Mali Food Security Policy Research Program

THE POTENTIAL ECONOMIC IMPACT OF GUINEA-RACE SORGHUM HYBRIDS IN MALI: A COMPARISON OF RESEARCH AND DEVELOPMENT PARADIGMS

By

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Institut d'Economie Rurale (IER). The IER was created on November 29, 1960, and serves as the main agricultural research institute in Mali with nearly 800 staff members, including 250 researchers in a variety of disciplines. It comprises six regional agronomic research centers, nine stations and 13 substations. Its scientific portfolio includes 17 programs.

Michigan State University (MSU). Established in 1855, MSU is the oldest of the "U.S. Land Grant" universities and has a long history of agricultural and food policy research in Africa, Asia and Latin America.

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Executive summary

Rural Malians who grow dryland crops depend on sorghum as a primary food staple. Achieving major gains in national sorghum yields in the complex and variable sorghum environments of Mali has been challenging despite steady advances in sorghum research.

Since 2000, Mali's sorghum research program has shifted from formal plant breeding with a state-managed seed system (FPB-S) toward a more participatory approach with on-farm tests and trials, and decentralized seed supply managed by local farmer associations (PPB-F). Recently, the program released the first Guinea-race sorghum hybrids developed in Mali, based largely on germplasm of local landraces. Of the five races of sorghum grown in Africa South of the Sahara, the Guinea race dominates the West African Savanna, where most of Africa's sorghum is produced. Aside from photoperiod sensitivity, the defining traits of the Guinea race are the shape of the grain and the fact that the grains turn inside the glumes at maturity, leaving open glumes and lax panicles that help to mitigate grain damage from insects and mold.

In this study, we assess the potential economic impact of the first, Guinea-race sorghum hybrids produced and diffused using the new research and development paradigm (PPB-F), comparing it to what would have been achieved through the earlier approach (PPB-S). To incorporate risk into our analysis, we augment the economic surplus model by applying Monte Carlo sampling to simulate distributions of model parameters. Thus, rather than provide a single estimate of the total economic surplus, net present value, and internal rate of return, the analysis generates a range of estimated values, their minima, maxima, means and modes. We then explore which factors most influence variation in economic returns; these lend insights for policy.

A census of sorghum varieties in 2430 growers in 58 villages in the Sudan Savanna serves as the adoption baseline. 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 this pilot phase of the hybrid program. Combined, all improved varieties and hybrids covered 24.3% of sorghum area in 2013, of which Guinea-race hybrids represented 2.3%.

Our findings indicate that research on sorghum hybrids is a sound investment when combined with locally-based seed dissemination. 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. Considering either or both of these two parameters, the results of our ex ante, Monte Carlo simulation imply that the economic potential of sorghum hybrids developed through a participatory plant breeding system is clearly superior to that of improved varieties (pure-line) developed through the formal plant breeding system that was the primary approach pursued in Mali before 2000. The cumulative distribution function of the Net Present Value (NPV) earned from investing in sorghum improvement is shifted toward higher values with PPB-F relative to FPB-S. The internal rate of return is substantially lower with FPB-S compared to PPB-F: the mode of the density of simulated values for the potential IRR with FPB-S is roughly half that of PPB-F, and 90% of the values lie between 11% and 43% as compared to 14% and 154%. Since the cost streams in both scenarios include the recurring expenses of the national program and the benefits scale includes only the regions of Koulikoro and Sikasso, these findings are conservative.

Sensitivity analysis underscores the importance of cost advantages associated with new sorghum hybrids, which are related to yield advantages and input costs. Complementary investments to support soil and water management can help sustain these advantages. Yet, the impressive yield gains of Guinea-race sorghum hybrids across a wide range of environments are not in and of themselves sufficient to ensure that the encouraging findings of the pilot project translate into actual, widespread productivity gains. Despite many years of efforts aimed at regulating the seed sector in Mali, the sorghum seed system remains largely farmer-centered. To disseminate hybrids effectively, public and private actors will need to continue investing in innovative ways to expand the reach of the sorghum seed system and reinforce its capacity to supply affordable, quality seed. The sensitivity of results to the price elasticity of supply suggests that linking seed supply to incentives for commercializing sorghum products would also support diffusion.

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I. Introduction

Rural Malians have long depended on sorghum as a staple foodcrop. Since the droughts that devastated this region in the 1970s-1980s, the Government of Mali (GOM) has sought to raise sorghum productivity, supported by donor agencies and international research organizations. Despite decades of research and development, sorghum yields reported from 1961 to 2012 by the Cellule de Planification et deStatistiques du Secteur du Développement Rural (CPS-SDR) in Mali show an average yield growth rate of only 0.49% for the nation.

In this region, efforts to raise sorghum productivity through genetic enhancement relied initially on use of local varieties of the Guinea race, and emphasis was subsequently shifted to introduction of exotic breeding materials which were almost exclusively of the Caudatum race. Five major morphological forms or "races" of sorghum are recognized worldwide (Harlan and de Wet, 1972; Olsen 2012). These include Caudatum (originating in eastern Africa), durra (found in the Horn of Africa and other arid regions), kafir (subequatorial eastern Africa), and bicolor (broadly distributed). The fifth form is the Guinea race, which is the predominant race in the West African Savanna from Senegal east through Mali and Burkina Faso.

