasticity is often used as a proxy for supply response because farmers have greater control over acreage than output, Rao (1989) found that in developing countries, acreage elasticities vary from 0 to 0.8 in the short run and from 0.3 to 1.2 in the long run. Yapi et al., 2000 applied an elasticity value of 0.40 in their sensitivity analysis, based on the fact that sorghum remains a subsistence crop produced primarily for home consumption. In cotton-producing areas of Mali, Vitale et al. (2009) found an acreage supply response to sorghum price of 0.285. Based on these findings, we posit a triangular distribution with a maximum of 1, a mode of 0.4 and a minimum of 0.285 in either scenario.

Price elasticity of demand: Masters et al. (2003) and Yapi et al. (2000) found a demand elasticity of -0.75 to be consistent with conditions typical to coarse grains in West and Central Africa. Again, this reflects the fact that demand is fairly inelastic (between -1 and 0). As above, we assume inelastic demand price and kept the same values in the two scenarios, with a minimum of -0.4, mode of -0.7, and maximum of -1.

III. Results

A. Adoption rates

Table 2 presents the total area and the percent of total crop area represented by each variety type including all growers of the crop, or the aggregated "extent" of use considering all 58 villages combined and all sorghum-growing family farm enterprises (*area diffusion rate*).

Areas planted to improved sorghum types grew from 2009-2013, more rapidly for improved variety types than for local types, and most rapidly for hybrids, although hybrid growers still represent a tiny minority in these early stages of hybrid testing (Table 2). Five years after they initial introduction to farmers, during this pilot phase of the hybrid program, Guinea-race sorghum hybrids represented only 2.3 % of area planted to sorghum in the 58 villages surveyed. Combined, all improved varieties and hybrids covered 24.3% of sorghum area in 2013.

The operational definition of improvement status, which we refer to as *variety type*, is important to consider when interpreting findings. Enumerators elicited the names of all sorghum varieties grown between 2009 and 2013. Names were then verified and classified by variety type (local, improved, hybrid. Focus groups and key informant interviews were conducted in order to cross-check some reported names. The final list is composed of 137 names, though not all could by identified by improvement status. Thus, in a count of 3496 sorghum plots associated with named varieties, 3487 have been grouped by variety type.

B. Simulation results

(1) Scenario A (PPB-F)

Table 3 presents statistics that summarize Monte Carlo simulation results obtained by applying @risk to the model equations and the parameter values shown in Table 1 for Scenario A, with 50,000 iterations. Total surplus (TS) and Net Present Value (NPV) are shown in million USD. Consumer surplus (CS) and producer surplus (PS) are depicted in terms of million USD and share (%) of the total surplus.

Considering the period spanning 2000-2019, and assuming the parameter values shown in Table 1 for Scenario A, we estimate a total surplus ranging between -$48 million and $206 million with a mode of $17 million from investing in sorghum improvement in Mali. The internal rate of return is estimated to vary from 0% to 410% with a mode of 50% per year. Consumer surplus ranges between -$24 million and $83 million with a mode of $7 million. Producer surplus varies from -$24 million to $123 million with a mode of $2 million. In the study area, of course, most producing farm families are also consuming families. Under favorable natural conditions the whole economy of the area could gain as much as $206 million.

The probability density functions generated by 50,000 iterations of samples drawn from Scenario A parameter values are depicted in Figure 2 for the total economic surplus. The upper panels show that roughly 90% of the densities in positive ranges, under 80 million USD for TS. The lower panel in Figure 2 illustrates the sensitivity of simulation results to specific parameters included in the economic surplus model. Thus, the key determinants of variation in TS are the price elasticity of supply, followed by the cost advantage of hybrids. In third place are average yield advantages attained in farmers' fields. In fourth place is the discount rate, or time value of money.

(2) Scenario B (FPB-S)

Table 4 presents comparable summary statistics for simulations conducted with parameter values associated with Scenario B. Overall, maximum surplus values (total, producer, consumer) are slightly lower in Scenario B than in Scenario A, although minima are similar. Modal values are similar, and mean values are slightly smaller in magnitude. In Scenario B, Monte Carlo simulations suggest a range in total surplus between -$9 million and $126 million, with a mode of $10 million, from investing in sorghum improvement in Mali. Consumers' surplus ranges between -$4 million and $60 million with a mode of about $4 million and producers surplus varies from -$5 million to $136 million with a mode of $4 million.

