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The potential economic impact of Guinea-race sorghum hybrids in Mali: A comparison of research and development paradigms

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Abstract

Rural Malians depend on sorghum as a staple food. Despite long-term investment in sorghum improvement, achieving major gains in sorghum yields has posed challenges. We assessed the potential economic impact of the first Guinea-race sorghum hybrids developed and diffused using participatory plant breeding with decentralised, farmer-based seed systems. We compared this approach to formal plant breeding with a centralised, state-managed seed system – the sole approach pursued in Mali prior to 2000. To incorporate risk, we augmented the economic surplus model by applying Monte Carlo sampling to simulate distributions of model parameters. A census of sorghum varieties in 58 villages of the Sudanese Savanna served as the adoption baseline. Our findings indicate that research on sorghum hybrids with the new approach is a sound investment. Public and private actors need to continue investing in innovative ways to expand the sorghum seed system. The sensitivity of results to the price elasticity of supply suggests commercialisation opportunities.

Key words: sorghum; hybrids; Mali; economic impact; R&D

1. Introduction

Rural Malians have long depended on sorghum as a staple food crop. Since the droughts that devastated this region in the 1970s and 1980s, the Government of Mali (GOM) has sought to raise sorghum productivity, supported by donor agencies and international research organisations. Despite decades of research and development, sorghum yields reported by the Cellule de Planification et de Statistiques du Secteur du Développement Rural ([CPS-SDR] 2013) in Mali from 1961 to 2012 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 the use of local varieties of the Guinea race, and emphasis was subsequently shifted to the introduction of exotic breeding materials, which were almost exclusively of the Caudatum race. Five major morphological forms or "races" of sorghum are recognised worldwide (Harlan & 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 bicolour (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 are the shape of the grain and that the grains turn inside the glumes at maturity, leaving open glumes and lax panicles, which serve to mitigate grain damage from insects and mould (Barro-Kondombo *et al.* 2008; Haussmann *et al.* 2012; Rattunde *et al.* 2013). 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 programme 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 programme 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. Meanwhile, the Alliance for a Green Revolution in Africa (AGRA) has supported the development of commercially oriented, small-scale seed companies and initiatives to raise farmer awareness of the market value of seed.

Even with a steady release of numerous well-adapted, improved varieties of sorghum in Mali, attaining more than a marginal (10%) yield advantage over local varieties has been difficult. In 1999, the sorghum research programme initiated the development of hybrid parents based on locally adapted, Guinea-race germplasm as a way to respond to the concerns farmers expressed 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 organisations in producing hybrid seed, appears to justify the establishment of a full-scale hybrid breeding programme 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 programme 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 centralised approach that primarily utilised photoperiod-insensitive, 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 the grain, glume and panicle traits preferred by farmers in the predominant zone of sorghum production in Mali (the Sudanese Savanna). This paradigm promotes farmer-managed seed systems for varietal dissemination and a decentralised 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 to highlight 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*. 2003; 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.

2. Methodology

2.1 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, and we mention only those studies we consulted to design our approach. 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 programme. 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 this 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), Hareau *et al*. (2006) and Horna *et al*. (2007) to analyse biotech crops.

The fundamentals of the economic surplus approach can simply be 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:

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

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

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

Conceptually, in these expressions K_t is the supply shift, P_0 represents the sorghum price and Q_0 represents 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 and technology adoption at time *t* (A_t). Thus,

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

where $\Delta Y/Y$ is the average proportional yield increase per hectare; ε is the elasticity of supply; $\Delta C/C$ 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 invoked 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 of the investment over the years considered (*t* = 1, ….. *k*). The aggregate NPV is calculated as:

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

where B is the benefits series corresponding to the change in economic surplus, and C is the series representing investment costs. Rather than assume a discount rate, the aggregate internal rate of return (IRR) "endogenises" the discount rate. The IRR is calculated as the rate that equates the aggregate net present value to zero:

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

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 for society.