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; Haussmann et al. 2012). The local Guinea-race varieties of Mali also possess multiple traits that contribute to adaptation. One such adaptive trait is photo-period sensitivity, which is extremely useful to farmers in risk-prone production environments (Soumaré et al. 2008). Photo-period sensitivity enables the crop to adjust its growth cycle so that flowering occurs at a predictable calendar date near the end of the rainy season, regardless of the sowing date.

Since 2000, Mali's sorghum improvement program has pursued the development of 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 their breeding efforts, including joint priority setting, on-farm selection and variety testing. In support of a demand-driven approach to seed dissemination, the Malian national program and ICRISAT have placed greater emphasis on promoting a locally-based system that is managed in collaboration with farmers (Diakité et al. 2008, Christinck et al. 2014). This approach has included seed testing and multiplication by farmers' associations and small-scale seed enterprises.

Even with a steady release of numerous well-adapted, improved varieties of sorghum in Mali, attaining more than a marginal (10%) yield advantage has been difficult. In 1999, the sorghum research program initiated development of hybrid parents based on locally-adapted, Guinea-race germplasm as a way to respond to farmers expressed concern for higher yields. 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 Sudan Savanna of West Africa. However, no systematic economic analysis has yet been conducted to confirm the potential economic impact of such a strategy.

Further, the national sorghum program has pursued two contrasting approaches to research for development over the past several decades, which we refer to here as paradigms. The first, a formal-plant breeding system denoted by (FPB-S), was a centralized approach that primarily utilized photoperiod-insensitively, introduced germplasm, targeted the broadest possible geographic area, and relied on a state-managed seed system to disseminate varieties. The second, a participatory plant breeding system (denoted by PPB-F), used germplasm with photoperiod-sensitivity and grain, glume and panicle traits preferred by farmers in the predominant zone of sorghum production in Mali (the Sudan Savanna). This paradigm promotes farmer-managed seed systems for varietal dissemination and a decentralized network of collaborative testing by farmers and researchers. Both approaches have produced and released hybrids and pure-line varieties. Pure-line varieties from both approaches and hybrids from the FPB-F approach are currently cultivated by Malian farmers.

To date, no comparison of potential returns to investment in these contrasting approaches has been attempted. A contribution of this analysis is that it highlights the differences in return to investment between two paradigms of research and development. In addition, the analysis includes an *ex ante* analysis of the potential economic impact of the first, Guinea-race sorghum hybrids produced and diffused in Mali. 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.

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 of research and development. Atlin et al. (2001) compared 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 environments. On a world scale, Mali's is clearly a low-yield environment.

II. Methodology

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 in the Sudan Savanna of Mali. A census of sorghum-growing households was conducted in 2014 in 58 villages of the Dioila and Kati Cercles (Koulikoro region) and the Koutiala Cercle (Sikasso region). These areas correspond to the zones where IER and ICRISAT conducted sorghum breeding activities during the period 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 document seed use patterns. Variety names were verified in consultation with ICRISAT technicians and sorghum breeders.

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) used the economic surplus approach to estimate the economic impacts of sorghum and millet research during the early decades of the national program. 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 Q0represents the quantity produced. The parameter η is the price elasticity of demand. Z_t is the relative reduction in price at time t, which is calculated as $Z_t = K_t\varepsilon/(\varepsilon+\eta)$, 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,

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

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:

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

where B is the benefits series corresponding to the change in economic surplus, and C is the series representing investement costs. 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:

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

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.

Stochastic simulation

Risk and uncertainty circumscribe the decision-making world of smallholder sorghum growers in the Sudan Savanna of Mali. Heavy rains too late in the season, insects and mold can cause heavy grain losses. Sorghum is a crop which is produced in Mali with relatively few and low amounts of external inputs. Use of purchased inputs is rare and mainly consists of small quantities of mineral fertilizer. Still, variation in timing and distribution of rainfall over the cropping season makes it difficult even for experienced farmers to choose the optimal input use schedule. 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 through volatility of observed and shadow prices for grain.

A limitation of the classical economic surplus model is that it is 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 in order to exploit 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 economic surplus model augmented by @Risk to evaluate the potential payoffs and economic risks of adopting transgenic cotton in five West Africa countries.

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.

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). However, we have not measured these here (see Dalton et al. 2011 for an example).

In their stylized depiction of the temporal distribution of the costs and benefits of agricultural research over time, Alston et al. (1995: 30) include five years for the research lag, which they define as “pretechnology” knowledge, followed by a development lag of four years until the product is released and adoption begins. Another period of six years follows until adoption reaches a maximum. These examples are only illustrative; the length of the research and development lag depends upon the type of research conducted, the extent to which it involves basic as compared to applied research, the quality of research infrastructure, and funding support. The authors 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.

