Economic analysis of 50% non-pollinating (FNP) maize varieties in Africa

by Hugo De Groote, Mariam Gharib, and Mike Olson

Economic analysis of 50% non-pollinating (FNP) maize varieties in Africa

Hugo De Groote[1], Mariam Gharib[1], and Mike Olson[1]*

[1]International Maize and Wheat Improvement Centre, Nairobi Kenya,

*Corresponding author, h.degroote@cgiar.org (others: gharibmariam@gmail.com, m.olson@cgiar.org)

Paper accepted for presentation

at the 31st International Association of Agricultural Economics Conference (ICAE)

August 17-31, 2021

Abstract

Maize is the most important food crop in Subsaharan Africa, but production cannot keep up with population growth. New technologies, in particular fo low N environment are needed. One technology is 50% non-pollinating (FNP) maize, which makes maize more N-efficient, and increase yields even on poor soils. Before the roll out, its benefits need to be compared to its costs. We estimate the direct effect of the yield increase from FNP at 192 kg/ha over SSA; the indirect yield effect (from the accelerated adoption of new varieties) is estimated at 891 kg/ha. Assuming an adoption of 10% of the current area in maize hybrids, a supply shift of 2 million tonnes of maize is estimated. The price reduction is estimated at 5%, and an adjusted production increase of 0.5M tonnes. The economic surplus is estimated at US$ 1.7 billion per year. The discounted benefits over the next 25 years are estimated at US$ 9.7 billion, compared to discounted costs of $20 million, a benefit cost ratio of 336. We conclude that the benefits of the technology are very high compared to the costs, and the technology is worth pursuing.

Keywords: maize, Africa, male sterility, benefit cost analysis

JEL classification: N57, Q16, Q11

Economic analysis of 50% non-pollinating (FNP) maize varieties in Africa

1. Introduction

Agricultural research improves not only the livelihood and food stability in a country but also sustains natural resources (Masters et al. 1996). Sub-Saharan Africa (SSA) faces a great risk of food insecurity; by 2050, the demand for cereals is expected to triple due to increased population (van Ittersum et al. 2016; Walker and Alwang 2015). Maize is the major staple food and the most important crop in most of SSA, having the largest share of cropland (FAOSTAT 2020; Tesfaye et al. 2015). SSA not only needs to increase productivity but also to adjust its agricultural practices (Baudron et al. 2015; Folberth et al. 2014). Several interventions have been introduced to tackle low soil fertility for resource-poor farmers including input subsidy programs, research and dissemination of good agronomic practices, and breeding of maize varieties that adapt to low soil fertility. One of these technologies uses the naturally occurring maize gene Ms44 to create female parent plants that do not produce pollen – resulting in maize varieties that produce 50% non-pollinating plants hence the name FNP. As these varieties save energy and nitrogen by savomg on pollination, they are more nitrogen efficient. Moreover, this technologies, when applied to new varieties, would be able to increase varietal turnover. However, the economic benefit of this technology, directly through yield increase or indirectly through increased varietal turnover, have so far not yet been analyzed.

Genetic improvement in food crops in SSA has resulted in maize varieties that are nutrient use efficient complimenting good agricultural practices. These varieties tackle low fertility production conditions and are incorporated with other traits including, drought tolerance, disease resistance, and high protein content making the maize varieties high yielding compared to early released varieties (Fisher et al. 2015). There are over 1700 maize varieties in SSA in 2014 and on average 73 new maize varieties are released annually (Abate et al. 2017). Compared to existing varieties, new varieties under drought and low soil fertility yield 20% more maize yield on average with the same level of resources (CIMMYT 2006). Improved maize varieties have been adopted by 52% of farmers in SSA (Abate et al. 2017). However, farmers tend to stick with old varieties they are familiar with and seed companies have had difficulty replacing the old varieties with newer released varieties (Smale and Olwande 2014; Rutsaert and Donovan 2020).

Several studies have reported that low variety turnover has worsened the situation of low productivity in SSA despite an increase in the number of cultivars released yearly, Smale and Olwande (2014)) in Kenya, Abate et al. (2015) in Ethiopia, and Ragasa et al. (2013) in Ghana. The weighted average age of all improved maize varieties in SSA has been estimated at 15 years, 18.1 years for OPV and 13.1 years for hybrid (Abate et al. 2017), although, this study only covered selected districts. The average age of varieties planted by farmers should be below 10 years to ensure farmers' benefit from genetic progress (Atlin et al. 2017; Walker et al. 2015). Adopting newer hybrid maize varieties on average increases maize yield by 20.9 kg ha^{-1} yr^{-1} under low nitrogen, 22.7 kg ha^{-1} yr^{-1} for random drought, 32.5 kg ha^{-1} yr^{-1} under managed drought, and 109.4 kg ha^{-1} yr^{-1} in optimal conditions (Masuka et al. 2017). On-farm evaluations show an increase in varietal age by a year has a potential yield increase of 75kg ha^{-1} yr^{-1} of improved variety (Cairns et al. 2021).

The Seed Production Technology for Africa (SPTA) project is a CIMMYT project that focuses on reducing seed production cost and increasing seed quality so that seed companies can produce sufficient quantities of high-quality hybrid seed using a single cross or three-way hybrids. Another area of interest of the project is to increase varietal turnover and adoption of superior hybrid maize varieties in SSA. Recently, a breeding technology was adapted –a naturally occurring maize gene Ms44 to create female parent plants that do not produce pollen – resulting in maize varieties that produce 50% non-pollinating plants hence the name FNP. Reduction in pollen production enables the plant to divert the saved nitrogen to the female plant that would have been used in the male flower increasing grain production. Recent research conducted in SSA shows that FNP varieties can increase yields on average by 200 kilograms/hectare (kg/ha) using the same level of inputs over a wide range of soil fertility conditions (Collinson et al., 2020), (Mashingaidze et al. 2020). Moreover, the FNP technology makes seed production cheaper, as it saves on time and detasseling labor cost, eliminating the need for castrating the male sterile lines and improves the pureness of hybrid seeds. It can therefore be incorporated in newly released varieties to replace hybrids that have been on the market for eight or more years, increasing the varietal turnover of maize varieties.

However, little is known about the economic impact of a yield increase from FNP on consumer or farmer surplus and the effect on prices and productivity.

The objectives of this study are to estimate the economic impact of the yield increase from FNP technology, using the economic surplus model. Specific objectives are to i) evaluate the effects of the technology on maize yields, productivity, and prices in SSA; ii) assess the direct benefits of FNP technology through increased yield to maize consumers and farmers, for the major maize producing countries, using the economic surplus model; and iii) estimate the indirect benefit through the effect of FNP on increasing varietal turnover. This is the first study to examine the impact of this new technology.

2. Methodology

2.1. The benefits of the FNP technology

The Seed Production Technology for Africa (SPTA) projectfocuses on introducing the FNP trait in existing new high-yielding varieties to increase varietal turnover by genetic improvement. The benefits are therefore two-fold. The direct effect is a yield increase inherent to the technology, estimated at about 200 kg/ha, almost regardless of soil fertility (Collinson et al., 2020). The indirect effect is that the technology makes seed production cheaper, so both seed companies and farmers will attracted to the technology, accelerating adoption and replacement of older varieties by newer, higher yielding varieties. On average, breeding increases maize yields by 75 kg ha $^{-1}$ year $^{-1}$ (Cairns et al. 2021).

The technology will be introduced at no cost to seed companies through Corteva's humanitarian use exemption and we expect the increase in productivity will increase food security that will translate to a decrease in maize prices. The economic surplus model quantifies the economic impact of a yield increase and changes in prices in terms of consumer and farmer surplus. A price decrease is offset by an increase in quantity demanded and farmers benefit from adopting FNP varieties as for consumers FNP is always a gain, a price reduction coupled with an increase in quantity. The economic impact will be higher when the technology replaces older varieties reducing the average weighted age of varieties and this causes an even higher increase in productivity and yield and decrease in prices.

