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Chapter

Blending Climate Action and Rural Development in Africa's Sahel

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Abstract

This paper describes the opportunity for combining climate action and improved food and nutritional security as mutual elements of rural development projects, with particular reference to the situation in the African Sahel. This progress is achieved by identifying climate-smart agricultural production technologies and bundling them into solutions for inclusion within larger projects and programs. Seventeen (17) such technologies are offered in this chapter that represent genetic innovations, improved soil and water management, and directed improvement across landscapes. Examples of the efficacy of these technologies are presented based on results from the African Agricultural Transformation Program (TAAT) with specific reference to improved cereal production. An example of the deployment of TAAT technologies for millet and sorghum involving 83,620 households managing 123,863 ha led to nearly 200,000 MT of increased food production worth about $42 million. This effort led to an estimated annual increase of 177,279 MT CO_2e in biomass and soil worth $3.9 million, assuming buyers could be found. The relationship between three principal drivers of agricultural transformation, the public, private, and farming sectors, is considered in terms of how these different technologies are mobilized and deployed. The potential for increasing food supply and carbon gains under current agricultural investment levels across the Sahel by International Financial Institutions, about $683 million per year, is described. This chapter then offers recommendations in how improved rural development projects combining climate action and food security in the Sahel may be designed in the future.

Keywords: African drylands, cereal crops, climate change, IITA, soil and water management, TAAT Program, technology deployment, transferable assets

1. Introduction

Adaptation to climate change by small-scale farmers is considered an important part for the climate solution agenda [1, 2]. This is specially the case in the Sahel where food security is tenuous and becoming more so due to rising temperatures and more episodic precipitation [3, 4]. Awareness of this situation is not new, and several farming technologies were identified and modified that allow rural households to cope with increased risks through reliance upon improved crop varieties, more efficient water harvesting, protection of soil quality and participation in well planned,

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systems-level improvements to their agro-ecosystems [5]. Indeed, isolated cases of successes are documented and used as the basis of designing larger, subregional projects [6] intended for the joint purpose of increasing food and nutrition security in ways that constitute climate action by legions of small-scale farming households [7, 8].

All rural development projects require inclusive and active participation by the public and private sectors, and the client farmers themselves, because local organizations acting through public works and as customers of proven production inputs represent a complete package toward change. Rural development projects are often financed by sovereign loans from International Financial Institutions (IFIs). It is the design and implementation of these projects that prove difficult. In some cases, countries receiving sovereign country loans rely upon suboptimal, existing technologies and are reluctant to involve what they perceive as overly expensive international partners. In other cases, it is not the technologies that are flawed, but rather the manner that they are bundled as solutions, because effective interventions seldom require only one new technology but rather balanced sets of accompanying production inputs and innovative practices [9]. In yet other cases, it is not the solutions that are inadequate, but rather their manner of deployment, often in expectation of too rapid adoption [10]. Complicating this arena is the growing recognition that small-scale farming households are both victims of climate change yet offer the means to effect corrective actions when offered the opportunity and incentive to do so [1].

2. The Sahelian situation

Dryland farming is the dominant mode of livelihood across the Sudano-Sahelian zone of Africa, a transition zone about 400–600 km wide that stretches from the Atlantic Ocean in Senegal to the Red Sea in Djibouti and Indian Ocean in Somalia [11]. Climate-smart solutions and modernization of technologies are critical to improving agriculture in the zone. The Sahel is home to a population of about 110 million persons, the majority of whom rely upon agriculture through the cultivation of about 30 million ha. Landscapes are flat to gently undulating and rainfall at theses latitudes is concentrated in a single growing season between June and September, with a total annual precipitation of only 150–600 mm that is often deposited by only a few heavy storms. Daytime temperatures often exceed 40°C. The natural vegetation ranges from semi-desert in the north to woody grassland in the south. Millet is widely grown in the Sahel and Sudanese zones, but so too is sorghum and maize. New varieties of wheat can be grown too, particularly during the cooler months [12]. Semi-nomadic pastoralism is widely practiced and overgrazing has led to extensive land degradation and desertification. Rice cultivation is possible in some areas, most notably the valleys of major rivers, and represents an important crop in household diets and livelihoods. The adjoined Sudanese Zone receives greater rainfall (600–1200 mm per year) but is confined to a 2–3 month window and its farmers are faced with similar challenges to crop production as their neighbors in the Sahel [5].