In Figure 1a, we have adapted the original figure by Alston at al. (1995) to depict the temporal distribution of benefits and costs. Adoption begins the year after the variety is released in year 10. We add a second benefits path to indicate an adoption process with an additional lag of 5 years before adoption begins and a lower maximum adoption rate (ceiling) due to institutional, policy or other constraints. In the analysis that follows, we refer to “the adoption lag” as the time from variety release to the first year of adoption.

Perhaps even more important for applied research on improved cereal varieties in rainfed environments of developing agricultural economies is that the cumulative adoption ceiling for all improved varieties may never reach 100% of the crop’s area. The “ceiling” is best understood as the percentage of the total crop area that represents the target zone for which the variety was bred, or its full potential. The adoption potential of most varieties in rainfed agriculture will not attain 100% of national crop area because each was bred for specific growing environments and farming objectives. In Mali, 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 has recurring constant expenditures to which targeted, specific investments, such as the development of cytoplasmic male-sterile lines as female parents in the new hybrid program constitute additional expenditures. To represent the recurring expenses of the overall program, we referred to those reported by Yapi et al. (2000) based on interviews with the principal researchers of the national program (see annexes of the document). The series was then converted to current nominal USD. By including these expenditures in our hybrid scenario, we are implicitly assuming that the hybrid program depends on the activities of the overall program—which probably overstates costs for the hybrid program.

In Scenario PPB-F (A), we assume a research and development lag that is shorter than the ideal type shown in Figure 1a, because the variety testing trials are on-farm and are used to justify release. In addition 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, because farmers already know the new varieties, and seed production was initiated before release.

The research expenses considered in Scenario PPB-F (A) include funding from the Rockefeller Foundation during 2000-2008 for the development of hybrid parents and testing of initial hybrids. From 2000 to 2004, sorghum breeders in Mali selected parents from their breeding materials and overcame the particular challenge of developing female parents in sorghum, which is needed to develop hybrids. Hybrids were tested on-station for only two years before farmer testing began in 2007, and then formally released to farmers in 2009, which was the first year included in our farmer survey. Costs representing financing form the McKnight Foundation during 2007-2013, to develop farmer-managed seed systems, are also included. The number of female parents in the program remains limited; the initial period analyzed here represents a “proof of concept” before the program embarks on a larger effort to exploit genetic diversity, maintain a collection of hybrids with proven performance, and upscale efforts to supply seed. Hybrids were tested on-station for only two years before testing by farmers began in 2007. The number of female parents in the program remains limited; the initial period analyzed here represents a “proof of concept” phase before the program embarked on a larger effort to exploit genetic diversity, maintain a collection of hybrids with proven performance, and upscale efforts to supply seed.

The costs of the hybrid program are added to the maintenance research expenses of the national program as reported by Yapi et al. (2000), inflated to current (nominal) values at the rate of 2011-2012 (0.03%). The time lag until adoption begins is a minimum of one year, and maximum adoption occurs in 10 years. Benefits and costs are simulated over a period of 20 years considering the reduced time lag between variety release and diffusion.

Scenario B (FPB-S) represents the state-managed approach pursued during the initial years of the national sorghum 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 than Scenario A (PPB-F). In Scenario B (FPB-S), varieties were not tested on farms before release and farmers’ preferences were not explicitly included in the research process. We represent this be adding 5 years to the adoption lag with the maximum adoption 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.

The area cultivated in sorghum in the regions of Koulikoro and Sikasso represents our zone of study, estimated at close to 500,000 ha according to the Cellule de Planification Statistique du Secteur du Développement Rural (CPS-SDR) in 2013 (294 196 ha and 205 904 ha per region, respectively). These two regions have the largest proportions of agricultural land located in the Sudan Savanna zone, and are thus the priority target areas for sorghum breeding and especially for hybrid development in Mali. In order of area cultivated and total production, they are the principal sorghum-producing regions. As of the 2012-2013 season, the two regions represented more than 51% of total sorghum area planted in the country (31% in Koulikoro and 20% in Sikasso).

We limit the analysis to this area in order to compare the two research and development approaches on the same scale, although it is important to recognize that the absolute magnitude of the benefits (both total and net) generated by either approach would be considerably greater if projected on a larger scale.

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.

Agronomic and research parameters vary by scenario (yield increase, cost advantage, adoption rate, number of years until adoption begins, total time of cost and benefits streams), while market parameters (price of sorghum, price elasticity of supply, price elasticity of demand, discount rate) are the same in both.

Yield increase (%). Rattunde et al. (2013) found that individual Guinea-race sorghum hybrids yielded 17 to 47% over the local check, with the top three hybrids averaging 30% based on farmer field trials. For the PPB-F Scenario (A), applied to the Sudan 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 compared to local varieties. For the FPB-S Scenario (B), we followed Yapi et al. (2000), assuming a minimum of 5%, mode of 20%, maximum of 30%. In fact, yield advantages can be negative due to the susceptibility of earlier improved varieties to grain mold, head bugs and Striga.

