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Technology Development For Semi-Arid Sub-Saharan Africa: Theory, Performance and Constraints

Abstract: The paper proposes a theory of technology development for semi-arid regions. It then evaluates the theory by reviewing the characteristics of technologies successfully introduced into the regions and, with modeling, identifying some constraints to further technology introduction of the type proposed. Some specific policy recommendations to accelerate technology introduction are recommended.

INTRODUCTION

Declining food production per capita over the last three decades, especially in the Sahel, but also in other parts of sub-Saharan Africa, leads many to be pessimistic about future agricultural performance in this region. High population growth turns even moderate agricultural production growth rates into declining per capita trends (Sanders and Ramaswamy, 1995, Ch. 2). The per capita declines have been especially serious in the semi-arid regions where rainfall is low and irregular, and soils are often fragile with low fertility. Historically, these regions have been contributors to the labour pool of the most prosperous higher rainfall regions through out-migration. However, there have been some successes in agricultural performance especially with maize and sorghum in this semi-arid region. A closer look at these successes is useful to formulate approaches to technology development and leads to some optimism about the future of agricultural development in semi-arid sub-Saharan Africa.

This paper formulates a theory of technology development for the semi-arid sub-Saharan region of Africa. Next it evaluates this theory. First, the adequacy of the theory in explaining observed technology successes in semi-arid West Africa is reviewed. Secondly, potential technologies of the type recommended are modeled, and the predictions from these models are compared with the observed shifts in technology. The last two sections of the paper make some policy recommendations and conclusions.

A THEORY OF INTENSIVE AGRICULTURAL TECHNOLOGY DEVELOPMENT

In the semi-arid regions of sub-Saharan Africa, the principal constraint to crop-output increases is almost given by definition. Semi-arid regions have inadequate soil water for most crop production through most of the year. Nevertheless, in the last two decades there has been little investment in irrigation in this region, mainly due to prohibitive costs (Matlon, 1987, p.66). Both construction and rehabilitation of existing schemes were estimated to cost between $5000 and $20 000 per ha in the 1980s (Matlon, 1990, p.19).

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The effects of low and irregular rainfall on crop yields are frequently aggravated by soil crusting, which leads to reduced water infiltration. In these crusting soils, water-retention techniques such as dikes and ridging become critical to reduce runoff and to use the available rainfall. Fortunately, there are numerous techniques for water conservation or retention, and these are potentially very important (Carr, 1989, pp.46–48; Reij *et al.*, 1988; Sanders *et al.*, 1990).

Making water available when nutrient levels in the soil are very low often results in only a small yield response. Even at slightly higher nutrient levels, cereals will quickly deplete the available nutrients. Conversely, applying fertilizers (organic or inorganic) without an assured water supply is economically risky because the response to fertilizer depends upon the availability of water at the critical stages of plant development.

Combined technologies to increase soil water and crop nutrient levels have been shown to raise sorghum yields by 50–100 percent and to be highly profitable (Sanders *et al.*, 1990, pp.11–15; Nagy *et al.*, 1988). These combined technologies are land substituting and increase the demand for labour. To what extent would these technologies be economically appropriate and profitable and fit into farmers' production systems in the semi-arid environment of West Africa?

The semi-arid regions of West Africa have had increasing population pressure on the land, causing a breakdown of the traditional fallow periods of 10 to 15 years. Shorter fallow periods, without replacing soil nutrients with purchased inputs, cause crop yields to decrease over time. Farmers must then increase their cultivated area to maintain production levels, thereby pushing crop production into more marginal areas and then decreasing communal grazing areas. As cattle are sold or entrusted to migrating herders, availability of manure as fertilizer declines.

Soil nutrient depletion leading to lower yields becomes a widespread problem with increased population pressure (Southgate *et al.*, 1990). As cultivated areas are extended, wind and water erosion, and soil crusting often occur as farmers intensively cultivate the previously marginal crop or grazing areas and follow the traditional cultural practices of utilizing or burning crop residues. With declining organic matter and soil nutrient levels, farmers must increase their labour inputs to maintain the same level of production (see Sanders *et al.*, 1990, p.3).

The induced innovation theory considers technological change to be responsive to the economic signals from relative factor and product prices. In this case, the reduction in availability and quality of land and reduced productivity of labour induces researchers and governments to produce and promote, and farmers to adopt, new technologies which substitute increased use of labour and/or inputs for degraded land. Critics of such more intensive water retention technologies have emphasized the large increases in labour requirements (Matlon, 1990, p.27). This labour use change is substantial. However, the soil degradation and the consequent fall in the marginal productivity of labour already required an increased amount of labour to produce the same level of output with less land. Thus, it is the degradation and the decreased value of farm family labour with few non-farm alternatives that result in the increase in labour use. The technological change is a response to this demand for a technology that substitutes for land.