Similarly to the situation we observe in Scenario A, the probability density functions simulated by @risk suggest a strong likelihood of positive change among the populations in the Sudanian Savannah (Figure 3). In Scenario B as compared to Scenario A, the cost advantage of hybrids appears to play a lesser role in explaining variation in total, consumer and producer benefits. However, as in Scenario A, the price elasticity of supply, yield advantages and discount rate are key determinants of variation in producer benefits under Scenario B.

The cumulative distribution function of the NPV is shifted toward higher values in Scenario A relative to Scenario B, but the possibility of negative NPV is greater in Scenario A than in B (Figure 4). In Scenario A, 90% of simulated NPV values fall between -5.9 and 74.4 mill USD. By contrast, 90% of simulated NPV values range between -0.5 and 43.0 mill USD in scenario B.

The internal rate of return, which is a parameter of great interest to investors, is substantially lower in Scenario B than in Scenario A, with a mean value of 26% (as compared to 65%) and a mode of 26% (as compared to 50%). Thus, the cumulative distribution function is shifted more toward lower values in the state-managed scenario. In Scenario A, 90% of the IRR values lie within the interval between 17% and 118%; by contrast, in Scenario B, 90% lie between 13% and 42% (Figure 5).

From an investor's perspective, the comparison between two investments depends most often on the calculation of only two parameters: the IRR and the NPV. When comparing project investments ex ante, Alston et al. (1995) state that it is the NPV which represents the criterion of choice for investors and priority settings; when conducting evaluations ex post, the IRR serves more in fixing priorities. Considering either or both of these two parameters, the results of our ex ante, Monte Carlo simulation imply that Scenario A is clearly superior to Scenario B.

IV. Conclusions

We have conducted an ex ante evaluation of the potential economic impact of the first Guinea-race sorghum hybrids introduced to farmers in the Sudanian Savanna of Mali. Based on the economic surplus model, we compared two scenarios. In the first, our parameter assumptions are designed to reflect the approach to on-farm selection and farmer-managed seed supply that has been encouraged in Mali since around 2000. In the second, we portray the state-managed approach to research that dominated previously.

Our findings indicate that research on sorghum hybrids in Mali is a sound investment, but particularly when combined with earlier on-farm selection and farmer-based mechanisms for disseminating seed. However, results illustrate the predicted variability of economic benefits to the cost advantages of hybrid seed under the current research paradigm. By contrast, the discount rate is a more important determinant of variability in the previous research paradigm. Variability in predicted total surplus appears to depend very much on the price elasticity of supply and yield advantages in either paradigm—and thus on the performance of the materials introduced but also the responsiveness of producers to price signals in the market.

Our conclusion concerning the superiority of the current paradigm reflects a contextual reality: despite manyICRIS years of efforts aimed at liberalizing the seed system in Mali, the seed system for sorghum remains largely farmer-based. Development and introduction of new materials by the national research program has been successful and frequent enough, but farmers tend to absorb these new materials into their own system and rely on each other more than on external sources.

VII. Policy implications

Comparing the advantages and disadvantages of formal plant breeding and participatory plant breeding, Atlin et al. (2001) recommend that in order to continue to make important contributions on a global scale, participatory systems will need to develop simple and robust designs for multiple-environmental trials. Related to this is the cost advantage of hybrids, which, according to our analysis, explains most of the variability in benefits accruing from the current research paradigm.

The price elasticity of supply is important in explaining variation in producer benefits and overall returns to investment. Strengthening sorghum markets and stimulating demand for sorghum products other than grain may encourage farmers to market their crop.

Other than germplasm, crop management factors and attention to soil fertility are priorities. On one hand, on-farm data indicates that the sorghum hybrids developed by the national program in Mali perform well with or without fertilizer relative to local variety checks. On the other, sustaining yield increases in sorghum production will depend on good crop management and attention to soil fertility. Certainly the yield benefits of sorghum hybrids are likely to be more evident when complementary inputs, including mineral and organic fertilizer and soil and water conservation practices are also used.

On-farm testing, variety selection and seed multiplication by farmers could facilitate more rapid diffusion and adoption of hybrids and other improved varieties, but this approach requires careful attention to training, monitoring of activities, and follow up. Interviews with farmers do confirm a problem with the availability of certified seed, and their cost is sometimes considered high by smallholders. Producing sufficient quantities of quality seed and ensuring that it is accessible to smallholder growers constitutes a major challenge.

To ensure large-scale diffusion of sorghum hybrids throughout the Sudanian Savanna, other sectors of the economy, including actors in the processing industry and commerce, must be engaged, and necessary legal frameworks established through national policy. To accomplish this objective, regional harmonization of seed laws is also essential.