2.2 Stochastic simulation

A limitation of the classical economic surplus model is that it is specified with deterministic values for key parameters. Yet risk and uncertainty circumscribe the decision-making world of smallholder sorghum growers in the Sudanese Savanna of Mali. To address this shortcoming, applied researchers often employ sensitivity analysis to test the robustness of their results. In recent studies, researchers have utilised 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 utilise @Risk. The @Risk software (Palisade Corporation, www.palisade.com/risk/) is a spreadsheet-simulation tool that performs risk analyses. We specified triangular distributions for key parameters of the model. 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. @Risk relies on Monte Carlo simulations to draw repeated samples from each of the distributions and generate summary statistics, density functions, cumulative distributions, and other statistics for each summary measure. The software also enables us to explore the sensitivity of results to changes in parameters by regressing each output variable on the parameters included in the simulation.

2.3 Construction of scenarios

2.3.1 Scenarios

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

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).[1] In their stylised 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, or “ceiling”. The example of Alston *et al*. (1995) is 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.

Perhaps even more important for applied research on improved cereal varieties in rain-fed 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 full potential within the target zone for which the variety was bred. The adoption potential of most varieties in rain-fed 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, illustrates that varieties will become obsolete and farmers will replace them.

In Figure 1a we have adapted the original figure by Alston *at al*. (1995) to depict the temporal distribution of benefits in two paths. In the path corresponding to the PPB-F scenario (A), adoption begins the year after the variety is released. Variety testing trials are conducted on farms and the results are used to justify official release. The adoption lag is shorter than was the case in the early years of Mali’s sorghum improvement programme, because farmers already know the new varieties and seed production was initiated before official release.

[1] On the benefits side, aside from productivity gains 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, the data do not permit this type of analysis here (see Dalton *et al*. 2011 for an example that includes other types of benefits).

We expect the time lag until adoption begins to be longer in scenario FPB-S (B). With FPB-S, varieties were not tested on farms before release and farmers' preferences were not explicitly included in the research process. We represent this by adding five years to the adoption lag, with the maximum adoption attained 15 years after official release.

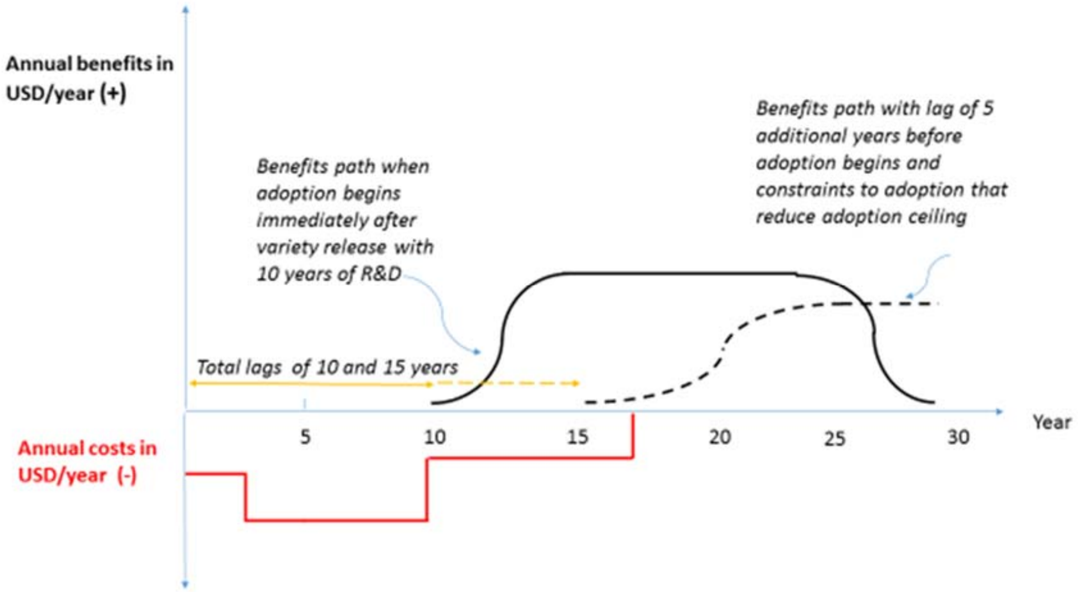


Figure 1a: Depiction of the temporal distribution of costs and benefits
Source: Authors, adapted from Alston *et al*. (1995)