2.2. Empirical Model: Welfare Analysis of FNP Maize

The economic surplus model is used to measure the welfare impact of a yield increasing agricultural technology (FNP). Various studies have used the economic surplus model to measure the impact of new technology on different crops in Africa and other continents, such as the impact of Bacillus thuringiensis (Bt) maize (De Groote et al., 2011), Bt cotton in the United States of America (Falck-Zepeda, Traxler and Nelson, 2000), and Bt eggplant in India (Krishna and Qaim, 2008). The economic surplus model has also been used to measure the most effective policy, for example different policies on testing and labelling aflatoxins maize in Kenya (De Groote et al., 2016). The advantages of the economic surplus model is that it does not requires large amounts of information and shows the change in economic surplus and how it is spread across different groups or time based on the project focus (Masters et al., 1996).

For our model, we assumed (1) a closed economy; (2) a discount rate of 10%; (3) it takes 10 years to reach maximum adoption (10% of hybrid adopters or 25%) of FNP; (4) adoption starts after 2 years after varietal release; (5) adoption increases proportionally per year and after 10 years' adoption remains constant; (6) no increase in cost due to adopting the new technology; (7) FNP technology produces a parallel change in supply; (8) average age of FNP variety is 3 years within 10 years, and (8) average age of FNP variety after 10 years is 5 years which is the least weighted average age of hybrid seeds in the study areas. The study period will span for 30 years after varietal release; afterwards, benefits become minute. The parameters for these assumptions are presented in Table 1.

Assume the supply curve before the technology is a linear function of the price, in an increasing function as shown in Figure 1. The inverse supply function is therefore given by:

$$P_s = a_s + b_s Q_s$$

Similarly, the inverse demand function is given by*:*

$$P_d = a_d + b_d Q_d$$

The slopes *bs* and *bd* are the inverses of the supply and demand elasticities (ε_s and ε_d) multiplied by the initial price/quantity ratio.

More elaborately, by definition demand elasticity: $\varepsilon_d = \frac{\partial Q_d}{\partial P_d}\frac{P}{Q}$ so at the initial point (P_0, Q_0) $\varepsilon_d = \frac{1}{b_d}\frac{P_0}{Q_0}$ or $b_d = \frac{P_0}{\varepsilon_d Q_0}$

Similarly, supply elasticity: $\varepsilon_s = \frac{\partial Q_s}{\partial P_s}\frac{P_0}{Q_0}$ or $\varepsilon_s = \frac{1}{b_s}\frac{P_0}{Q_0}$ or $b_s = \frac{P_0}{\varepsilon_s Q_0}$

Setting the equilibrium at the initial condition as $P_0 = P_s = P_d$ allows calculation of the intercepts:

$P_0 = a_s + b_s Q_s = a_s + \frac{P_0}{\varepsilon_d Q_0} Q_0$, so: $a_s = P_0 - \frac{P_0}{\varepsilon_d}$ and similarly, $a_s = P_0 - \frac{P_0}{\varepsilon_s}$

So the equations become:

$$\begin{cases} P_s = P_0 - \dfrac{P_0}{\varepsilon_s} + \dfrac{P_0}{\varepsilon_s Q_0} Q_s \\ P_d = P_0 - \dfrac{P_0}{\varepsilon_d} + \dfrac{P_0}{\varepsilon_d Q_0} Q_d \end{cases}$$

The FNP technology has a direct effect of an increase in yield of 200 kg ha $^{-1}$ and an indirect effect of 75 kg ha $^{-1}$ year $^{-1}$ for an increase in varietal turnover. Both the direct and indirect effect of the FNP technology is referred as the combined effect of FNP technology. Now the FNP technology makes the supply shift to the right (horizontal shift) by *J*.

$$J = t\,\Delta Y A$$

This is equivalent to a price shift downward (vertical) of δ *(*Masters et al. 1996 *calls it K)*

$$\delta = \frac{P_0 J}{\varepsilon_s Q_0} \quad \text{(or} \quad J = \frac{Q_0 \delta \varepsilon_s}{P_0} \quad)$$

At the same time, δ determines ΔQ, the final/equilibrium increase in production, through:

$$\delta = \left(\frac{1}{\varepsilon_s} - \frac{1}{\varepsilon_d}\right)\frac{P_0}{Q_0}\,\Delta Q = \gamma \frac{P_0}{Q_0}\Delta Q$$

This is the reduction in price.

Further, $\gamma \frac{P_0}{Q_0}\Delta Q = \frac{P_0 J}{\varepsilon_s Q_0}$ and $\Delta Q = \frac{J}{\varepsilon_s \gamma}$ while $\Delta Y = \frac{(\Delta Q)}{A}$

Next, δ can be split into $\delta_d = \frac{\Delta Q\, P_0}{-\varepsilon_d Q_0} = \frac{\delta}{-\varepsilon_d \gamma}$ and $\delta_s = \frac{\delta}{\varepsilon_s \gamma}$ .The equilibrium price P_1 can now be derived from the supply shift:

$$\Delta P = -\delta_d = \frac{\Delta Q P_0}{\varepsilon_d Q_0}$$

Finally, the change in economic surplus is the sum of the consumer and producer surplus which can now be derived as:

$$\Delta ES = \delta Q_0 \left(1 + \frac{\delta}{2\gamma P_0}\right)$$

The economic surplus can further be divided into the proportion for consumer surplus (δ_d/δ) and producer surplus (δ_s/δ):

$$\Delta CS = \Delta ES \frac{\delta_d}{\delta}$$

$$\Delta PS = \Delta ES \frac{\delta_s}{\delta}$$

To quantify the direct ($_{\mathrm{dr}}$) and indirect effect($_{\mathrm{ind}}$) of FNP technology, we first compute the proportion ΔY as a result of the direct effect of the technology ($\propto Y_{\mathrm{dr}}$) and the indirect benefit of an increase in varietal turnover ($\propto Y_{\mathrm{ind}}$).

$$\propto Y_{dr} = \frac{\Delta Y_{dr}}{\Delta Y} \qquad \propto Y_{ind} = \frac{\Delta Y_{ind}}{\Delta Y}$$

To get the proportion ΔY, ΔQ , J, ΔP,δ_d, δ_s, and δ as a result of the direct effect of FNP technology only, we take the computed values from the combined effect and multiply each by $\propto Y_{dr}$ (ΔY_{dr}, ΔQ_{dr} , J_{dr}, ΔP_{dr},${\delta_{dr}}_d$, ${\delta_{dr}}_s$, and δ_{dr}) and multiply by $\propto Y_{ind}$ for the indirect benefit of an increase in varietal turnover (ΔY_{ind}, ΔQ_{ind} , J_{ind}, ΔP_{ind},${\delta_{ind}}_d$, ${\delta_{ind}}_s$, and δ_{ind}). However, for ΔES_{dr}, ΔCS_{dr}, and ΔPS_{dr} we have to plug in the computed values in the equation as shown below to get the direct effect. For the indirect effect (ΔES_{ind}, ΔCS_{ind}, and ΔPS_{ind}) we change the values of δ_{dr} to δ_{ind}, ${\delta_{dr}}_d$ to ${\delta_{ind}}_d$, and ${\delta_{dr}}_s$ to ${\delta_{ind}}_s$ from the equations below.

$$\Delta ES_{dr} = \delta_{dr} Q_0 \left(1 + \frac{\delta_{dr}}{2\gamma P_0}\right)$$

$$\Delta CS_{dr} = \Delta ES \frac{{\delta_{dr}}_d}{\delta}$$

$$\Delta PS_{dr} = \Delta ES \frac{\delta_{dr_s}}{\delta}$$

2.3. Market data and study area

The economic surplus calculations were conducted for the major maize producing countries in Sub-Saharan Africa, in particular the 22 Sub-Saharan African countries with more than 100,000 hectares harvested with maize. Mali and Benin were dropped because hybrid maize seed varieties are not grown there, while for Madagascar, South Sudan, and Burundi no information on the adoption of improved maize varieties was found.