In the previous section, the principal constraints to output increases in semi-arid Sub-Saharan African agriculture are hypothesized to be water and soil nutrients. Are the new technologies being successfully introduced in semi-arid West Africa consistent with the above theory?

RECENT INTRODUCTION OF INTENSIVE TECHNOLOGIES: A PRELIMINARY EVALUATION OF THE THEORY

The Sahelian region exhibiting the most rapid technological change, the Sudano-Guinean zone, has the highest rainfall. Technically, this zone is in the transition to semi-humid rather than semi-arid, so fertilization can be practised with less concern for first improving water retention. Here, the introduction of new cotton cultivars has been combined with increasing levels of chemical fertilizer application (Table 1). Moderately high levels of inorganic fertilizer were utilized on both cotton and maize. Sorghum often benefits from being in the rotation. Introduction of new cotton and maize cultivars along with use of better production practices then complemented the yield effects of increased fertilizer application, enabling substantial increases in cotton and maize yields. New technology development and diffusion have been very successful in this region.

Dykes to slow runoff have been rapidly introduced in the last five years in the Sudanian and the Sahelo-Sudanian regions in Burkina Faso and Niger. In northern Burkina Faso alone, these dykes are found on 60 000 ha (World Bank, 1989, p.98; Sanders *et al.*, 1990)[1]. Dykes are predominantly found in the most severely degraded regions and are constructed in the off-season when opportunity costs of family labour are generally lower than during the crop season. This is consistent with the theory presented earlier. In the most degraded regions, the available opportunities for labour are much fewer compared to areas with higher population pressure and more adequate resources. Hence, sufficient labour becomes available for these extremely labour intensive technologies only with soil degradation and low opportunity costs. In the Sudanian zone of Mali, animal traction with oxen is predominant in contrast with the almost exclusive use of donkeys in the Sudanian zone of Burkina Faso. In Mali the use of ridging on the contour with animal traction is undertaken during the crop season when cultivating for weeds and has been shown to have almost as large a yield effect as tied ridges. As with the dykes the collection and spreading of the manure requires large labour inputs (Sanders, 1995, Ch. 4).

Another important innovation in both the Sudanian and the Sahelo-Sudanian zones has been development of shorter season cultivars (sorghum, millet, and cowpeas). There has been diffusion of new cultivars between farmers and from the experiment stations (Vierich and Stoop, 1990; Matlon, 1990, pp. 25, 26; Coulibaly, 1987). Since the start of the drought of 1968–73, rainfall has been one standard deviation below the long-term normal in semi-arid West Africa (Glantz, 1987, p.39). Hence, the payoff from early or short-season varieties has increased, since earliness allows drought escape. Moreover, improved farmer cultivars have been selected under low soil fertility conditions. Therefore, the early cultivars are a partial response to both constraints of water availability and soil nutrient levels. This introduction of new cultivars alone gives only small income increases in average years of good rainfall but raises yields in adverse rainfall seasons. This is only a temporary solution as all cultivars need fertilizers or they will mine the soil nutrients. In the sandy dune soils of the Sahelo-Sudanian zone of Niger, chemical phosphorous fertilization is being rapidly introduced in several regions (Mokwunye and Hammond, 1992). Here, crusting is less common, so fertilizer use alone is less risky than in the Sudanian zone (Shapiro *et al.*, 1993).

Due to high capital, maintenance, and recovery costs of irrigation, only small-scale and supplementary irrigation has tended to be promoted in Africa over the last two decades. Nevertheless, in some regions, old irrigation projects have been important for farmers. In

Niger, irrigation projects frequently serve as an income base for dryland farmers. In one zone, each farmer was given 0.4 ha of irrigated area; the farmers also produced crops on 4 to 5 ha of dryland. On the irrigated area, farmers produced rice with improved cultivars and high levels of chemical fertilizer. Clearly, these technologies resolved both constraints (Shapiro, *et al.*, 1993).