Cost distributions in the two scenarios are shown in Figure 1b. The research expenses considered in scenario PPB-F (A) include funding from the Rockefeller Foundation from 2000 to 2008 for the development of hybrid parents and the 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 are needed to develop hybrids. Hybrids were tested on-station for only two years before farmer testing began in 2007, and they were formally released to farmers in 2009, which was the first year included in our farmer survey. Costs representing financing from the McKnight Foundation form 2007 to 2013 to develop farmer-managed seed systems are also included. The number of female parents in the programme remains limited; the initial period analysed here represents a "proof of concept" before the programme 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 programme were added to the maintenance research expenses of the national programme as reported by Yapi *et al*. (2000), inflated to current (nominal) values at the rate in 2011/ 2012 (0.03%). By adding these together, 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 programme, constitute supplementary expenditure. Thus, we are implicitly assuming that the hybrid programme depends on the activities of the overall programme – which probably overstates costs for the hybrid programme.

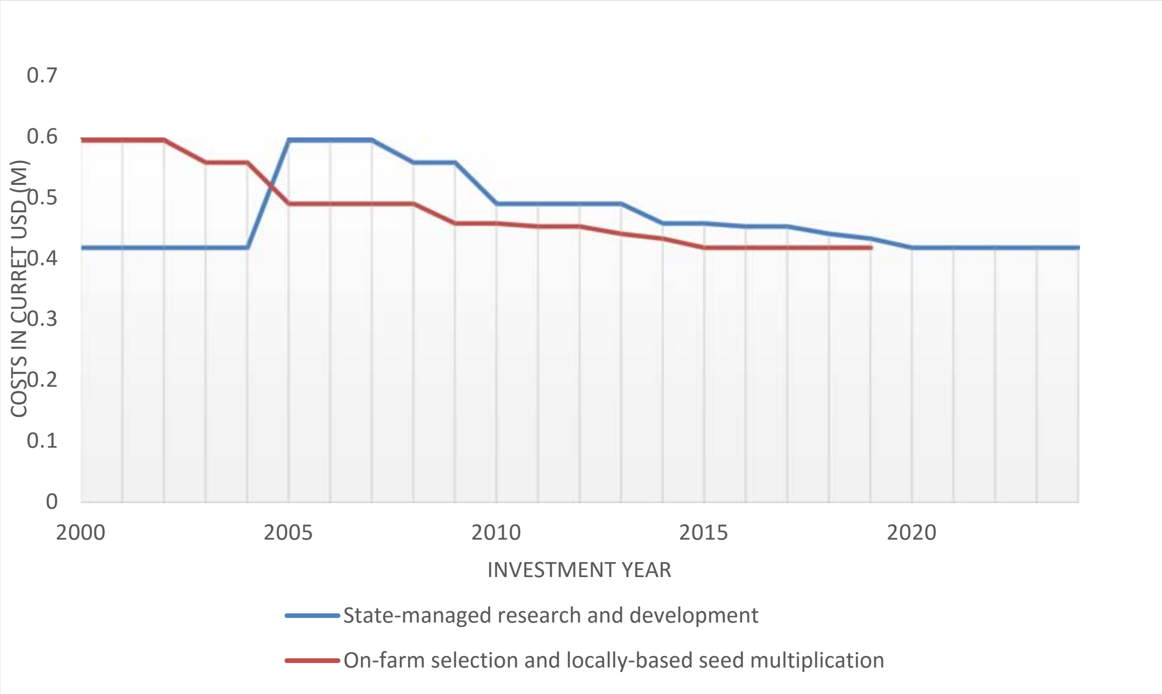


Figure 1b: Distribution of costs

Source: Authors, based on data provided by ICRISAT, IER and Yapi *et al*. (2000)

The FPB-S scenario (B) represents the state-managed approach pursued during the initial years of the national sorghum programme, updated – in some sense, a "counterfactual" for scenario A. To generate this cost series, we took 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 programme but distributed over a longer period (25 years) to represent a different paradigm with a similar investment constraint. As portrayed by Yapi *et al*. (2000), costs are initially lower, rising to a maximum and then gradually diminishing. Globally, the cost series assembled in Yapi *et al*. (2000) show a similar shape to that observed in Figure 1a.