Agricultural production in the Sahel is perilous because of severe and cyclical droughts [13]. Other soil limitations exist due to low water-holding and nutrient retention capacities and soils are often sandy and acidic [14]. Because of their unfavorable soil physical properties and low nutrient reserves, soils of the African drylands present a challenge to farmers [15]. Clearly, farmers in the Sahel are acutely aware of drought as a chronic risk and are prepared to adjust their cropping strategies accordingly. Population densities in the agricultural areas remain relatively low, with

0.5–1.5 ha available per capita. Land availability alone does not assure rural prosperity in the Sahel owing to the poor crop productivity resulting from low rainfall and chronic risk of drought. Despite the severe conditions experienced by farmers in the Sahel, large opportunities are available for employing improved soil and water management technologies, including those important to climate actions [5].

The Technologies for African Agricultural Transformation Program (TAAT) deploys proven technologies to African farmers, including those in the Sahel. TAAT arose as a joint effort of the International Institute of Tropical Agriculture (IITA) and the African Development Bank (AfDB) and is a crucial component of the latter's Feed Africa Strategy [10]. It is organized around 15 "Compacts" that represent priorities and partnerships to achieve food security in Africa and advance its role in global agricultural trade [16]. TAAT operates a Regional Technology Delivery Infrastructure that offers a menu of tested and proven food production technologies for nine priority commodities to program partners and stakeholders. These technologies are bundled into "technology toolkits" [17] that are included within country projects and deployed through extension campaigns. These technologies include improved crop varieties, seed systems innovations, accompanying soil fertility and pest managements, harvest and postharvest handling, digital applications, and value addition processes [18], providing Regional Public Goods that attract broad public interest and recognizable benefits. TAAT offers a unique collaborative platform where government, international donors, private actors, and nonstate actors committed to advancing transformative agricultural technologies connect with those who need them most, particularly within programs addressing agricultural production and rural development. It offers a mechanism for the development community to buy into proven technical advances [19]. This paper describes how TAAT's technologies are of benefit to the Sahel and how they may be better integrated within climate action efforts.

3. Appropriate solutions

Solutions are available that assist farmers in the Sahel to increase productivity and achieve food security while also being able to tackle environmental challenges posed by drought, land degradation, and climate change. The solutions are based on greater access to proven technologies that remain under-recognized, inadequately delivered or too difficult to access. Once mobilized, however, key technologies may be bundled into toolkits offering solutions to those seeking to modernize and transform dryland agriculture by combining improved crop varieties, more effective water conservation practices and proven approaches for soil fertility management [9, 17]. Cereal improvement in the Sahel focuses upon millet, sorghum, maize, and wheat that are both drought- and heat-tolerant [20]. Better water management achieves water storage from contour bunds, water harvesting within zaï pits, diversion of seasonal floods, and small-scale irrigation schemes [21, 22]. Practices for integrated soil fertility management involve rotation with legumes, fertilizer micro-dosing, strategic timing of nitrogen application and effective use of organic resources [14]. Larger-scale impacts are achieved through transition from open fields to agroforestry parklands, improved rangeland management and other climate actions specifically targeted to semiarid agro-ecologies. It is essential that these technologies become incorporated into larger rural development projects, but first they must be readily understood by development planners, extension supervisors, and business persons seeking to enhance the lives and livelihoods of farmers. The Sahel is one of the areas of the world that is unfairly penalized by industrial polluters in developed countries, and the impacts of climate change it suffers are not of its own making. Inclusion of these technologies into rural development projects, including those financed with sovereign loans from International Financial Institutions, and embedding them into country-level climate actions serve to correct this disparity.