The parameters used in the economic surplus model were obtained from secondary sources. Production (Q_0), the total area under maize *(A)*, and yield per acre *(Y)* in FAOSTAT (2020). The average prices (P_0) were acquired from the Food Security Portal[a]. For countries with missing P_0, we use price level from neighboring countries and if no information is available we use regional average prices[b]. The elasticity of demand (ε_d) and supply (ε_s) are derived from previous research, and for missing value for both ε_d and ε_s for Angola we use Zambia elasticities, as for the other missing values of ε_s, we apply regional average ε_s. The adoption rates of hybrid maize for each country are also from previous research (see references in Appendix 1), for countries without information in the literature on maize hybrid adoption rates, regional averages are used from Abate et al. (2017). The adoption rate of FNP maize seed varieties *(t)* was assumed to be 10% of hybrid maize adopters and 25% under pessimistic conditions.

2.4. Data analysis

The first step of the analysis was, for each of the countries, to estimate the supply shift based on the assumed adoption rate of FNP varieties and the yield increase of these varieties, found in experimental studies (see the different steps in Figure 1). Based on the relation between demand and supply, through their elasticities (with estimates found in the literature) the resulting shift in demand was calculated (step 2). Using the linear economic surplus model presented above, the change in prices was calculated (step 3). Next, the actual shift in production was calculated (step

---

[a] http://www.foodsecurityportal.org/api/countries/maize and had only price information for Kenya, Nigeria, Ethiopia, Mozambique, Malawi, Uganda, and Chad.

[b] Countries in which we used neighboring country price level are Tanzania, Democratic republic of Congo, Cameroon, Zimbabwe, Ghana, Burkina Faso, Rwanda, South Africa, and Lesotho. The rest of the countries we computed average regional prices from two to three countries depending on the availability of information.

4), and from there the actual change in prices (step 5). Finally, the economic surplus was calculated, both for producers (step 6) and consumers (step 7).

3. Results

3.1. Overview of maize production in SSA

In Sub-Saharan Africa, agriculture is the main source of income and maize is the most important crop grown in most countries. From the map with the geographic distribution of maize production in SSA, three main production areas can clearly be distinguished; Eastern Africa, Western Africa, and Southern Africa as shown in Figure 2 (based on SPAM2017 data, numbers are maize production per km^2 of total land area). Maize area is generally about 40% of cropland except for West Africa where it is only 20%.

[Figure 2]

Maize area has been expanding rapidly over the last six decades, from 14 million ha in 1961 to 37.5 million ha in 2018, an annual increase of 1.7% (Figure 3). However, most of that increase took place in Eastern Africa, where it started early and kept steadily over time. In West Africa, the increase only started in 1980. In Middle Africa, the increase was small and slow and only started to pick up in the 2000, while in Southern Africa, the maize area is actually decreasing. Yields, on the other hand, did not change much, except for Southern Africa where they increased rapidly. In early 1960, yields in all regions of SSA were around 1 tonne/ha, and in Middle Africa they stayed at that level. In East and Western Africa, yields gradually increased to about 2 tonnes/ha, while in Southern Africa, they increased to more than 5 tonnes/ha .

[Figure 3]

In 2018, SSA produced 70.4 million tonnes of maize on 36.6 million ha (Table 1). Most of this production is from Eastern Africa (40%) and Western Africa (32%), with smaller amounts produced in Southern Africa (18%) and Middle Africa (10%). Although production in Eastern Africa is much higher than Southern Africa, maize yield in the latter regions is about three times as high . The differences in yields can be largely explained by the difference in the adoption of modern technology, in particular the use of improved maize varieties (IMVs) and fertilizer. The adoption rates of maize hybrids are high in Southern Africa (80%), medium in Eastern Africa (41%), but low in Middle Africa (10%) and West Africa (3%) (Table 1).

3.2 Direct, indirect, and combined impact of FNP on agricultural production in SSA.

We estimated the effect of FNP technology on agricultural production in SSA through an increase in yield using an economic surplus model. The production parameters used in this model are the current yields and production, the adoption rates of maize hybrids (in % of total area), and the weighted average age of the maize hybrids (in years since their release) for the 25 major maize producing countries in SSA (Table 1). The economic parameters used are the maize prices, and the supply and demand elasticities for these same countries (Appendix 1).

The yield increase of FNP technology increases slightly with current yield, see Equation (1). Based on this equation, we calculate the expected direct yield increase of FNP varieties in each country (Table 1). The resuls show an average yield increase of 192 kg/ha, with only minor variations: from 184 kg/ha in Zimbabwe to 213 kg/ha in South Africa.

The new FNP varieties are also expected to be younger (with an average age of three years since release) than the varieties they replace (11.3 on average) (Table 1). As younger varieties have a higher yield, estimated at 75 kg/ha for each year (Table 2), we can calculate the indirect yield increase of FNP varieties by multiplying this parameter with their age difference compared to current hybrids. The results show that the indirect yield effect is much higher than the direct effect, on average 696 kg/ha (Table 3). The indirect effect also has substantially more variation, with the lowest levels in Senegal and Ghana (just above 400 kg/ha) and the highest in Tanzania, Kenya and Nigeria (all above 800 kg/ha).

Adding up the two yield effects leads to an expected yield increase of 918 kg/ha, from a low in Cameroon (341 kg/ha), to high levels in Tanzania and Nigeria (more than 1 tonne/ha). Multiplying the yield increase with the expected area in FNP varieties leads to the supply shift, or the increase in production if prices would stay the same (represented by *J* in Figure 1). This supply shift is calculated at 2 million tonnes for the whole of SSA (Table 3).

3.3. Economic surplus

Unfortunately for farmers, and this the world over, the increased yield from new agricultural technologies does not usually lead to a proportionate income for farmers. What typically happens is that the increased production translates into a decrease in prices, which is good for consumers, but not for farmers. In response, farmers reduce their supply and consumers their demand, both in functions of their price elasticities (Appendix 1), to reach a new equilibrium. As we calculated the supply shift *J* and the price elasticities of supply ε_s and demand ε_s (Appendix 1), we can calculate the increase in production at the new equilibrium ΔQ (Table 4). The production increase for SSA is thus estimated at 0.514 million tonnes, about a quarter of the supply shift. The countries with the highest production increase are Tanzania (139k tonnes), South Africa (99k) Ethiopia (75k) and Kenya (46k).

Similarly, we can calculate the price shift ΔP, estimated at an average of US$16/tonne or, at an initial average price of $303, a reduction of 5% (Table 4). The price reduction varies strongly between countries, based on their supply shift and price elasticities, and ranges from less than US$1/tonne in several West African countries, to US$99 in Zimbabwe.

Once the new production and prices are established, the economic surplus can be calculated. For the whole of SSA, it is calculated at US$ 1,780 million. More than two thirds of the economic surplus goes to East Africa, and about a quarter to South Africa. The counties that will benefit the most are South Africa (US$ 410 million) Tanzania (US$365 million) and Ethiopia (US$ 194 million). To illustrate the importance of East Africa in the impact of the technology, all countries in the region except for Rwanda expect an economic surplus exceeding US$50 million, more than the country with the highest economic surplus in West Africa, Nigeria ($39 million).

The main reason is the large areas in maize production and the high levels of hybrid adoption.