Table 1 *Rainfall by Region and Technologies Successfully Introduced in the Three Principal Agro-Ecological Regions for Crop Production of the Semi-Arid Tropics in West Africa*

	Expected Rainfall at 90% Probability		Responses to Principal Constraints	
Zones	(mm)	Technologies	Water Availability	Soil Fertility
Sudano-Guinean	800–1100	New cotton and maize cultivars with chemical fertilizer and improved agronomic practices. Rapid increase in use of organic fertilizers	Sufficient rainfall in most years in this zone	Fertilizer used in the combined-technology package
Sudanian	600–800	Contour dykes and organic fertilizer. Early cereal and cowpea cultivars. In Mali, ridging and increases in organic fertilizers	Holds the runoff water. Earliness gives drought escape	Organic fertilizer. Selected for low soil-fertility conditions
Sahelo-Sudanian	350–600	Supplementary irrigation.[a] Early cereal and cowpea cultivars and P fertilizer. Contour dykes and organic fertilizers	Full water control. Drought escape with earliness. Holds the runoff	Rice heavily fertilized. In several regions, chemical fertilizers are being introduced. Organic fertilizers

Note: [a] Only small areas of supplementary irrigation (<1 ha) provided by the government of Niger to farmers; these are a type of income stabilization for dryland farmers.

Source: Sandra, Ramasaramy and Shapiro, 1995, Chapter 3.

In summary, sub-Saharan Africa is usually considered a land-surplus region, with seasonal labour availability as the main constraint to increased output. However, in semi-arid West Africa, the general failure to adopt animal traction, except where intensive, yield increasing technologies were introduced, may indicate the need for re-evaluation of this conventional analysis. The major thesis here is that the principal constraints to increasing agricultural output in much of sub-Saharan African agriculture are water availability and soil nutrient level. In semi-arid regions, improving soil nutrient level generally requires increased water availability at critical times of crop production, as well as higher nutrient levels. Water retention or conservation devices tend to be extremely labour intensive. Hence, they have been adopted first in those regions with land degradation and high population pressures where labour has the fewest alternatives. In regions with lower population densities and better resources, other technologies to increase water retention are expected to be adopted as the available crop area for expansion decreases and the value of agricultural products increases.

POTENTIAL TECHNOLOGIES AND CONSTRAINTS IN THE SUDANIAN REGION

There are many other high-yielding water-retention/soil-fertility techniques besides the dykes/organic-fertilizer combination, including the combination of tied ridges and inorganic fertilizer. Tied ridging is a water retention device constructed by creating perpendicular ridges, leaving a depression in the middle where water collects rather than running off[2]. As the available land is reduced with higher population pressure, model results predict an increasing area shift into the more intensive new technologies of tied ridges and fertilization. These combined technologies would be adopted by farmers, according to the model, and they provide moderate income increases even where there is severe degradation. Higher population pressures leading to decreasing land availability will induce more rapid shifts to the new technologies proposed (Ramaswamy and Sanders, 1992, p.368).

Another critical factor affecting technology introduction is the profitability of agriculture. As output and input prices are changed with improved transport and new policies, model results indicate that farmers shift to more intensive production practices, extending the area in tied ridges and increasing fertilization (Ramaswamy and Sanders, 1992, p.371). In the past, many African parastatal marketing agencies were not as concerned with the profitability of agriculture as with keeping food prices low and taxing agriculture to pay for public investments and services in urban areas (Bates, 1981, pp.30–44; World Bank, 1986, pp.61–73). Increased profitability of agriculture does result in the more rapid adoption of more intensive or sophisticated technologies.

The model results are confirmed by numerous field observations in the Sudanian region. First, as reported earlier, the dirt and stone dykes, combined with organic fertilizers, are being rapidly introduced on the Central Plateau of Burkina Faso, as is ridging on the contour with animal traction cultivators in Mali. Moreover, field studies in Burkina Faso during the 1980s indicated farmer adoption of several other intensive techniques, including the growth of a cash market for manure in Fulani regions, some utilization of inorganic fertilizer on sorghum, and increased out of season fruit and vegetable production with supplementary irrigation using organic fertilizer and watering by hand (Vierich and Stoop, 1990). Moreover, in the early 1990s, farmers introducing new maize cultivars with fertilizer were also reported as using tied ridges on the Central Plateau (Berry, Personal Communication, 1993). The areas in tied ridges have been expanding slowly, as this is an extremely labour intensive practice that has to be performed at one of the two peak labour demand periods. Expanding the areas in these intensive technologies in the Sudanian zone of Burkina Faso may require not only increased water availability and higher soil fertility but also an animal traction ridger to overcome the seasonal labour constraint.