The area cultivated to 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 (2013) 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 Sudanese 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 limited the analysis to this area in order to compare the two research and development approaches on the same scale, although it is important to recognise 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.

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

2.3.2 Parameter values

Table 1 presents the definitions of parameters and the values assigned to them to simulate the comparison of economic impacts between 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). Aside from the fixed area mentioned above, total years of simulation and the investment costs series, 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.

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.

Adoption rate (%). For scenario A (PPB-F), we based our minimum adoption rate for hybrids on a 2014 census of sorghum-growing households conducted in 58 villages of the Dioila and Kati Cercles (Koulikoro region) and the Koutiala Cercle (Sikasso region) of the Sudan Savanna of Mali, where IER and ICRISAT conducted sorghum-breeding activities over a number of years and pilot-tested sorghum hybrids from 2009 to 2013 (Smale *et al.* 2014). Teams composed of an *animateur* and enumerators implemented the survey instrument in each household, totalling 2 430 family farm enterprises. The instrument included a list of all sorghum varieties grown from 2009 to 2013, but no other data pertinent to this analysis.

Since we had no local example yet for sorghum hybrids in Mali, we drew from the example of pearl millet hybrids in India for the maximum and mode. In 2006, hybrids covered more than 60% of the area sown to pearl millet (Pray & 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 *et al*. 2005). For a maximum, we posited 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 of sorghum and millet hybrids.

In scenario B (FPB-S) we utilised Matlon's (1987) estimate of 5% for the minimum in the region. Our maximum (33%) is based on Ndjeunga *et al*.'s (2012) recent estimate of Mali's national adoption rate. We used a mode of 20%, which is close to the area share in our census for improved varieties. Higher estimates were reported by Yapi *et al*. (2000), but these studies were geographically targeted. It is important to recognise, 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 also likely to be generous for the FPB-S approach.

Yield increase (%). Estimates of yield advantages for hybrids in scenario A (PPB-F) are drawn from the analysis by Rattunde *et al*. (2013), which is based on 27 farmer-managed trials in the Sudanese Savanna and two on-station trials. Rattunde *et al*. (2013) found that individual Guinea-race sorghum hybrids yielded 17% to 37% over the local check, with the top three hybrids averaging a 30% yield advantage. For scenario B (FPB-S), we followed Yapi *et al*. (2000) and assumed a minimum of 5%, mode of 20% and maximum of 30%. In fact, yield advantages could be negative due to the susceptibility of earlier improved varieties to grain mould, head bugs and Striga. This scenario represents the counterfactual, which was the dominant situation before 2000.

As a check, we also examined yield data reported by 623 farmers sampled in the census of sorghum growers in the Sudanese Savanna. Median yield advantages calculated from the survey data were

36% and 89% for improved varieties and hybrids respectively. However, since plots were sampled within households for the survey, we were unable to control for selection bias by matching local, improved and hybrid plots for the same household. Regression adjustment analysis to predict yields based on labour, equipment, land, seed and fertiliser inputs showed average impacts that were 33% for improved varieties and 78% for hybrids (Smale *et al*. 2016). Since we were less able to control for management factors with the sample survey data, or for measurement errors due to farmer recall or small plot sizes, we preferred the more modest estimates of Rattunde *et al*. (2013) and Yapi *et al*. (2000).

Cost advantage (CFA/kg). Again using the farmer-managed trial data, 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 employed 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 farmer-managed 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. We applied these estimates for scenario B (FPB-S).

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)	
Ceiling adoption rate (%)	3%, 50%, 80%	5%, 20%, 33%	Matlon (1987); Yapi *et al*. (2000); Ndjeunga *et al*. (2012); Smale *et al*. (2014)
Yield increase (%)	17%, 30%, 37%	5%, 20%, 30%	Yapi *et al*. (2000); Rattunde *et al*. (2013)
Cost advantage (%)	-16%, 24%, 62%	-3%, 10%, 18%	Authors, based on farmer field trials conducted by ICRISAT (Rattunde *et al*. 2013)
Number of years until adoption starts	1, 3, 5	5, 8, 10	Discussion with sorghum programme 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 & 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 *et al*. (2009)
Discount rate (%)	5%, 10%,15%	5%, 10%,15%	Lopez (2008)
Total investment (US$ M nominal)	9 641 618	11 730 273	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