Overall, producers benefited more than the consumers, with a producer surplus of US$ 1,008 (57%) versus a consumer surplus of US$ 772 million. however The distribution of economic surplus between consumers and producers varies strongly between countries however, mostly because of differences in elasticities. In West Africa, consumers receive the largest share of the benefits (80%), and this is also the case for some Eastern countries such as Malawi (68%), Zambia (88%), Zimbabwe (86%) and Kenya (67%)

3.4. Benefit cost analysis

To compare the benefits of the technology to its cost we have to compare the stream of both benefits and costs over time, and calculate the sum of their discounted annual value. The economic surplus we just calculated is the benefit of the technology at the assumed adoption rate of 10% of the maize hybrid area. However, that level will not be reached immediately at the release of the new varieties, expected in 2023. Moreover, we assume in the baseline scenario that it will take 10 years to reach that level, with a constant annual increase.

We assume for simplicity that all countries go through the same process at the same time, and show the evolution in economic surplus for some key countries as examples as well as the total in Table 5. The maximum economic surplus is reached at an adoption rate of 10% of area in hybrids, at a value of US$ 410 million for South Africa and a total of 1,780 for SSA. The first year after the release, in 2024, 10% of the target is reached, or 1% of maize hybrid area, so the economic surplus is about 10% of the maximum value (it is not an exact linear relationship). The economic surplus increases by 10% each year to reach the maximum value after 10 years, in 2032, after which it remains constant for the remaining years.

We discount the benefit stream as well as the costs (Table 6). For each year, substracting the discounted costs from the discounted benefits presents the net present value (NPV) and the total of those amounts to US$ 9.7 billion. As the costs are relatively small, the discounted benefits add up to almost the same value, US$ 9,693 million, compared to the discounted costs of US$ 20.1 million, or a very high benefit cost ratio of 336. The internal rate of return is 66%.

4. Discussion

In this study, we calculate the economic impact of the new FNP technology. We estimate the direct yield effect in SSA at 192 kg/ha, but estimate the indirect yield effect (from the accelerated adoption of new varieties) to be much higher, at 891 kg/ha. This yield increase, assumed to be realized at 10% of the current area in maize hybrids, leads to an supply shift of 2 million tonnes of maize. However, given the reduction in price, estimated at 5% on average, leads to an adjusted increase of maize production of half a million tonnes. The economic surplus generated by the price reduction and production increase is estimated at US$ 1.7 billion per year. The discounted benefits over the next 25 years are estimated at US$ 9.7 billion, compared to discounted costs of $20 million, a benefit cost ratio of 336.

Similar studies have observed positive impacts due to the uptake of new agricultural technology. Increase in productivity is generally a result of improvement in existing agricultural technologies (Walker et al. 2015). Further, varietal turnover by itself already achieves a substantial increase in productivity (Walker et al. 2015; Spielman and Smale 2017; Walker and Alwang 2015). Other studies have recommended multiple trait integration to achieve greater benefits of innovations (Saidaiah 2020).

The study has several limitations. First, the calculations are based on several assumptions, and rely on a number of paratmeters that have not been measured with accuracy, in particular adopton rates and price elasticities. Further, adoption rates and yield increases vary substantially by agroecological zones, but the available data only allow for calculatons at the aggregate, national

5. Conclusion

Our results show that that the direct benefits, through increased yield of the actual FNP technology and resultion production increase, are quite high. However, the indirect yield increase, through the increased varietal turnover, are much high. Moreover, there are large benefits to both farmers and consumers. Finally, as the costs to develop and deploy the technology are relatively modes, the benefits of the technology is are much higher than the costs.

The technology has a distinct advantage to seed companies, as it reduced the cost of production. Therefore, we recommend that the technology be carefully used, and only applied to superior new maize varieties, to help increase the varietal turnover. As our analysis shows, the advantage of the increased turnover is much larger than the direct yield benefit of the technology.

Acknowledgement

We thank the Bill and Melinda Gates foundation for supporting this study through the SPTA project.

References

Abate, T., M. Fisher, T. Abdoulaye, G.T. Kassie, R. Lunduka, P. Marenya, and W. Asnake. 2017. “Characteristics of maize cultivars in Africa: How modern are they and how many do smallholder farmers grow?” *Agriculture & Food Security* 6(1):30.

Abate, T., B. Shiferaw, A. Menkir, D. Wegary, Y. Kebede, K. Tesfaye, M. Kassie, G. Bogale, B. Tadesse, and T. Keno. 2015. “Factors that transformed maize productivity in Ethiopia.” *Food Security* 7(5):965–981.

Atlin, G.N., J.E. Cairns, and B. Das. 2017. “Rapid breeding and varietal replacement are critical to adaptation of cropping systems in the developing world to climate change.” *Global Food Security* 12:31–37.

Baudron, F., B. Sims, S. Justice, D.G. Kahan, R. Rose, S. Mkomwa, P. Kaumbutho, J. Sariah, R. Nazare, G. Moges, and B. Gérard. 2015. “Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement.” *Food Security* 7(4):889–904.

Bergea, H.F.M. ten, R. Hijbeekb, M.P. van Loonb, J. Rurindac, K. Tesfayed, S. Zingorec, P. Craufurde, J. van Heerwaardenb, F. Brentrupf, J.J. Schrödera, H.I. Boogaardg, H.L.E. De

Groot, and M.K. van Ittersumb. 2019. “Maize crop nutrient input requirements for food security in sub-Saharan Africa.” *Global Food Security*:13.

Binswanger-Mkhize, H.P., and S. Savastano. 2017. “Agricultural intensification: The status in six African countries.” *Food Policy* 67:26–40.

Bold, T., K.C. Kaizzi, J. Svensson, and D. Yanagizawa-Drott. 2017. “Lemon Technologies and Adoption: Measurement, Theory and Evidence from Agricultural Markets in Uganda.” *The Quarterly Journal of Economics*:qjx009.

Chianu, Jonas N., Justina N. Chianu, and F. Mairura. 2012. “Mineral fertilizers in the farming systems of sub-Saharan Africa. A review.” *Agronomy for Sustainable Development* 32(2):545–566.

Chibwana, C., G. Shively, M. Fisher, C. Jumbe, and W. Masters. 2014. “Measuring the impacts of Malawi’s farm input subsidy programme.” 9(2):16.

CIMMYT. 2006. “Winning in the long run.” *nternational Maize and Wheat Improvement Center (CIMMYT)*. Available at: https://www.cimmyt.org/news/winning-in-the-long-run/.

Druilhe, Z., and J. Barreiro-Hurlé. 2012. “Fertilizer subsidies in sub-Saharan Africa.”

FAOSTAT. 2020. “FAOSTAT Production Data Base.” Available at: http://www.fao.org/faostat/en/#data/.

Fisher, M., T. Abate, R.W. Lunduka, W. Asnake, Y. Alemayehu, and R.B. Madulu. 2015. “Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa.” *Climatic Change* 133(2):283–299.

Folberth, C., H. Yang, T. Gaiser, J. Liu, X. Wang, J. Williams, and R. Schulin. 2014. “Effects of ecological and conventional agricultural intensification practices on maize yields in sub-Saharan Africa under potential climate change.” *Environmental Research Letters* 9(4):044004.

Fox, T., J. DeBruin, K. Haug Collet, M. Trimnell, J. Clapp, A. Leonard, B. Li, E. Scolaro, S. Collinson, K. Glassman, M. Miller, J. Schussler, D. Dolan, L. Liu, C. Gho, M. Albertsen, D. Loussaert, and B. Shen. 2017. “A single point mutation in *Ms44* results in dominant male sterility and improves nitrogen use efficiency in maize.” *Plant Biotechnology Journal* 15(8):942–952.

ICRISAT. 2009. “Fertilizer microdosing-Boosting production in unproductive lands.” Available at: http://oar.icrisat.org/id/eprint/5666.

van Ittersum, M.K., L.G.J. van Bussel, J. Wolf, P. Grassini, J. van Wart, N. Guilpart, L. Claessens, H. de Groot, K. Wiebe, D. Mason-D’Croz, H. Yang, H. Boogaard, P.A.J. van Oort, M.P. van Loon, K. Saito, O. Adimo, S. Adjei-Nsiah, A. Agali, A. Bala, R. Chikowo, K. Kaizzi, M. Kouressy, J.H.J.R. Makoi, K. Ouattara, K. Tesfaye, and K.G.