Adoption rate (%): We utilize Matlon's 1987 estimate of 5% for the minimum in Scenario B (FPB-S). Our maximum (33%) is based on Ndjeunga et al.'s (2012) estimate of the national adoption rate. We use a mode of 20%. Higher estimates were reported by Yapi et al. (2000) and in our baseline, but these studies were geographically targeted. It is important to recognize, however, that the materials included in the estimates by Matlon and Yapi et al. included reselected ("purified") landraces in addition to newly created materials; a closer comparison would include only the new germplasm. Moreover, the minimum adoption rate is probably closer to 0% if reflecting the experiences of the earlier period. Thus, our estimates are likely to be generous for the FPB-S approach.

In Scenario A (PPB-F), we use as the minimum (3%) we observed in the baseline census. For the maximum, since we have no local example, 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% as a midpoint between these two estimates; for a mode, 50%. These estimates are also generous, and reflect the role of India's dynamic seed industry in facilitating widespread adoption.

Number of years until adoption begins: In our Scenario A (PPB-F), 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 before adoption is initiated. Reflecting the more centralized, state-managed seed system described for Scenario B (FPB-S), we assume a minimum of 5 years, a mode of 8, and a maximum of 10 years. Alene and Coulibaly (2009) also a period of 8 years across Sub-Saharan Africa. Yapi et al. (2000) reported a 10-year period for sorghum in Mali.

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

Cost Advantage (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 1.5 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 (PPB-F). With respect to improved varieties, a parallel analysis conducted by ICRISAT based on the farm trial data showed that with a maximum yield of 1.3 MT/ha, the production cost advantage of improved varieties 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 (FPB-S), we apply these estimates.

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 USD 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 USD per ton during the period. Crop price distributions do not change by scenario. These prices are substantially higher than those recorded during the period studied by Yapi et al. (2000).

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 price elasticity of demand and apply the same values in either scenario, with an absolute value ranging from a minimum of (-1), to a mode of (-0.7) and a maximum of (-0.4). Diao et al. (2008) report an absolute value of 0.424 for the price elasticity of demand across 17 countries of Sub-Saharan Africa, including Mali. Since the food price crisis, although all grains prices have risen, sorghum is still cheaper than rice or maize. The relative inelasticity of demand expresses the fact that sorghum remains a staple food crop.

III. Results

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 (2,430) included in the baseline. We refer to this as the area diffusion rate.

Areas planted to improved sorghum types rose from 2009-2013, more rapidly for improved variety types than for local types, and most rapidly for hybrids, although hybrid growers still represent a 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 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). The improved varieties considered here are pure line. 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 production plots associated with named varieties, 3487 could be classified by variety type. While the team is certain that all plots classified as 'improved type' were actually improved, it is possible that farmers assigned local names to improved varieties, they have been growing for a few years. We assume that the baseline estimates for adoption are thus conservative. Since data represent a census rather than a sample, estimates may include measurement error but not sampling error.

Simulation results

Tables 3 and 4 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 (PPB-F) and Scenario B (FPB-S) 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.

(1) Summary Statistics

We estimate a total surplus (TS) ranging between -$48 million and $206 million with a mode of $17 million from investing in sorghum hybrids using participatory plant breeding with a farmer-based seed system (Scenario A, PPB-F, shown in Table 3). The internal rate of return (IRR) varies from 0% to 410% with a mode of 50% per year. Consumer surplus (CS) ranges between -$24 million and $83 million with a mode of $7 million. Producer surplus (PS) varies from -$24 million to $123 million with a mode of $2 million. In the area of study, of course, most producing farm families are also consuming families. Under the best conditions of Scenario A (PPB-F), findings suggest that the whole sorghum economy of the Koulikoro and Sikasso Regions could gain as much as $206 million from this investment.

The overall, maximum surplus values (total, producer, consumer) are slightly lower with formal plant breeding (Scenario B, FPB-S) compared to the PPB-F Scenario, although minima are similar (Table 4). Modal values are similar, and mean values are slightly smaller in magnitude. The Monte Carlo simulations suggest that investing in sorghum improvement in the area of study using the FPB-S approach would give a range in total surplus between -$9 million and $194 million, with a mode of $10 million. Consumer surplus ranges between -$4 million and $60 million, with a mode of about $4 million. Producer surplus varies from -$4 million to $136 million with a mode of $4 million. The internal rate of return is substantially lower for FPB-S relative to PPB-F, with a mean value of 26% (as compared to 65%) and a mode of 26% (as compared to 50%).

(2) Comparison of distributions

The left side of Figure 2 shows the probability density function of 50,000 iterations of values generated for the total surplus (TS) based on parameter values for the PPB-F scenario. Roughly 90% of the density is in the positive range and under 80 million USD. The right side of Figure 2 illustrates the sensitivity of simulation results to the parameters included in the economic surplus model. The key determinants of variation in TS are the price elasticity of supply, followed by the cost advantage of hybrids. In third place is the yield advantage attained in the fields of farmers. In fourth place is the discount rate, or the time value of money.