TAAT offers 17 technologies useful to both rural development and climate action (see **Table 1**). These technologies are grouped according to their relationship to improved field crop varieties (four crops), better management of water resources (four technologies), relationship to integrated soil fertility management (four technologies),

Technology objective	TAAT holder[1]	Approach	Mechanism
New varieties			
Improved pearl millet	ICRISAT	Conventional breeding	Community-based seed production
Improved Sorghum	ICRISAT	Conventional breeding	
Drought-tolerant maize	AATF/IITA	Conventional breeding	Commercial hybridization
Heat-tolerant wheat	ICARDA	Conventional breeding	Public-private partnership
Water management			
Bund walls	IFDC	Soil & water conservation	Community-based action
Zaï pits	IFDC	Soil & water conservation	Farmer action
Spate irrigation	IWMI	Seasonal water harvesting	Community-based action
Small-scale irrigation	IWMI	Year-round cultivation	Commercial suppliers
Soil quality			
Fertilizer micro-dosing	IFDC	Better fertilizer placement	Extension information
Strategic timing of N	IFDC	Improved fertilizer timing	Extension information
Inoculation and BNF	IITA	Symbiotic N fixation	Commercial suppliers
Organic resource management	IITA	Farmer-available resource	Farmer action
Systems transformation			
Control insect invasions	IITA	Combat episodic pests	Public project leadership
Overcoming *striga*	AATF/IITA	Eliminate soil infestation	Public project leadership
Transition to parklands	IITA	Agroforestry intervention	Public project leadership
Improved range management	ILRI	Combat land degradation	Public project leadership
Local biogas	Clearinghouse	Alternative rural energy	Commercial suppliers

[1]*TAAT lead partner organization (see TAAT website https://taat-africa.org).*

Table 1.
A summary of TAAT's 17 climate-smart dryland technologies.

and possibilities for system-level improvement (five technologies). Not considered among these technologies is rice (*Oryza sativa*), an important irrigated crop of Sahelian river basins, and animal enterprises that are extremely important across the Sahel but beyond the scope of this paper.

3.1 Improved field crop varieties

These technologies relate to four cereal crops with unrealized potential in the Sahel: millet, sorghum, maize, and wheat.

3.1.1 Improved millet

Pearl millet (*Pennisetum glaucum*) is the staple cereal in the harshest of the world's major farming areas: the arid and semiarid region extending between Senegal to Somalia. Withstanding hot, dry, sandy soils, it is adapted toward survival under harsh conditions [20]. It is amazingly drought-tolerant and able to germinate at high soil temperatures and in crusted soil, it withstands "sand blasting" and grows under low soil fertility, and it resists pests and diseases such as downy mildew, stem borer, and parasitic striga. It also grows well in both acidic and saline soils. But its most rugged land races are characteristically low yielding and may not respond well to inputs, and for this reason there is need for improved varieties and their accompanying seed systems. Breeding efforts have led to increased micronutrients (e.g. iron and zinc), and some improved "sugary" types can be harvested at the milk stage, and roasted and consumed like sweet corn. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is responsible within TAAT for millet improvement, offering many new varieties for testing by national systems or release to development efforts.

3.1.2 Improved sorghum

Sorghum (*Sorghum bicolor*) is a physiological marvel; it is extremely drought tolerant and light efficient, with one of the highest dry matter accumulation rates among cultivated crops [20]. It is versatile in its use with some types boiled like rice, others cracked like oats, others malted for brewing, and some milled and baked. The whole plant may be used as forage or hay. ICRISAT is also responsible for sorghum improvement, including in the Sahel. Currently available improved varieties and land races have several favorable characteristics including good seedling emergence and rapid early root development, rapid tillering leading to multiple heads, and long growing cycles to make the best of favorable rains. It can be manufactured into a wide variety of foods and used to substitute for imported grains. These properties combined with sorghum's use as an animal feed suggest that national planners are well advised to regard sorghum as more than a drought-hardy subsistence food.