Cassman. 2016. “Can sub-Saharan Africa feed itself?” *Proceedings of the National Academy of Sciences* 113(52):14964–14969.

Janssen, B.H. 1998. “Efficient use of nutrients: an art of balancing.” *Field Crops Research* 56(1–2):197–201.

Jayne, T.S., N.M. Mason, W.J. Burke, and J. Ariga. 2018. “Review: Taking stock of Africa’s second-generation agricultural input subsidy programs.” *Food Policy* 75:1–14.

Jayne, T.S., and S. Rashid. 2013. “Input subsidy programs in sub-Saharan Africa: a synthesis of recent evidence.” *Agricultural Economics* 44(6):547–562.

Kihara, J., P. Bolo, M. Kinyua, S.S. Nyawira, and R. Sommer. 2020. “Soil health and ecosystem services: Lessons from sub-Sahara Africa (SSA).” *Geoderma* 370:114342.

Lehmann, J., and G. Schroth. 2002. “Nutrient leaching.” In G. Schroth and F. L. Sinclair, eds. *Trees, crops and soil fertility: concepts and research methods*. Wallingford: CABI, pp. 151–166. Available at: http://www.cabi.org/cabebooks/ebook/20033029502 [Accessed November 9, 2020].

Liu, J., L. You, M. Amini, M. Obersteiner, M. Herrero, A.J.B. Zehnder, and H. Yang. 2010. “A high-resolution assessment on global nitrogen flows in cropland.” *Current Biology* 7(3):R126.

Masso, C., F. Baijukya, P. Ebanyat, S. Bouaziz, J. Wendt, M. Bekunda, and B. Vanlauwe. 2017. “Dilemma of nitrogen management for future food security in sub-Saharan Africa – a review.” *Soil Research* 55(6):425.

Masters, W.A., B. Coulibaly, Diakalia Sanogo, M. Sidibé, A. Williams, J.H. Sanders, and J.L. DeBoer. 1996. *The Economic Impact of Agricultural Research: A Practical Guide*. USA: Purdue University.

Masuka, B., G.N. Atlin, M. Olsen, C. Magorokosho, M. Labuschagne, J. Crossa, M. Bänziger, K.V. Pixley, B.S. Vivek, A. von Biljon, J. Macrobert, G. Alvarado, B.M. Prasanna, D. Makumbi, A. Tarekegne, B. Das, M. Zaman-Allah, and J.E. Cairns. 2017. “Gains in Maize Genetic Improvement in Eastern and Southern Africa: I. CIMMYT Hybrid Breeding Pipeline.” *Crop Science* 57(1):168–179.

Michelson, H.C., A. Fairbairn, A. Maertens, B. Ellison, and V.M. Manyong. 2018. “Misperceived Quality: Fertilizer in Tanzania.” *SSRN Electronic Journal*. Available at: https://www.ssrn.com/abstract=3259554 [Accessed September 28, 2020].

Odhiambo, J.A., U. Norton, D. Ashilenje, E.C. Omondi, and J.B. Norton. 2015. “Weed Dynamics during Transition to Conservation Agriculture in Western Kenya Maize Production” J. L. Gonzalez-Andujar, ed. *PLOS ONE* 10(8):e0133976.

Ragasa, C., A. Dankyi, P. Acheampong, A.N. Wiredu, A. Chapoto, M. Asamoah, and R. Tripp. 2013. “Patterns of Adoption of Improved Maize Technologies in Ghana.” :33.

Ricker-Gilbert, J., and T.S. Jayne. 2017. "Estimating the Enduring Effects of Fertiliser Subsidies on Commercial Fertiliser Demand and Maize Production: Panel Data Evidence from Malawi." *Journal of Agricultural Economics* 68(1):70–97.

Rutsaert, P., and J. Donovan. 2020. "Sticking with the old seed: Input value chains and the challenges to deliver genetic gains to smallholder maize farmers." *Outlook on Agriculture* 49(1):39–49.

Smale, M., and J. Olwande. 2014. "Demand for maize hybrids and hybrid change on smallholder farms in Kenya." *Agricultural Economics* 45(4):409–420.

Tesfaye, K., S. Gbegbelegbe, J.E. Cairns, B. Shiferaw, Prasanna, K. Sonder, K.G. Cassman, D. Alexandre, and R. Robertson. 2015. "Maize systems under climate change in sub-Saharan Africa: Potential impacts on production and food security." *International Journal of Climate Change Strategies and Management* 7(3):247–271.

Walker, T.S., and J. Alwang. 2015. *Crop Improvement, Adoption, and Impact of Improved Varieties in Food Crops in Sub-Saharan Africa*. CGIAR and CAB International.

Walker, T.S., J. Alwang, A. Alene, J. Ndjuenga, R. Labarta, Y. Yigezu, A. Diagne, R. Andrade, R.M. Andriatsitohaina, H. de Groote, K. Mausch, C. Yirga, F. Simtowe, E. Katungi, W. Jogo, M. Jaleta, S. Pandey, and D.K. Charyulu. 2015. "Varietal adoption, outcomes and impact." In T. S. Walker and J. Alwang, eds. *Crop improvement, adoption, and impact of improved varieties in food crops in sub-Saharan Africa*. Wallingford: CABI, pp. 388–405. Available at: http://www.cabi.org/cabebooks/ebook/20153367555 [Accessed September 14, 2020].

Wanzala, M.N. 2011. "Implementation of the Abuja Declaration on Fertilizer for an African Green Revolution." The New Partnership for Africa's Development (NEPAD).

Collinson, Sarah, Esnath Hamadzipiri, Hugo De Groote, Michael Ndegwa, Jill Cairns, Marc Albertsen, Dickson Ligeyo, Kingstone Mashingaidze and Michael Olsen 2020. Seed Production Technology for Africa: Delivering Improved Grain Yield of Maize Hybrids to Smallholder Farmers in Sub-Saharan Africa. Unpublished manuscript.

De Groote, H., C. Narrod, S. Kimenju, C. Bett, R. Scott and M. Tiongco 2016. Measuring rural consumers' willingness to pay for quality labels using experimental auctions: the case of aflatoxin free maize in Kenya. Agricultural Economics 47: 33–45. doi: http://onlinelibrary.wiley.com/doi/10.1111/agec.12207/

De Groote, H., W. A. Overholt, J. O. Ouma and J. Wanyama 2011. Assessing the potential economic impact of *Bacillus thuringiensis* (Bt) Bt maize in Kenya. African Journal of Biotechnology 10: 4741-4751.

IFPRI. 2020. Spatially-Disaggregated Crop Production Statistics Data in Africa South of the Sahara for 2017", https://doi.org/10.7910/DVN/FSSKBW, Harvard Dataverse, V2.

Krishna, V. V. and M. Qaim 2008. Potential impacts of Bt eggplant on economic surplus and farmers' health in India. 38 167-80.

Masters, William A., Bakary Coulibaly, Diakalia Sanogo, Mamadou Sidibé, Anne Williams, John H. Sanders and Jess Lowenberg-DeBoer 1996. The Economic Impact of Agricultural Research: A Practical Guide. West Lafayette, IN: Department of Agricultural Economics, Purdue University.