Similarly to the situation we observed with PPB-F, the probability density functions simulated by @risk suggest a strong likelihood of positive change among the populations in the Sudan Savanna (Figure 3). 90% of the comparable values also lie in the positive range, but below 48 million USD. The cost advantage of hybrids appears to play a smaller role in explaining variation in total surplus (TS) of FPB-S as compared to PPB-F, ranking sixth. However, as in the PPB-F scenario, yield advantages, the price elasticity of supply, and the discount rate are among the top four determinants of variation in producer benefits under the FPB-S scenario.

The cumulative distribution function of the NPV is shifted toward lower values in the FPB-S scenario, but with a smaller possibility of negative NPV (Figure 4). The FPB-S simulation shows 90% of NPV values falling under 43.0 mill USD as compared to the maximum of 74.4 mill USD for PPB-F.

Figure 5 shows that cumulative distribution function is also shifted more toward lower values in the centralized, state-managed scenario with improved varieties than in the participatory plant breeding scenario with hybrids. Whereas 90% of the IRR values for PPB-F lie within the interval ranging between 14.4% and 154.4%; those of FPB-S lie between 11.3% and 42% (Figure 5).

From an investor's perspective, the comparison between two investments depends most often on only two parameters, the NPV which represents the criterion of choice for investors and priority settings ex post, and the IRR which serves in fixing priorities when conducting evaluations ex ante (Alston et al. 1995). Considering either or both of these two parameters, the results of our ex ante, Monte Carlo simulation imply that the PPB-F scenario with sorghum hybrids is clearly superior to the FPB-S scenario with improved varieties.

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 Sudan 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 pursued in Mali since around 2000. In the second, we portray the state-managed approach to research that dominated previously.

Our findings indicate that PPB-F on sorghum hybrids in Mali is a sound investment—not only because of the obvious yield advantages, but also the reduced research and adoption lags achieved by earlier on-farm selection, on-farm testing, and farmer-managed seed dissemination. They suggest that the national sorghum program has made important advances in overall approach over the past decades.

Simulation results predict sensitivity of total economic benefits to the cost advantages of hybrid seed. The cost advantage is closely linked to the yield advantage of hybrids, which ranks lower as a determinant of benefits variability in the PPB-F paradigm. As the cost advantage depends on the level of productivity at which the comparison is made, this finding indicates that support to farmers for enhanced soil fertility and thus productivity could have a large and positive effect on the total economic benefits of sorghum varietal improvement.

In addition to the central role of yield advantages, variability in predicted total surplus appears to depend very much on the price elasticity of supply in either paradigm—and thus on the performance of the materials introduced but also the responsiveness of producers to price signals in the market.

The superiority of the current paradigm by either the NPV or IRR criterion reflects a contextual reality not only the yield advantages of sorghum hybrids across a range of environments, but more rapid development, introduction and initial adoption. Despite many years of efforts aimed at formalizing and regulating the seed system in Mali, the seed system for sorghum remains largely farmer-centered. 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.

This process will not be as straightforward in the case of sorghum hybrids, for which farmers and farmer associations that produce seed will require the seed of parental lines. The interest of farmer associations and cooperatives in producing and marketing seed, and the diversity of actors now engaged in the formal seed system, suggest that decentralized approaches have the potential to supply improved seed effectively and more broadly among smallholders (Christinck et al. 2014; Coulibaly et al. 2014; Haggblade et al. 2015; ICRISAT 2015).

V. 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. Our results support the findings of Rattunde et al. (2013) that the system used for the identification of hybrids is efficient.

According to our analysis, the cost advantage of hybrids, which is related to yield advantages and price factors, explains most of the variability in predicted benefits accruing from the current research paradigm. 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 soil and water management over time. Our findings with respect to yield and cost advantages support investments in complementary soil and water management practices.

The price elasticity of supply, which expresses the percentage change in sorghum sold on markets relative to a percentage change in per unit price, is also a key determinant of variation in producer benefits and overall returns to investment. Providing incentives for farmers to market their crop through strengthening markets for grain and other sorghum products is crucial for supply response, but historically, this type of investment in Mali has favored other cereals (rice and maize, as a rotation crop with cotton).

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 that while certified seed is more available to them than was the case in the past, and they more often make seed purchases, the cost of seed 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. Opportunities to further broaden the range of actors involved in seed supply remain to be explored, including those that would strengthen the capacity of commercial seed producers, cooperatives and community enterprises to supply more foundation seed and better market certified seed. Successful approaches are likely to involve the pursuit of a multi-crop strategy (Christinck et al. 2014; ICRISAT 2015).

The total economic benefits we have predicted underestimate the size of benefits under either paradigm because we have confined the study to the sorghum-growing areas of the Koulikoro and Sikasso regions in order to compare on an equivalent scale. We also underestimate net benefits of the participatory approach by including the recurring expenditures of the overall program in addition to the investments in the hybrid program.

Our study did not include the value of stover and its potential use as animal fodder in the prediction of economic benefits. Many of the new hybrids combine superior grain yield with superior stover quality, encouraging farmers to store the stover as feed especially for draft animals. Similarly, the nutritional value of the grain has not been considered here. Some of the hybrids have been identified as having higher than average mineral (Fe and Zn) content, thus providing additional benefits to the food system.