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Table 1: Parameter values used to estimate investment rate of return to sorghum hybrids, by research paradigm

Parameter	Scenario[1]		Source
	A (PPB-F)	B (FPB-S)	
Area targeted	348,000 ha	1.25 M ha	CPS, SDR: ICRISAT
Yield increase (%)	17%, 30%, 47%	5%, 20%, 30%	Rattunde et al. (2013), Yapi et al (2000)
Cost advantage (%)	62%, 24%, -16%	18%, 10%, -3%	Authors, based on farmer field trials conducted by ICRISAT (Rattunde et al. 2013)
Ceiling adoption rate (%)	3%, 50%, 80%	5%, 20%, 33%	Matlon (1987), Ndjeunga et al. (2012), Yapi et al., (2000), Smale et al. 2014
Number of years until adoption starts	1, 3, 5	5, 8, 10	Discussion with Sorghum program officer at IER-Mali; ICRISAT.
Number of years until maximum adoption	5, 8, 10	8,10, 15	Authors' experience; Yapi et al., 2000
Price elasticity of supply	0.258, 0.4, 1	0.258, 0.4, 1	Rao (1989); Masters and Ly (2003); Yapi et al.(2002), Vitale et al. (2009)
Price elasticity of demand	1, 0.7, 0.4	1, 0.7, 0.4	Yapi et al. (2000): Vitale and Sanders (2005)
Discount rate (%)	5%, 10%,15%	5%, 10%,15%	Lopez H. (2008)
Total investment (US$ M nominal)	9641618	11730273	Yapi et al.(2000); ICRISAT; IER-Mali
Total years of simulation	20	25	Authors' experience; Yapi et al.,(2000)
Sorghum price $/ton	200, 300, 600	200, 300, 600	Sorghum market price reported by OMA, 2000-2014

Source: Authors

[1]PPB-F=participatory plant breeding with farmer-based seed systems; FPB-S=formal plant breeding with state-based seed systems.

Table 2. Total area and percent of sorghum area by type of variety, all varieties, all households

	Total area planted (ha)				
	2009	2010	2011	2012	2013
hybrids	74.6	71.4	98.5	95.7	166
improved varieties	1143	1167	1290	1356	1605
local varieties	4953	4999	5290	5375	5516
all sorghum varieties	6171	6238	6678	6827	7287
	Share (%)of total sorghum area				
hybrids	1.21	1.14	1.48	1.40	2.28
improved varieties	18.5	18.7	19.3	19.9	22.0
local varieties	80.3	80.1	79.2	78.7	75.7
all sorghum varieties	100	100	100	100	100

Source: Authors, based on village census of sorghum varieties conducted by LAAE, ICRISAT and MSU.

Table 3: Summary statistics for simulations results under Scenario A (million USD)

	TS	IRR	CS		PS		NPV
			value	share	value	share	
Maximum	206	410%	83	40%	123	60%	201
Minimum	-48	0%	-24	-50%	-24	-50%	-53
Mode	17	50%	7.5	44%	2.5	14%	14
Standard deviation	26	45%	10	38%	16	62%	26
Mean	30	65%	12	40%	18	60%	25

Source: Authors

Table 4: Summary statistics for simulations results under Scenario B (million USD)

	TS	IRR	CS		PS		NPV
			value	share	value	share	
Maximum	194	126%	60	31%	136	69%	187
Minimum	-9	0%	-4	44%	-4	56%	-15
Mode	10	26%	4	40%	4	60%	5
Standard deviation	14	9%	5	36%	9	64%	14
Mean	19	26%	8	42%	11	58%	15