3.1.3 Drought-tolerant maize

Considerable gains in maize (*Zea mays*) improvement have been achieved in the area of drought tolerance that now make this crop less risky in the southern reaches of the Sahel. Drought tolerant maize varieties have a 20–35% larger grain harvest under moderate drought conditions but may not respond as favorably to occasional years of excellent rains due to their shorter maturity times [23]. Hybrid varieties are marketed under commercial license, while open pollinating varieties can be multiplied and sold free of royalty by farmers and community-based producers. The African Agricultural Technology Foundation has sublicensed 22 seed companies to produce Drought TEGO™ for commercial distribution, and more will follow [18]; but these hybrids have been slow to reach West Africa.

3.1.4 Heat-tolerant wheat

The trait of heat tolerance is now incorporated into improved varieties of wheat (*Triticum* spp). Heat stress and drought are among the most predominant constraints affecting wheat across Africa [24], especially at the reproductive stage during flowering and grain filling, leading to low grain yield or even crop failure [25]. Wheat production has increased significantly in the Sahel over the past several years due to the rapid increase of area planted to these newly released heat-tolerant varieties. Varieties that can withstand temperatures up to 4°C greater than previous lines are available. As a result, farmers are achieving higher and more stable yields, reaping up to 6 t ha^{-1}. The success also has policy implications by convincing country decision-makers that domestic wheat production is a solution to reduce the massive dependence upon wheat imports.

3.2 Improved water management

These technologies relate to different forms of water management, including the design of small-scale irrigation systems.

3.2.1 Combined soil and water conservation

Bunds refer to a micro-catchment technique where low raised walls are arranged in specific patterns on farmlands to collect and conserve water and to reduce soil erosion and gully formation [26]. Bund walls are constructed with soil and/or rock, either by hand or tractor. Designs of bund walls are adjusted to local conditions and sociocultural contexts, but the two main types are contour bunds (or contour ridges) and semicircular bunds (or half-moons). Contour bunds are suitable for uniformly sloping terrains with even runoff, and the retaining walls can stretch hundreds of meters across landscapes. Semicircular bunds operate in a more localized manner [21]. Installing contour bunds can increase grain yields of sorghum by 80% and maize by 300% compared to traditional land management without micro-catchment. Community works that stabilize slopes and better harness seasonal rainfall by constructing and reinforcing bunds are an important element of agricultural development projects in the Sahel.

3.2.2 Water harvesting with zaï pits

Micro-catchment approaches to water harvesting in the Sahel include planting pits, locally known as zaï [15]. Zaï pits also rehabilitate crusted and degraded lands. These structures are made by digging shallow basins of 20–40 cm diameter and 10–20 cm deep into the soil. The pits are prepared during the dry season by farmers allowing the shallow holes to collect water, wind-driven soil particles, and plant debris [5]. Moisture becomes collected inside and below the pits that also serve as localized targets for soil fertility improvement. The technique can improve millet and sorghum production by

60–90% depending on precipitation and soil fertility. When properly managed, these pits become a permanent feature of the field that collects off-season or early rainfall.

3.2.3 Spate management of seasonal water

Exploiting water from rivers and streams during the rainy season to fill channels and direct them to adjacent fields by construction of spates is a strategic small-scale irrigation system. Spate is an ancient approach but under some circumstances, it remains relevant today [5]. This system diverts water from normally dry riverbeds at the onset of seasonal rains and directs it to croplands, converting them into seasonal flood plains. Community consensus assures equitable distribution of these floodwaters, including those further downstream that also rely upon the same water. Managing floodwater is inherently difficult because of the power they hold, but the rewards to managing these waters in arid and semiarid areas are great, and for this reason, the opportunity exists in public support of spate irrigation as a localized civil engineering challenge.

3.2.4 Small-scale irrigation schemes

Irrigation assures that the water requirements of crops are met and the development of community-based irrigation schemes is an essential component of agricultural development in the Sahel [5]. Irrigation consists of two phases, the first where water is diverted from its source and delivered to the vicinity of croplands, and the second where it is applied to fields in a scheduled and calculated manner. Application strategies vary with the volumes, quality, and pressure of water delivery and may be grouped into flood, furrow, sprinkler, and drip irrigation. Irrigation presents a key solution to addressing present and future crop production constrains due to the effects of climate change on weather patterns. Within the context of practical rural development, a focus upon small-scale irrigation schemes in addition to larger, more centralized schemes should be considered.