The analysis presented here, which is based on evidence from a pilot project and ex ante modeling, underscores the economic potential from investing in well-targeted plant breeding programs linked to effective seed dissemination. In addition, the results indicate that overall benefits can be increased by supporting farmers in an integrated manner, so that they can use the most efficient soil fertility management strategies with the appropriate varieties and hybrids. Continued large-scale diffusion of hybrids throughout the Sudan Savanna will depend on continued support for a decentralized, farmer-managed seed system, with close research collaboration. Enlarging the network of farmer unions engaged in seed production and dissemination will be important to ensure that more farmers can access seed of new varieties and hybrids they can trust. Enhancing exchange and coordination among the growing number of seed producers will be critical for enhancing future gains and ensuring positive impacts for a larger number of small-holder sorghum growers, including women.

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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)	
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), Ndjeungaet 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

	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 census of all sorghum varieties reported by 2430 farming families in 58 villages of the Sudan Savanna in Mali (described in text).

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. Note: Scenario A=Participatory plant breeding system (see text). TS=Total economic surplus. IRR=Internal rate of return. CS=Consumer surplus. PS=Producer Surplus. NPV=Net Present Value.

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. Note: Scenario B=Formal plant breeding system (see text). TS=Total economic surplus. IRR=Internal rate of return. CS=Consumer surplus. PS=Producer Surplus. NPV=Net Present Value.

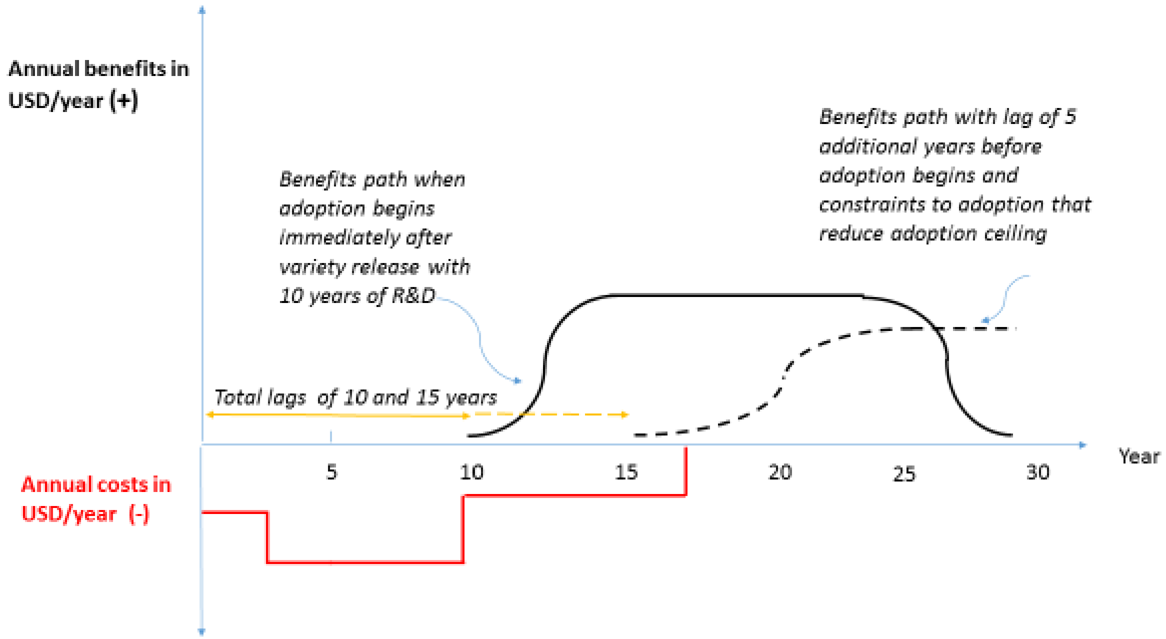


Figure 1a. Depiction of the temporal distribution of costs and benefits
Source: Authors, adapted from Alston et al. (1995)