(FNP economics) Tables and Figures

Table 1. Maize production in SSA in 2018 (25 top producing maize countries)

Region	Country	Area (1000 ha)	Production (1000 tonnes)	Yield (kg/ha)	Adoption (% IMV)	Adoption (% hybrids)	Average age hybrids
			A	Q	*Y*	*t*	*X*
Eastern	Tanzania	4,101	5,987	1,460	71.8	40.2	14.2
	Ethiopia	2,236	7,360	3,292	77.3	66.0	10.6
	Kenya	2,142	4,014	1,874	82.1	65.0	13.7
	Mozambique	1,827	1,654	906	30	24.9	10.5
	Malawi	1,685	2,698	1,601	78.5	65.7	10.7
	Zimbabwe	1,191	730	613	97.5	95.4	13.4
	Uganda	1,131	2,964	2,621	95.2	37.6	10.7
	Zambia	1,086	2,395	2,205	63.8	61.5	12.8
	Rwanda	296	410	1,387	32	22.4	13.0
	Madagascar	129	215	1,667	4	-	
	Eastern	15,823	28,428	1,797	72	40.7	12.3
Western	Nigeria	4,853	10,155	2,092	26.3	11.6	14.8
	Ghana	1,184	2,306	1,947	53.4	3.1	6.0
	Benin	1,158	1,510	1,304	12.8	-	
	Mali	1,129	3,625	3,211	51.2	-	
	Burkina Faso	1,019	1,700	1,668	37	3.8	8.0
	Togo	715	887	1,240	5	0.5	13.0
	Guinea	611	819	1,339	67	6.9	13.0
	Cote d'Ivoire	473	1,006	2,126	54	34.4	13.0
	Senegal	180	264	1,470	97	10.0	6.0
	Western	11,323	22,272	1,967	34	2.8	9.9
Southern	South Africa	2,319	12,510	5,395	97	84.2	12.4
	Lesotho	128	100	785	75	65.1	12.4
	Southern	2,447	12,610	5,154	96	80.0	12.4
Middle	DRC	2,680	2,078	775	15	9.6	13.0
	Angola	2,655	2,271	856	5.6	4.1	12.4
	Cameroon	1,316	2,345	1,782	82	52.2	5.0
	Chad	342	438	1,281	70	44.6	13.0
	Middle	6,993	7,132	1,020	27	10.2	11.3
Total	(25 top countries)	36,586	70,441	1,925	192.54	25.7	11.3

Table 2. Assumptions to calculate the economic surplus of FNP (50% non-pollinating) maize hybrids in Subsaharan Africa

Parameters	Scenario1 (middle)	Scenario2 (pessimistic)	Scenario 3 (optimistic)
Discount rate	0.100	0.100	0.05
Adoption of FNP (proportion hybrid area)	0.100	0.050	0.25
Yield increase per year of improved variety (tonne/ha/year)	0.075	0.050	0.075
Average age of FNP variety within 10 years	3	7	3
Start year of the project	2020	2020	2020
Start of adoption (first year)	2023	2025	2023
Period to reach maximum adoption (Proportional increase of adoption)	10	20	5
Base year production	2018	2018	2018
Base year price	2019	2019	2019
Average age of FNP variety after 10 years (the least weighted average age of hybrid)	5	7	4
No increase in cost due to adoption of the new technology	X	X	X
Technical change produces a parallel shift	X	X	X

Table 3. Changes in maize yield and supply shift from FNP in SSA (25 top maize countries)

Region	Country	Production (1000 tonnes)	Yield (kg/ha)	Yield change (t/ha)			Area in FNP (ha)	Supply shift (tonnes)
				Direct	Indirect	Total		
Eastern	Tanzania	5,987	1,460	0.189	0.840	1.029	164,843	169,617
	Ethiopia	7,360	3,292	0.200	0.570	0.770	147,568	113,620
	Kenya	4,014	1,874	0.191	0.803	0.994	139,213	138,370
	Mozambique	1,654	906	0.186	0.563	0.748	45,484	34,028
	Malawi	2,698	1,601	0.190	0.578	0.767	110,727	84,962
	Zimbabwe	730	613	0.184	0.780	0.964	113,662	109,556
	Uganda	2,964	2,621	0.196	0.578	0.773	42,524	32,889
	Zambia	2,395	2,205	0.193	0.735	0.928	66,789	62,009
	Rwanda	410	1,387	0.189	0.750	0.939	6,625	6,217
	Madagascar	215	1,667	0.190				
	Subtotal	28,428	1.80	0.180	0.71	0.90	837,435	751,269
Western	Nigeria	10,155	2,092	0.193	0.885	1.078	56,299	60,676
	Ghana	2,306	1,947	0.192	0.225	0.417	3,672	1,531
	Benin	1,510	1,304	0.188			-	-
	Mali	3,625	3,211	0.199			-	-
	Burkina Faso	1,700	1,668	0.190	0.375	0.565	3,876	2,191
	Togo	887	1,240	0.188	0.750	0.938	368	345
	Guinea	819	1,339	0.188	0.750	0.938	4,211	3,951
	Cote d'Ivoire	1,006	2,126	0.193	0.750	0.943	16,275	15,347
	Senegal	264	1,470	0.189	0.225	0.414	1,791	741
	Subtotal	22,272	1.97	0.180	0.79	0.98	86,490	84,781
Southern	South Africa	12,510	5,395	0.213	0.705		195,247	179,153
	Lesotho	100	785	0.185	0.705		8,313	7,397
	Subtotal	43,182	2.41	0.180	0.71	0.92	203,560	186,550
Central	DRC	2,078	775	0.185	0.750		25,611	23,943
	Angola	2,271	856	0.185	0.705		10,884	9,691
	Cameroon	2,345	1,782	0.191	0.150		68,737	23,432
	Chad	438	1,281	0.188	0.750		15,244	14,297
	Subtotal	85,460	2.20	0.180	0.40	0.59	120,477	71,362
Total	(25 top countries)	164,323	2,013	0.192	0.70	0.89	2,375,447	2,116,562

Table 4. Economic surplus due to the introduction and adoption of FNP, direct and indirect effects, on the major producing countries in SSA (Scenario 1)

Countries	1. Supply shift FNP (horizontal tonnes)	2. Reduction production costs ($)	3. Change quantity (ΔQ)	4. Change prices (US$)	5. Change ES Surplus (US$ 1000)	6. Change CS (US$ 1000)	7. Change PS (US$ 1000)
	$\boldsymbol{J} = t\,\Delta YA$	$\delta = K = (PJ/\varepsilon sQ)$	$\Delta Q = J/(\varepsilon_s\gamma)$	$\boldsymbol{\Delta P = -}\delta_d = (\Delta QP)/(\varepsilon dQ)$	$\Delta ES = \delta Q(1+\delta/(2\gamma P))$	$\Delta CS = \Delta ES\ \delta d/\delta$	$\Delta PS = \Delta ES\ \delta s/\delta$
SouthAfrica	179,129	33	98,864	-14.6	410,424	183,904	226,520
Tanzania	169,617	60	139,489	-10.7	364,515	64,747	299,769
Ethiopia	113,620	26	74,817	-9.0	194,204	66,323	127,881
Mozambique	34,028	107	24,287	-30.6	178,156	51,000	127,156
Malawi	84,962	51	26,791	-34.8	137,922	94,431	43,491
Zambia	62,009	43	7,271	-37.9	102,956	90,884	12,071
Zimbabwe	109,556	116	15,735	-99.3	85,612	73,317	12,296
Democratic Republic Congo	23,943	32	20,336	-4.9	67,646	10,190	57,455
Kenya	138,370	14	46,123	-9.4	56,909	37,939	18,970
Uganda	32,889	19	25,373	-4.3	55,601	12,707	42,895
Nigeria	60,676	4	11,919	-3.1	38,856	31,223	7,632
Lesotho	7,397	169	5,715	-38.5	17,467	3,972	13,495
Angola	9,691	7	1,136	-6.2	16,069	14,185	1,884
Cameroon	23,432	6	4,603	-5.1	15,011	12,063	2,949
Chad	14,297	26	2,808	-21.0	11,474	9,220	2,254
Cote d'Ivoire	15,347	11	3,015	-8.6	10,736	8,627	2,109
Rwanda	6,217	26	4,810	-5.8	10,663	2,413	8,250
Guinea	3,951	3	776	-2.7	2,761	2,219	542
Burkina Faso	2,191	1	430	-0.7	1,436	1,154	282
Ghana	1,531	0	301	-0.3	980	787	192
Senegal	741	2	146	-1.6	518	416	102
Togo	345	0	68	-0.2	241	193	47
Total			514,812	**-15.9**	1,780,157	771,915	1,008,242