The model results for potential technology introduction are consistent with our theory of technology development. The difficulty of simultaneously introducing three new inputs (a water retention technique, fertilizer, and a new animal traction implement) may explain previous failures in technology introduction (Byerlee and Hesse de Polanco, 1986). Now, with increasing pressure on the land, and African governments being encouraged by funding agencies to create a more profitable environment for agriculture, several of these intensive or yield increasing technologies are being adopted. This process needs to be adapted to different soils, labour availabilities, and economic environments (Sanders *et al.*, 1990; Shapiro *et al.*, 1993).

ACCELERATING THE INTRODUCTION OF INORGANIC FERTILIZER

In the agro-ecological zones discussed in the last two sections, a key technology component was inorganic fertilizer. Numerous alternatives to inorganic fertilizer have been researched. Most would substitute locally produced materials, by-products, or sophisticated production techniques such as inoculation. Many are claimed to be lower cost or lower risk. Unfortunately, in evaluating these alternatives in field trials in the Sahel, inorganic fertilizer was still the only viable alternative for increasing yields (Nagy *et al.,* 1988; for a brief policy article reviewing those alternatives to inorganic fertilization see Deuson and Sanders, 1990, p.197). There is a notable exception. Structural reform programs eliminated the subsidies on chemical inputs in the late 1980s in many countries. Moreover, the 50 percent devaluation of the currency (CFA) of the French Economic Community in January 1994 further reduced the relative prices of organic to inorganic fertilizers. Where farmers have animal stocks or can build them up, as in southern Mali, there have been increases in the manure production technology (covered compost heaps, cutting of millet and sorghum straw for the corrals), thus improving the quality and increasing the quantity of organic fertilizers from animals, household wastes, and crop residues. Again, these are extremely labour intensive processes. The supply is limited by the size of the animal herds and the transformation technologies available, so there are limits to the substitution potential between organic and inorganic fertilizers (Sanders, 1994, Ch. 4).

Substitutes for inorganic fertilizer in semi-arid regions have been evaluated by researchers for at least a decade. Further research to find low cost complementary activities to inorganic fertilizer and thereby reduce the costs to farmers should not affect the present development strategy. Inorganic fertilizer is a known technology backed by a substantial body of knowledge. It needs to be combined with increased water availability in the Sudanian region. Even higher returns are possible with the further addition of improved cereal cultivars for the Sudanian and Sahelo-Sudanian zones[3].

In the past, one principal constraint to fertilizer use was physical shortages. Government policy makers have typically put a low priority on fertilizer in their rationing of foreign exchange for imports. With the low priority given to fertilizer imports by governments, farmers often had to depend upon concessional imports from donors and upon irregular distribution systems. As sub-Saharan African countries adjust their overvalued exchange rates and remove import rationing by licensing and quotas, it will be easier for private or public distribution agencies to import fertilizer[4]. Achieving timely, low cost delivery of fertilizer to farmers needs to be an important public concern. With the generally poor state of transport infrastructure in most of sub-Saharan Africa, substantial public investments are required to assure the availability of fertilizers at the appropriate times and to facilitate the marketing of increased cereal yields.

CONCLUSIONS

Semi-arid sub-Saharan Africa has often been identified as a land-surplus region with seasonal labour as the limiting constraint. This paper challenges this view and argues that in the semi-arid regions, the dual problems of low soil fertility and lack of water availability at critical times of crop development are the factors leading to poor yields. Once the soil fertility and water management conditions are improved, there will be a much larger impact from the introduction of a new cultivar. The failure to identify these principal constraints has had important implications for both research and development policies.

Governments need to put a higher priority on fertilizer imports especially if they have not yet completely eliminated the overvaluation of their currencies. For some time, researchers and others have been claiming that a local input use, such as rock phosphate, a grain/legume rotation, crop residues, or the development of a low soil-fertility-tolerant cultivar would enable African governments to save foreign-exchange and the African farmers to avoid input purchases. Soil fertility improvement is a critical requirement for crop yield increases in this region and the gains from inorganic fertilizer use are well documented. Future research can reduce the long-run requirements for inorganic fertilizers by finding more efficient utilization methods. Nevertheless, African farmers need to take advantage now of the yield increases possible with this input. More public and private investments supporting the fertilizer and seed industries are also expected to accelerate the development of those agricultural systems.

NOTES

1 These dykes are constructed on the contour at fairly wide intervals of 10 to 30 metres, depending on the slope. The dykes accumulate soil from higher up on the toposequence for one or two metres behind them. This soil accumulation is often accompanied by the application of organic fertilizer (Wright, 1985, p.56). Higher value crops are planted here. These combined techniques respond to both of the key constraints; water availability and soil nutrient level.