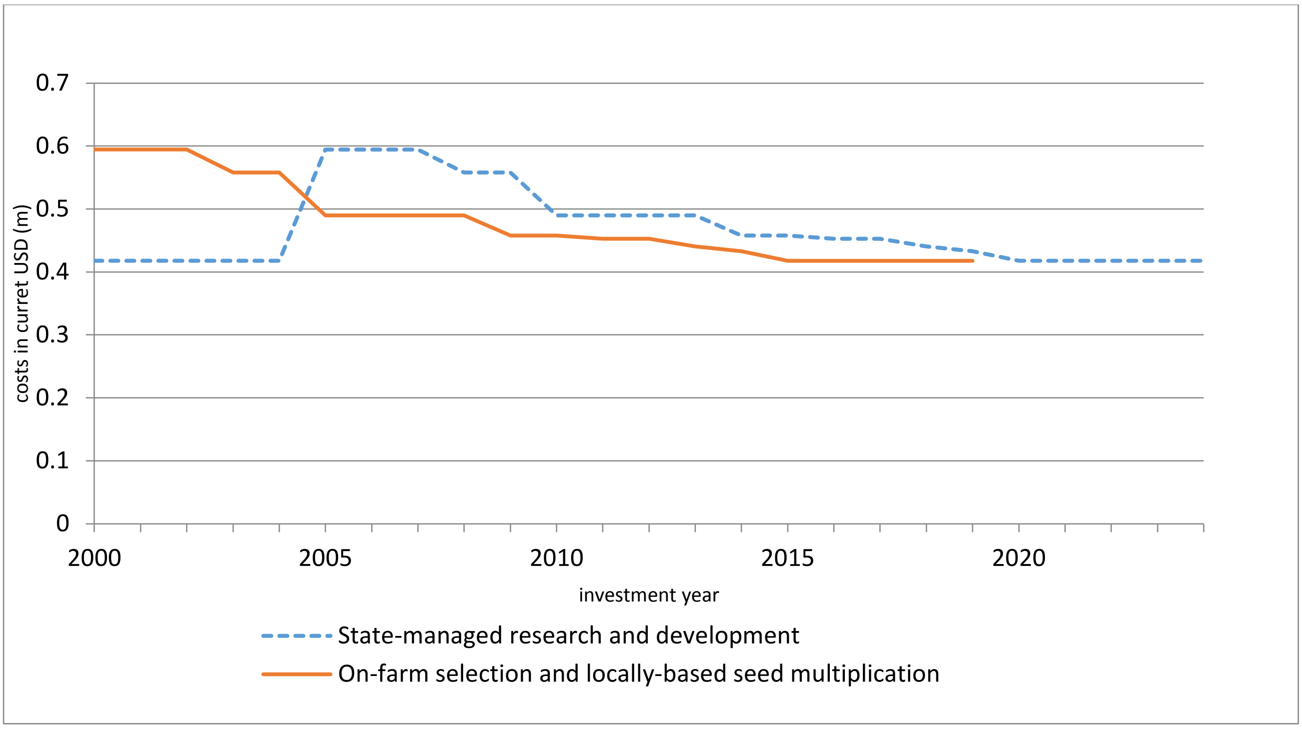
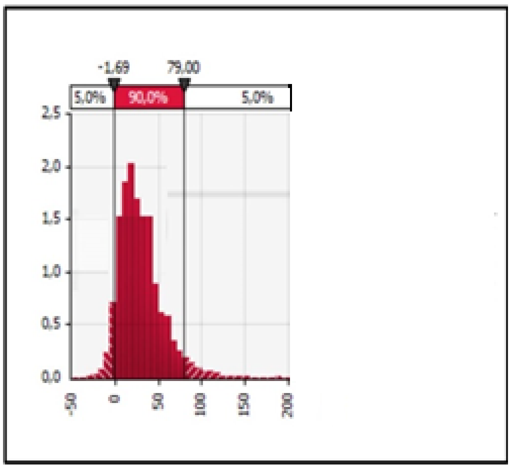


Figure 1b. Distribution of costs
Source: Authors, based on data provided by ICRISAT and IER, and Yapi et al. (2000)

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

(a) Total economic surplus



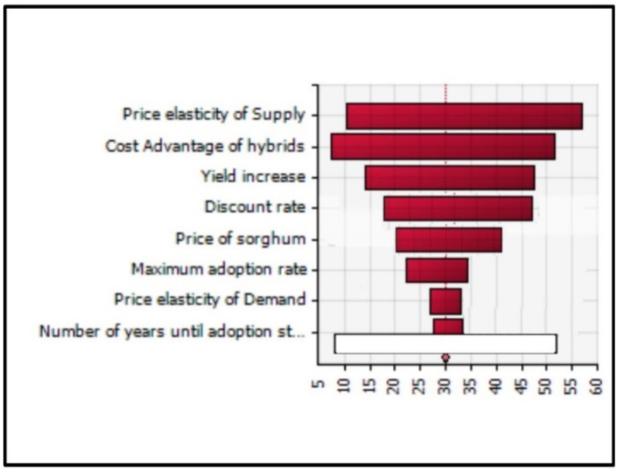
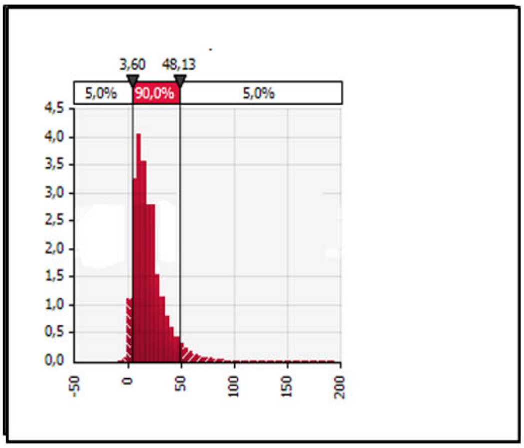


Figure 3: Scenario B : The probability distribution of economic surplus and parameters that influence its variation