Table 5. Economic surplus over time (in US$ 1000)

	Year	South Africa	Tanzania	Ethiopia	Kenya	Nigeria	Total
Maximum Economic Surplus (US$) (first row)	Maximum	410,424	364,515	194,204	56,909	38,856	1,780,157
Annual economic surplus (US$)	2021	-	-	-	-	-	-
	2022	-	-	-	-	-	-
	2023	-	-	-	-	-	-
	2024	40,897	36,074	19,332	5,662	3,884	176,994
	2025	81,826	72,231	38,684	11,330	7,767	354,213
	2026	122,788	108,473	58,055	17,004	11,652	531,660
	2027	163,782	144,799	77,446	22,685	15,537	709,334
	2028	204,808	181,208	96,856	28,373	19,422	887,236
	2029	245,866	217,702	116,287	34,067	23,308	1,065,366
	2030	286,957	254,279	135,736	39,768	27,194	1,243,722
	2031	328,080	290,941	155,206	45,475	31,081	1,422,307
	2032	369,236	327,686	174,695	51,189	34,968	1,601,119
	2033	410,424	364,515	194,204	56,909	38,856	1,780,159
	2034	410,424	364,515	194,204	56,909	38,856	1,780,159
	2048	410,424	364,515	194,204	56,909	38,856	1,780,159
	2049	410,424	364,515	194,204	56,909	38,856	1,780,159

Table 6. Economic analysis of FNP, including net present value (NPV), discounted values of benefits and costs, internal rate of return (IRR) and benefit/cost analysis (BC).

BC parameters	Year	Year	Cost ($1000)	Benefit ($1000)	NPV (2020 $1000)	Costs discounted ($1000)	Benefits discounted ($1000)
	2010	-11	1,000	-	-2,853	2,853.1	-
	2011	-10	1,000	-	-2,594	2,593.7	-
	2020	-1	1,600	-	-1,760	1,760.0	-
	2021	0	1,250	-	-1,250	1,250.0	-
	2022	1	1,250	-	-1,136	1,136.4	-
	2023	2	1,250	176,994	145,243	1,033.1	146,276
	2024	3	1,250	354,213	265,186	939.1	266,126
	2025	4	800.00	531,660	362,584	546.4	363,131
	2026	5	500.00	709,334	440,130	310.5	440,441
	2027	6	300.00	887,236	500,652	169.3	500,822
	2028	7	100.00	1,065,366	546,650	51.3	546,701
	2029	8	-	1,243,722	580,206	0	580,206
	2030	9	-	1,422,307	603,197	0	603,197
	2031	10	-	1,601,119	617,301	0	617,301
	2042	21		1,780,159	240,554	0	240,554
	2049	28		1,780,159	123,442	0	123,442
Net Present Value (NPV)			20,100	40,034,805	9,664,176	28,883	9,693,059
Internal rate of return (IRR)					0.66		
Benefits (discounted)					9,693,059		
Costs (discounted)					28,883		
Benefit cost ratio (BCR)					336		

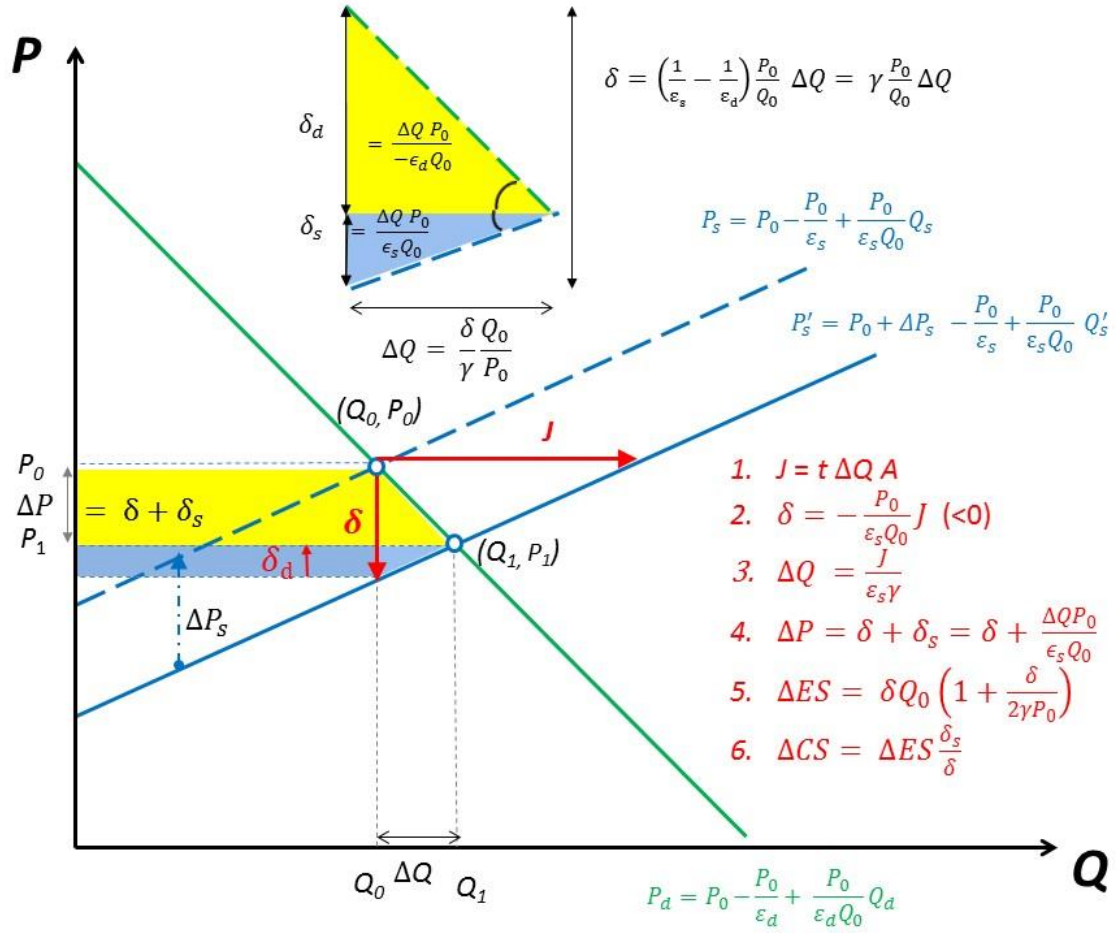

Figure 1. Calculating the Economic surplus from a production shift-empirical framework

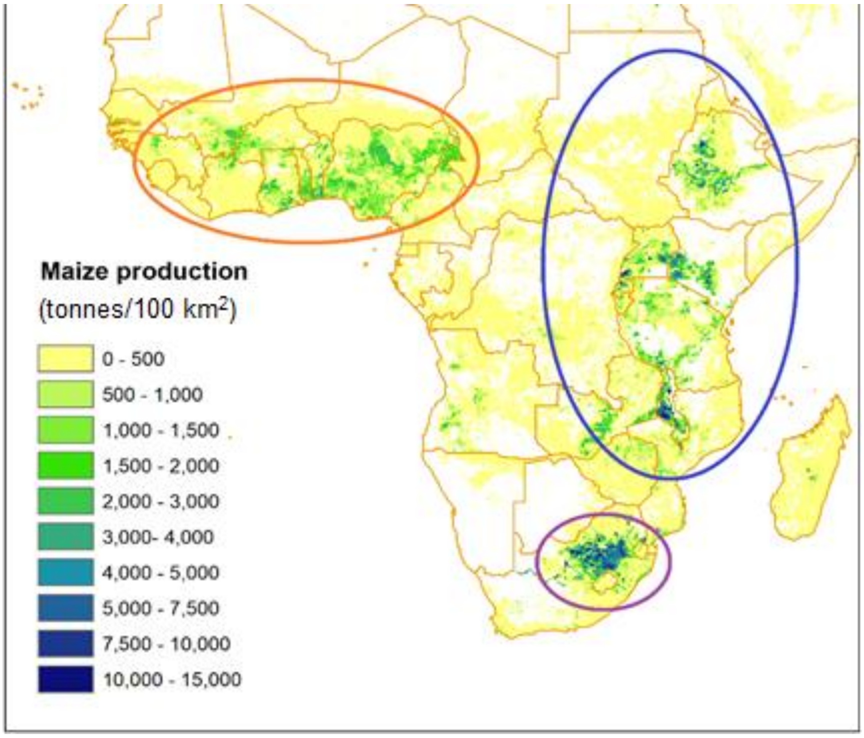

Figure 2. Major maize production areas in SSA (each pixel represents 100 km^2,color codes indicate maize production in tonnes per 100 km^2**,** map was generated from SPAM2017 data (IFPRI, 2020) with ArcGIS Desktop version 10.8.1 from ESRI, https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview)