Source: Authors

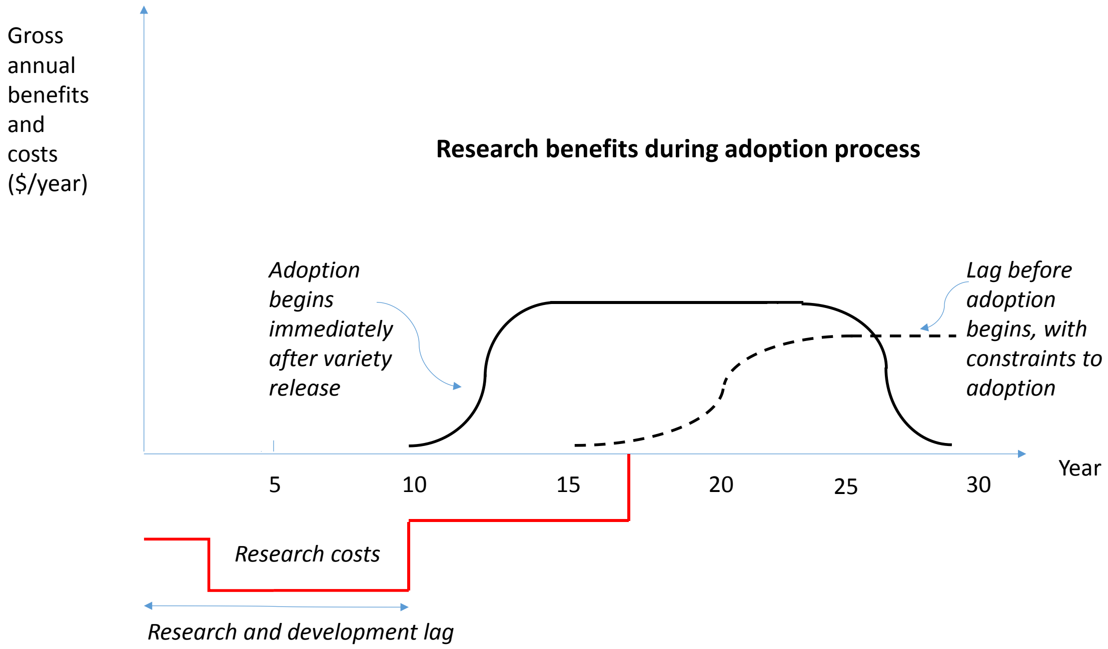


Figure 1a. Classic depiction of the temporal distribution of costs and benefits
Source: Authors, adapted from Alston et al. (1995)

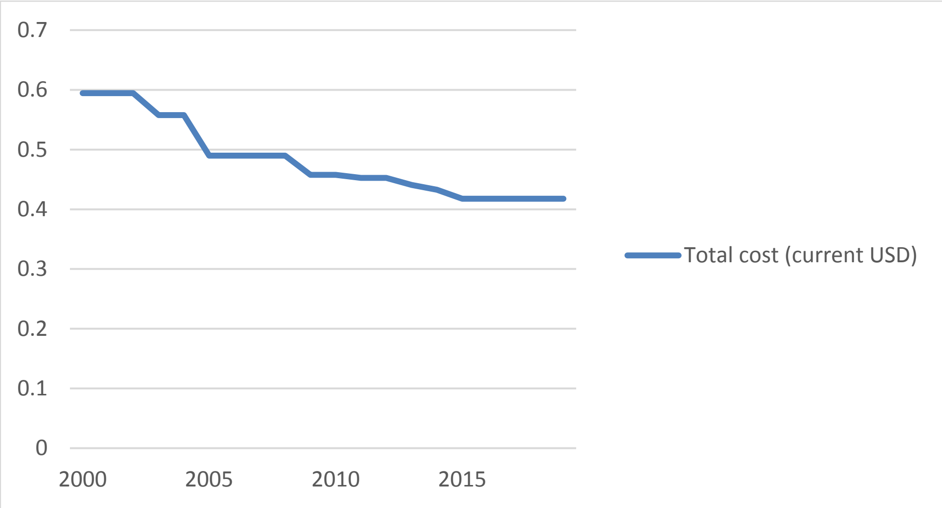


Figure 1b. Distribution of costs, on-farm selection and locally-based seed multiplication
Source: Authors, based on data provided by ICRISAT and IER.