2 A similar very labour intensive technique of digging small holes in the field ('zia') and planting around them has also been adopted in the degraded Sudanian regions of Burkina where farmers have utilized the rock and stone dykes. Again the labour input is undertaken outside the crop season.

3 Developing new cultivars for moderate input levels should be a higher return activity than attempting to develop genetic tolerances to drought and low soil fertility at low or zero input levels under harsh conditions. Increasing farm level yields and incomes without higher levels of input use may be impossible. The riskiness of fertilization alone is considerably reduced with increased water availability.

[4] There is a short run problem of the increasing price of inorganic fertilizer resulting from the elimination of fertilizer subsidies and from devaluation. However, devaluation also increases the price of imported food products relative to domestically produced food crops. This will increase the demand for domestic food crops increasing their prices. The relevant fertilizer price is then the cost of fertilizer relative to the domestically produced food price.

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DISCUSSION OPENING — Douglas Graham *(The Ohio State University, USA)*

My comments will focus on three areas; the strong recommendation for more focussed use of fertilizers, the suggestion that an induced innovation model is operating here and the question as to whether the study areas fall into the high potential or low potential area discussed earlier in the conferences for Africa by Otsuka and Delgado.

In my judgement the authors make a good case for qualifying the land surplus labour scarcity hypothesis with one that emphasizes the constraints of low soil fertility and lack of available water. They also argue that the failure to identify these constraints correctly has led to inappropriate research and development policies. I wish they would be more explicit and elaborate further on what these inappropriate policies were and how their current recommendations could correct this bias.

The authors also argue that governments should place a higher priority on fertilizer imports. I had always thought that, in the 1970s and early 1980s, governments in Africa had in fact given high priority to fertilizer imports and use through usually high subsidies to encourage fertilizer use. Of course, in the wake of structural adjustment policies, these subsidies are being removed and with higher real exchange rates emerging from these macro reforms, it is becoming expensive to use fertilizers across many crop lines in Africa.

In light of this it is not clear how the authors expect to overcome this high cost hurdle in recommending that governments support increased use of fertilizers in combination with their new water retention technology.

An additional issue is the authors' relative pessimism for the substitution of chemical fertilizers by organic manures and other local indigenous inputs or practices. In light of what I perceive to be a 'high cost' fertilizer solution, I am not sure how warranted this pessimism is for this region. Finally, there is mention at the end of the need for more public and private investment in fertilizer and seed industries. How do the authors see the logical division of labour here? Are private traders currently substituting for previous parastatal fertilizer distribution in these areas? If not, why not? What does this imply for the appropriate roles for each to achieve a cost effective fertilizer distribution network?

Secondly, what is the Induced Innovation path of technological change in the semi-arid region of SSA? The authors really do not address or explain this in the paper perhaps because of space limitations. Nevertheless, the paper does proprose a theory of technological development for semi-arid regions. Perhaps they could elaborate on this further. For example, in the classic induced innovation reasoning farmers suffering from an input constraint limiting their profits and growth, work through their farmer organizations to procure relevant government authorities and public research establishments to solve their problem by directing research to break, or at least reduce, the costs of this constraint. In the Hayami–Ruttan world this decentralized, bottom up path of including technological change in frequently cited with examples from Japan, the USA and European countries.

I don't see this political economy model of induced innovations in agricultural technology working out the same way in semi-arid west Africa. Farmers do not have the organizational 'clout' to pressure political authorities, and national research systems usually are weak or do not exist. No doubt regional or international centres or scientists come in to play a role here. This suggests a top down, not a bottom-up path of induced changed in agricultural technology. In this framework it is not clear what the relative roles of farmers, national governments, national and international research centres are and how they play out their respective roles to shape the path and direction of technical change in agriculture in this more rudimentary political and socio-economic setting. One thing is clear. It is not very likely to follow the decentalized institutional path of action and reaction that Hayami and Ruttan laid out for developed countries. At first glance it would appear that farmers would play less of a role and international research organizations more of a rule in shaping the priorities and policy initiatives.This this may be a necessary and logical fall back strategy given the level of socio-economic development in semi-arid African countries. It would be helpful if the authors would share their thoughts with us on this issue.

Finally, it would be instructive to get the authors' view on where they see the semi-arid regions of their study fitting into the high potential — low potential dichotomy laid out by Otsuka and Delgado in this conference. If it is a high potential area for yields, then the investment called for in this paper would make sense given the alleged high pay-off from these invested resources. On the other hand, if it is a low yield area, their recommendations could be questioned (if one accepts the Otsuka–Delgado position).