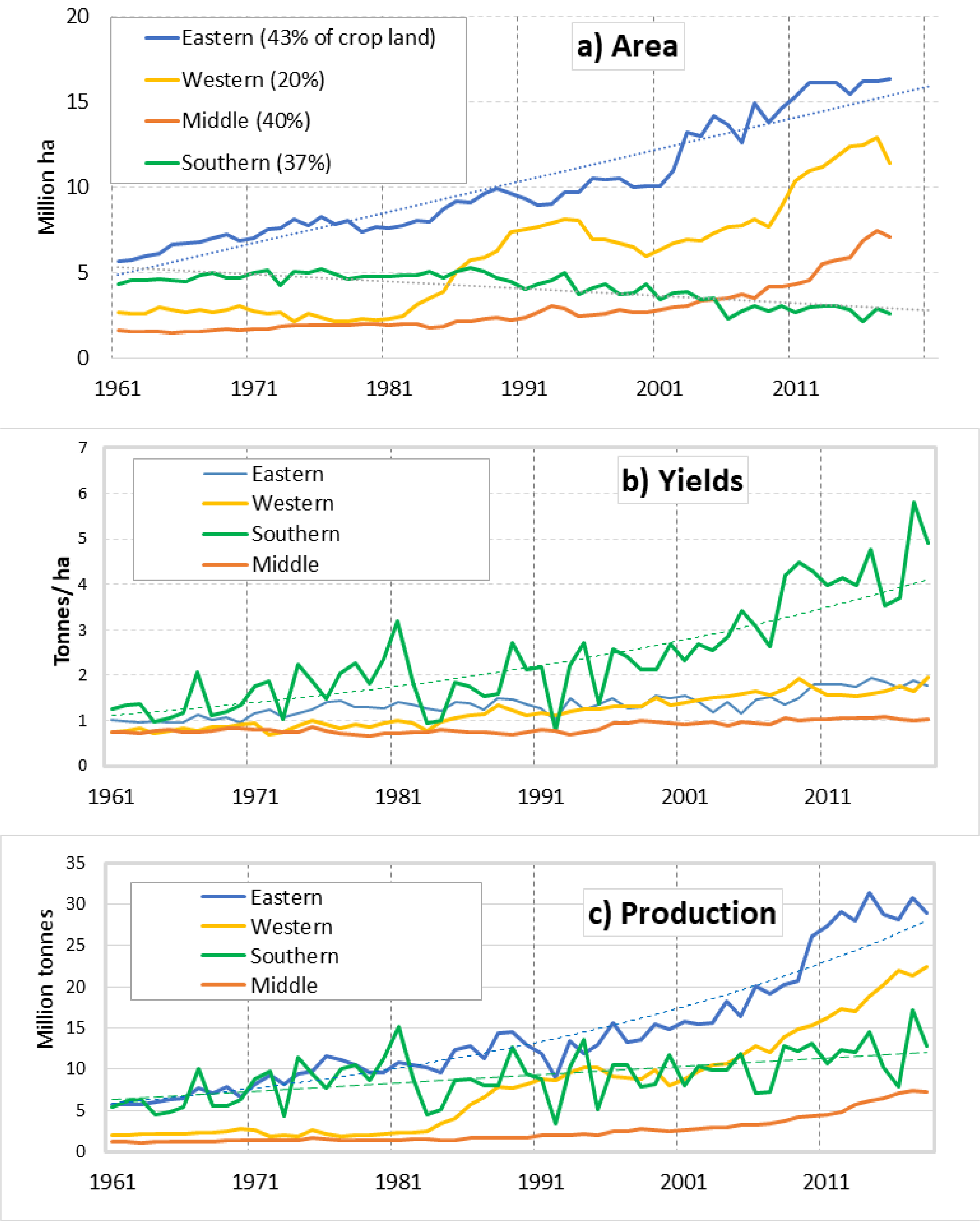

Figure 3. Trends in maize area and yields in Subsaharan Africa (1961-2018)

Collinson, Sarah, Esnath Hamadzipiri, Hugo De Groote, Michael Ndegwa, Jill Cairns, Marc Albertsen, Dickson Ligeyo, Kingstone Mashingaidze and Michael Olsen 2020. Seed Production Technology for Africa: Delivering Improved Grain Yield of Maize Hybrids to Smallholder Farmers in Sub-Saharan Africa. Unpublished manuscript.

De Groote, H., C. Narrod, S. Kimenju, C. Bett, R. Scott and M. Tiongco 2016. Measuring rural consumers' willingness to pay for quality labels using experimental auctions: the case of aflatoxin free maize in Kenya. Agricultural Economics 47: 33–45. doi: http://onlinelibrary.wiley.com/doi/10.1111/agec.12207/

De Groote, H., W. A. Overholt, J. O. Ouma and J. Wanyama 2011. Assessing the potential economic impact of *Bacillus thuringiensis* (Bt) Bt maize in Kenya. African Journal of Biotechnology 10: 4741-4751.

IFPRI. 2020. Spatially-Disaggregated Crop Production Statistics Data in Africa South of the Sahara for 2017", https://doi.org/10.7910/DVN/FSSKBW, Harvard Dataverse, V2.

Krishna, V. V. and M. Qaim 2008. Potential impacts of Bt eggplant on economic surplus and farmers' health in India. 38 167-80.

Masters, William A., Bakary Coulibaly, Diakalia Sanogo, Mamadou Sidibé, Anne Williams, John H. Sanders and Jess Lowenberg-DeBoer 1996. The Economic Impact of Agricultural Research: A Practical Guide. West Lafayette, IN: Department of Agricultural Economics, Purdue University.

Appendix 1.Economic parameters used in the calculation of the economic surplus

Countries	Maize price 2019 (US$/tonne)	Demand elasticity	Supply elasticity
	P0	ε_d	ε_s
South Africa	347	-0.187	0.152
Tanzania	327	-0.713	0.154
Ethiopia	284	-0.322	0.167
Mozambique	347	-0.166	0.067
Malawi	215	-0.061	0.133
Zambia	281	-0.023	0.169
Zimbabwe	347	-0.075	0.448
Democratic Republic Congo	264	-0.530	0.094
Kenya	327	-0.400	0.800
Uganda	264	-0.530	0.157
Nigeria	288	-0.110	0.450
Lesotho	347	-0.513	0.151
Angola	281	-0.023	0.169
Cameroon	288	-0.110	0.450
Chad	360	-0.110	0.450
Coted'Ivoire	314	-0.110	0.450
Rwanda	264	-0.530	0.155
Guinea	314	-0.110	0.450
BurkinaFaso	295	-0.110	0.450
Ghana	288	-0.110	0.450
Senegal	314	-0.110	0.450
Togo	314	-0.110	0.450