(a) Total economic Surplus



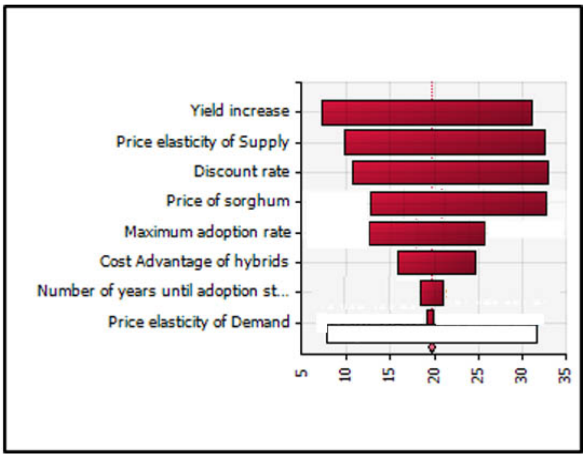
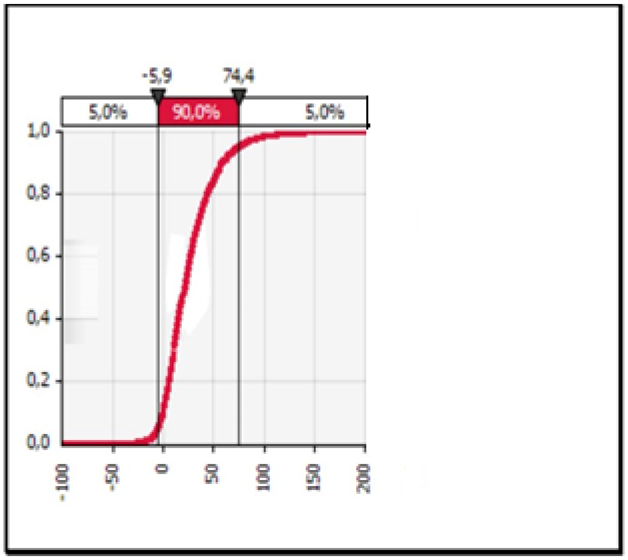


Figure 4: Comparison of cumulative distribution functions of NPV, Scenarios A and B

(a) Scenario A



(b) Scenario B

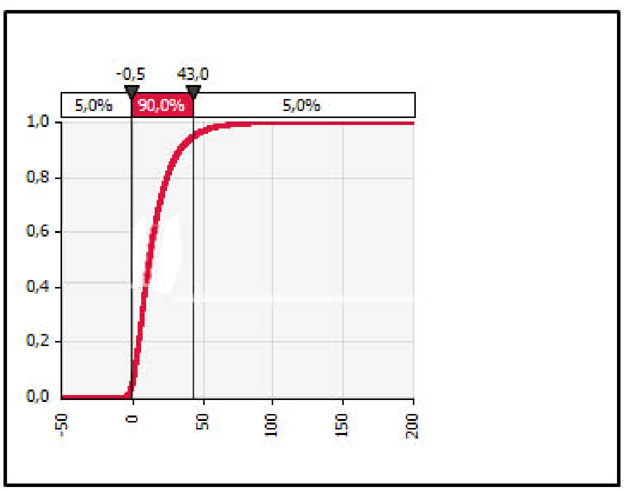
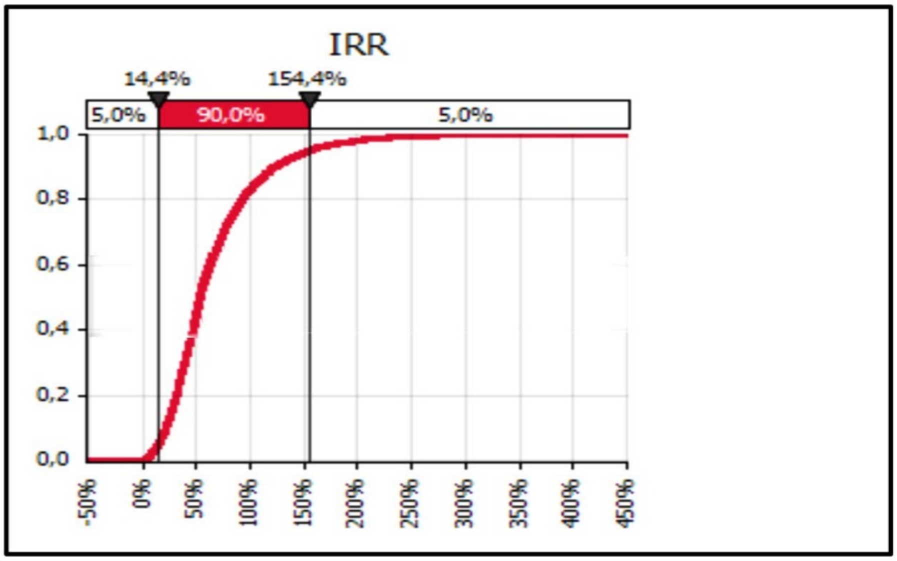


Figure 5. Comparison of cumulative distribution functions of the IRR, Scenarios A and B

(a) Scenario A



(b) Scenario B