Number of years until adoption begins and maximum adoption. In our scenario A (PPB-F), where seed systems are more decentralised, 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 three years), with a maximum of five years before adoption is initiated. Reflecting the more centralised, state-managed seed system described for scenario B (FPB-S), we assumed a minimum of five years, a mode of eight, and a maximum of 10 years. Alene and Coulibaly (2009) also assume a period of eight years across Sub-Saharan Africa. Yapi *et al*. (2000) report 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), reflecting the state-managed, centralised breeding programme. In scenario A (PPB-F), we predict that, after 20 years of use of the best-performing hybrids, farmers, guided by their benefit-maximising objectives, will switch from existing to newer hybrids.

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

Price of sorghum (CFA/ton). Price was assigned a normal distribution with a mean of US $334 per ton and a standard deviation of US $45.9 per ton, based on time series data from the *Observatoire du Marché Agricole* (OMA) during the period 2000 to 2012. The same source provides a maximum price of US $600 per ton and a minimum price of US $200 per ton, with a mode of US $300 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. Given imperfect markets for sorghum in rural Mali, and the large proportion of farmers who did not report sorghum sales (70%), our survey data for sorghum prices at the farm gate are not reliable. In the cotton-producing areas of Mali, Vitale *et al*. (2009) found an acreage supply response to sorghum price of 0.285. 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. 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 of coarse grains in West and Central Africa. Again, this reflects the fact that demand is fairly inelastic (between -1 and 0). As above, we assumed that demand is price inelastic and applied 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 in 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.

3. Results

3.1 Adoption rates

Table 2 presents the total area and the percentage 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.

Areas planted to improved sorghum types rose from 2009 to 2013, more rapidly for improved varieties 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 initially were introduced to farmers, Guinea-race sorghum hybrids represented 2.3% of area planted to sorghum in the 58 villages surveyed during this pilot phase of the hybrid programme. Combined, all improved varieties and hybrids covered 24.3% of sorghum area in 2013.

Table 2: Total area and percentage of sorghum area by variety

Variety type	Total area planted (ha)				
	2009	2010	2011	2012	2013
Hybrids	74.6	71.4	98.5	95.7	166
Improved varieties	1 143	1 167	1 290	1 356	1 605
Local varieties	4 953	4 999	5 290	5 375	5 516
All sorghum varieties	6 171	6 238	6 678	6 827	7 287
	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: Smale *et al.* (2014)

The operational definition of improvement status, which we refer to as variety type, is important to consider when interpreting the findings. Enumerators elicited the names of all sorghum varieties grown between 2009 and 2013. The 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, although not all could by identified by improvement status. Thus, in a count of 3 496 sorghum production plots associated with named varieties, 3 487 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.

3.2 Simulation results

Tables 3 and 4 present statistics that summarise the 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.

3.2.1 Summary statistics

We estimated 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. The 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, most producing farm families of course also are consuming families. Under the best conditions of scenario A (PPB-F), the 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 for total and consumer surplus are lower, although maximum producer surplus is higher and the minima are less negative with formal plant breeding (scenario B, FPB-S) compared to the PPB-F scenario. 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 of 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%).

Table 3: Summary statistics for simulation 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
Mean	30	65%	12	40%	18	60%	25
Standard deviation	26	45%	10	38%	16	62%	26

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 simulation 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
Mean	19	26%	8	42%	11	58%	15
Standard deviation	14	9%	5	36%	9	64%	14