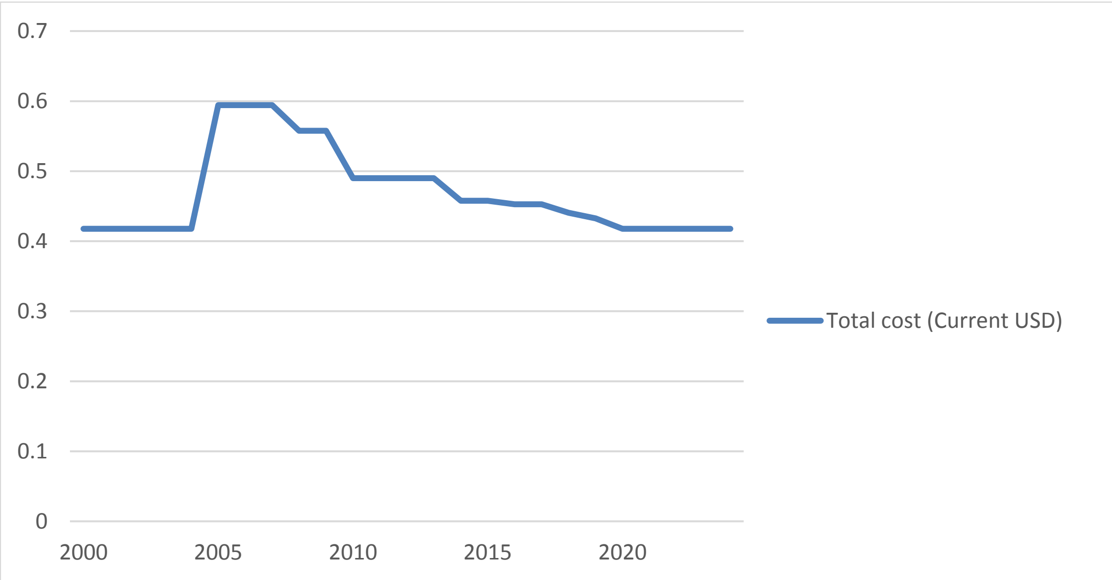
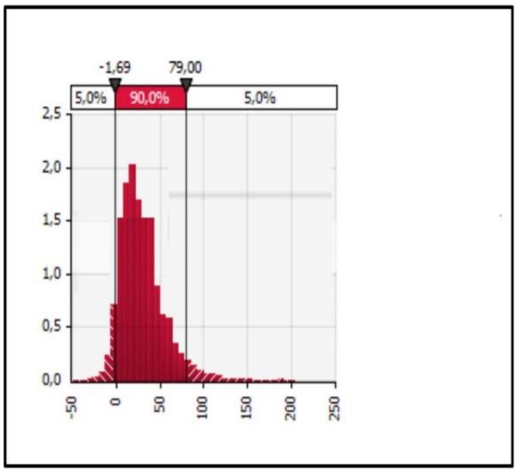


Figure 1c. Distribution of costs, state-managed research and development
Source: Authors, based on data provided by ICRISAT and IER, and Yapi et al. (2000a)

Figure 2: Scenario A : The probability distribution of economic surplus and parameters that influence its variation

(a) Total economic surplus



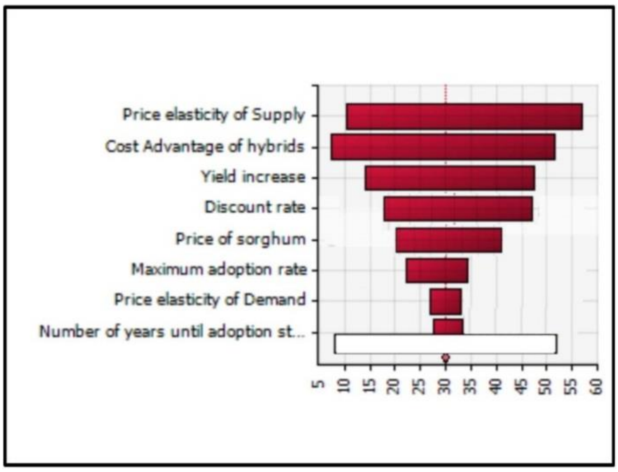
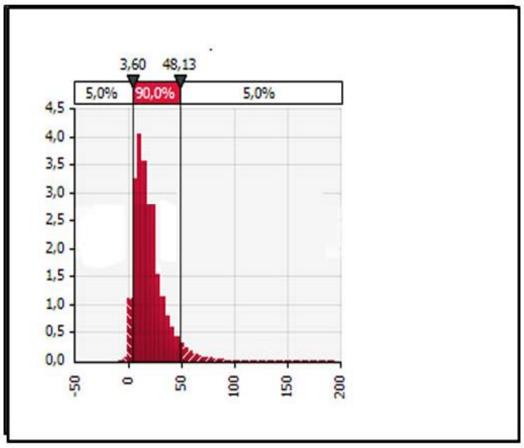


Figure 3: Scenario B : The probability distribution of economic surplus and parameters that influence its variation

(a) Total Economic Surplus



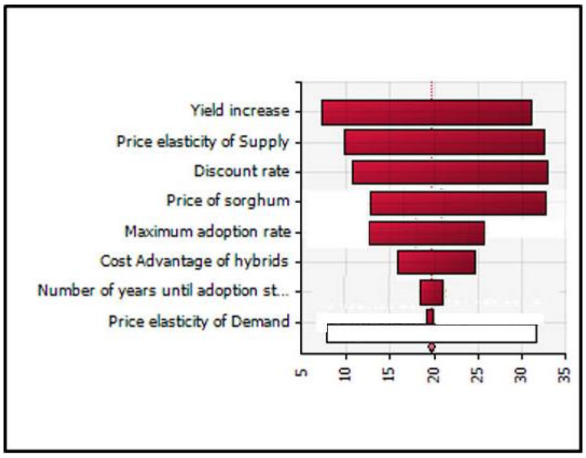
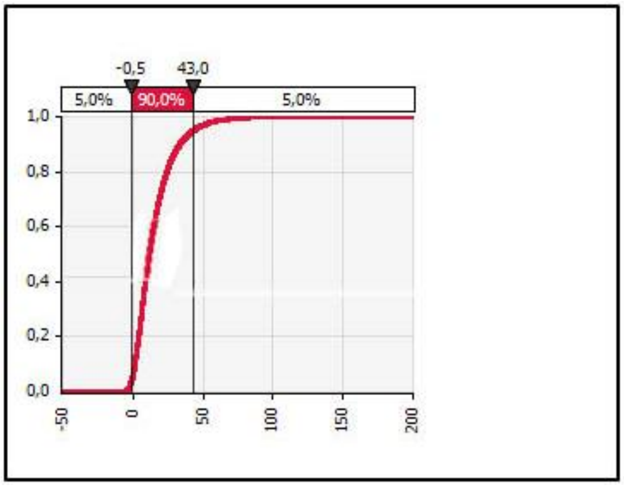


Figure 4: Comparison of cumulative distribution functions of NPV, Scenarios A and B

(a) Scenario A



(b) Scenario B

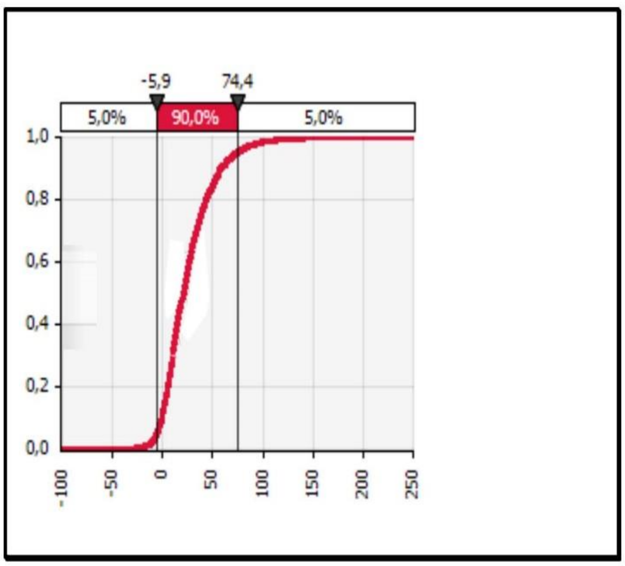
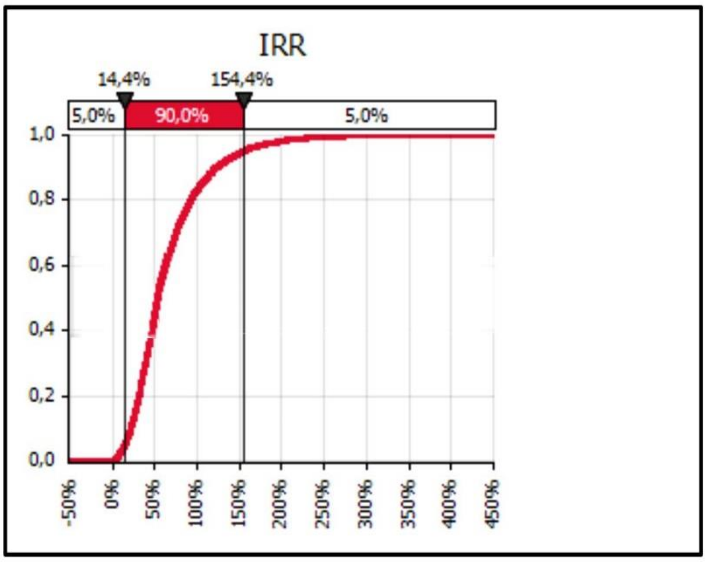


Figure 5. Comparison of cumulative distribution functions of the IRR, Scenarios A and B

(a) Scenario A



(b) Scenario B