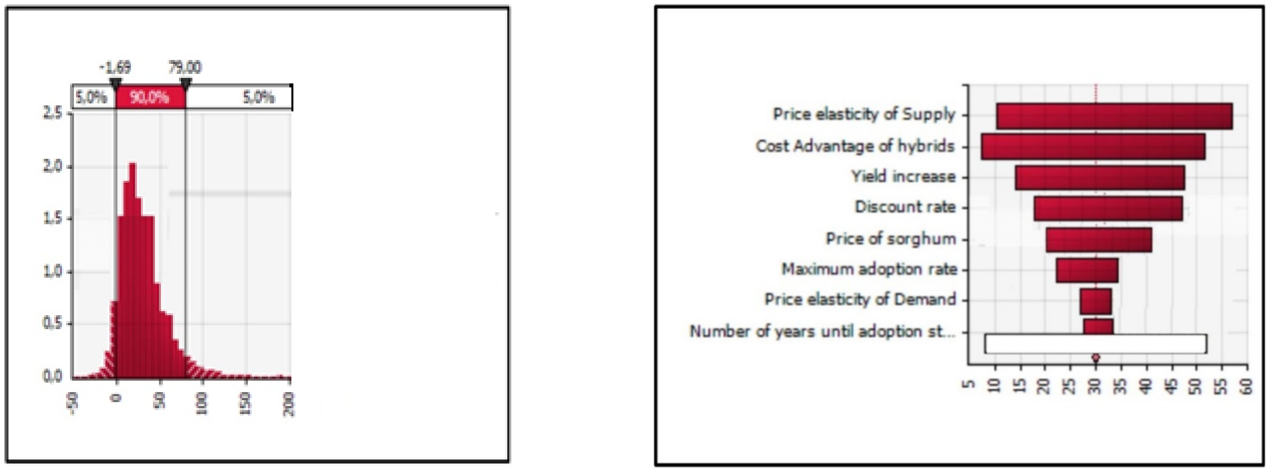
Source: Authors

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.

3.2.2 Comparison of distributions

The left-hand 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-hand 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 Sudanese Savanna (Figure 3). About 90% of the comparable values also lie in the positive range, but below 48 million USD. The cost advantage appears to play a smaller role in explaining variation in total surplus (TS) of FPB-S 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.



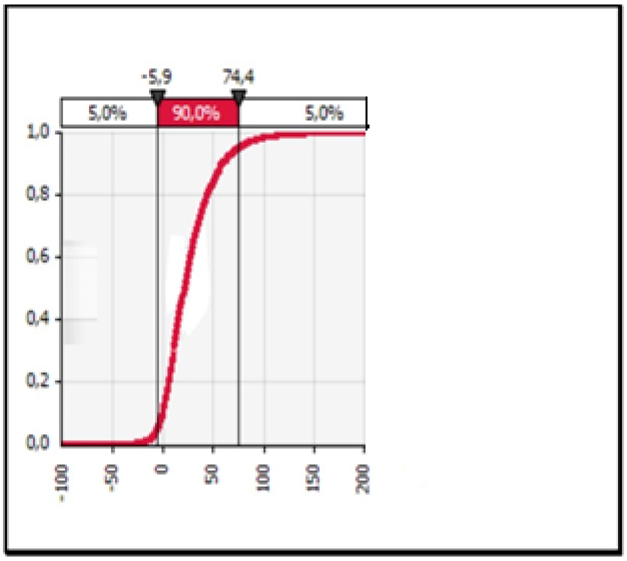
Total economic surplus

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

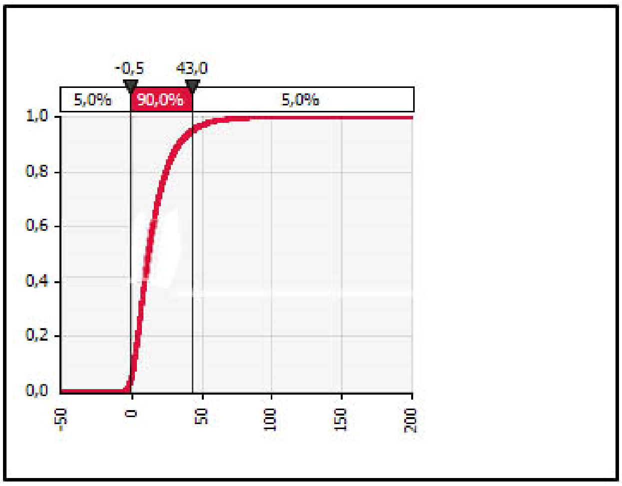
Total economic surplus

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

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 that 90% of NPV values fall below 43.0 mill USD, compared to the maximum of 74.4 mill USD for PPB-F.



Scenario B

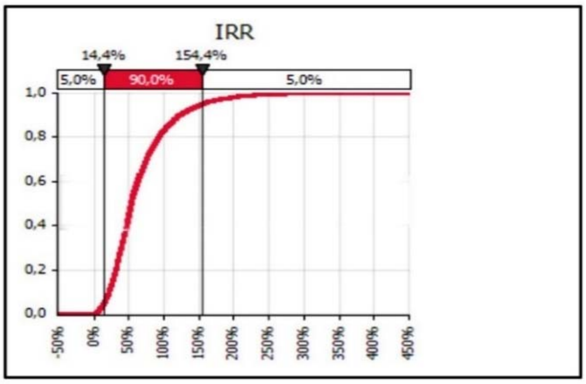


Scenario A

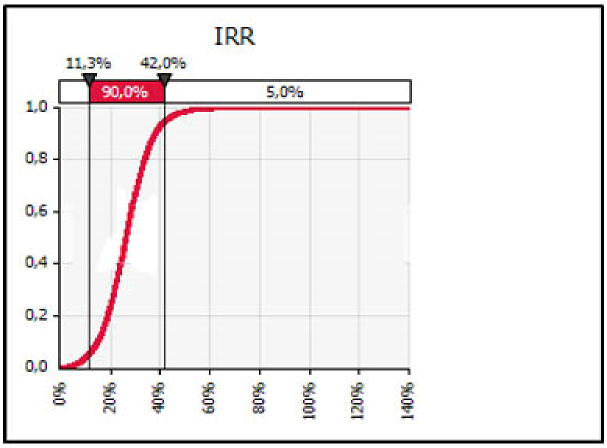
Figure 4: Comparison of cumulative distribution functions of NPV, scenarios A and B

Figure 5 shows that the cumulative distribution function is also shifted more toward lower values in the centralised, 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, namely 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.



Scenario A



Scenario B

Figure 5: Comparison of cumulative distribution functions of the IRR, scenarios A and B

4. Conclusions

We conducted an ex ante evaluation of the potential economic impact of the first Guinea-race sorghum hybrids introduced to farmers in the Sudanese Savanna of Mali, comparing two research and development paradigms. We compared two scenarios, based on the economic surplus model augmented with risk analysis. In the first, our parameter assumptions were 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 portrayed the state-managed approach to research that dominated previously.

Our findings indicate that, in Mali, PPB-F research and development with sorghum hybrids is a sound investment – not only because of the obvious yield and unit-cost advantages, but also because of more rapid development, introduction and initial adoption. In terms of either the IRR or NPV criterion, the findings suggest that the national sorghum programme has made important advances in overall approach over the past decades.

The simulation results demonstrate the sensitivity of total economic benefits in the PPB-F scenario to the per-unit cost advantages of hybrid seed, which are also closely linked to yield advantages. Maintaining these yield advantages thus is crucial for results. In either scenario, variability in total economic benefits depends heavily on the price elasticity of supply, in addition to the central role of yield advantages.

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 the net benefits of the participatory approach by including the recurring expenditures of the overall programme, in addition to the investments in the hybrid programme. On the other hand, the results for the PPB-F scenario are based only on initial, pilot efforts in 58 villages of the Sudanese Savanna.

5. Policy implications

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 the one hand, on-farm data indicate that the sorghum hybrids developed by the national programme in Mali perform well with or without fertiliser relative to local variety checks. On the other hand, sustaining yield increases in sorghum production will depend on good soil and water management over time. Thus 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 commercial responsiveness of producers to 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 this type of investment in Mali historically has favoured other cereals (rice and maize, as rotation crops with cotton).

On-farm testing, variety selection and seed multiplication by farmers could facilitate the 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 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 constitute 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).

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 modelling, underscores the economic potential of investing in well-targeted plant-breeding programmes linked to effective seed dissemination. In addition, the results indicate that overall benefits can be increased by supporting farmers in an integrated manner to protect yield gains, 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 Sudanese Savanna will depend on continued support for a decentralised seed system, with close research collaboration. Enlarging the network of farmer associations and small-scale seed companies engaged in seed production and dissemination will be important to ensure that more farmers can access seeds 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 smallholder sorghum growers, including women.

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