3.3 Improved soil management

These technologies relate to more efficient use of mineral fertilizers, maximizing symbiotic biological nitrogen fixation and improved use of farmer-available organic resources.

3.3.1 Fertilizer micro-dosing

Fertilizer micro-dosing is based on the application of small amounts of mineral fertilizer in a shallow hole about 5 cm away from the crop stem [15]. Micro-dosing is as simple as applying one bottle cap filled with 3–5 g of fertilizer to each planting hole and is best combined with the addition of organic materials, particularly composts and manures. The total amount of fertilizer used in micro-dosing can vary significantly depending on the planting density, ranging from 50 to 100 kg of fertilizer per ha. This addition results in healthier crops that are better able to counteract mid- and late-season drought as a means to adapt to increased climate variability. A well-timed dose of fertilizer results in increased crop yields ranging from 40% to 120%, providing high returns to modest investment. The micro-dosing technique significantly increases the use efficiency of nutrients and water, particularly when combined with other climate-smart practices such as zaï pits [5].

3.3.2 Better timed nitrogen application

The key to achieving high crop yields and maintaining soil fertility is to apply the right fertilizers at the correct rate and time. Too often, timing is ill considered, particularly in relation to nitrogen (N) topdressing of field crops. Typically, N fertilizer is added to soils once or twice over the season, first as a pre-plant addition and second as a single topdressing, but more frequent and smaller doses are more efficient [27]. The basic principle of this approach is to apply a small quantity of N at planting and progressively add moderate amounts as topdressing during periods with sufficient rainfall when plant nutrient demand is largest. Farmers can top-dress N using readily accessible types of fertilizers such as urea and calcium ammonium nitrate, and the total application rate is based on yield targets and regional recommendations [5]. In some cases, N can be added just prior to, and worked into the soil during weeding, resulting in more efficient combined field operations.

3.3.3 Nitrogen fixation from field legumes

Legumes are very important to the rainfed cropping systems of the Sahel, particularly cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*) [20]. Intercropping is best practiced by farmers during years of favorable rainfall by growing understory grain legumes between cereal rows at very low densities. More common is crop rotation of cereal and legumes, with a few (e.g. two–four) cycles of cereals punctuated by legumes [15]. Legumes access atmospheric nitrogen through symbiosis with rhizobia, a process that provides both additional protein to the household and residual nitrogen to the land [28]. The rhizobia needed for biological nitrogen fixation of these crops are often native, but their populations may be suppressed in hot, dry soils [14]. When well nodulated, nitrogen fixation is sufficient to secure a grain legume harvest and contribute about 50 kg or so organic nitrogen to the following crop. Unfortunately, legume inoculants containing elite strains of rhizobia are not widely available across the Sahel, so need exists to develop the capacity to manufacture and distribute them through commercial channels [5].

3.3.4 Organic resource management

A majority of soils in the Sahel are characterized by low water holding capacity and limited availability of plant nutrients because of their low clay and high sand content [15]. Farmers across these cereal-based drylands must better manage organic resources in ways that optimize limited rainfall and costly inputs of mineral fertilizer [13]. The maintenance of soil organic matter and carbon stocks is strongly determined by the amount of crop residues available for addition to soils and the competing need for livestock feed and stalks as cooking fuel and building material. Mulches that cover soil surfaces greatly reduce soil erosion, runoff, and evaporation, leading to about 70% increased cereal harvest. Incorporating fresh plant materials or animal manure is another option to compensate for unfavorable soil physical properties. At the same time, mineral fertilizers applied in conjunction with organic resources have greater nutrient use efficiencies. These examples of Integrated Soil Fertility Management illustrate the need for farmers to make best and balanced use of crop residues and other available organic resources [14].

3.4 Systems-level improvements

Several systems improvements result in more resilient agricultural landscapes and are best implemented at the community or landscape levels including the control of insect invasions, elimination of parasitic striga, introduction of trees to open croplands, improvement to rotationally grazed lands, and the local production of biogas.

3.4.1 Controlling insect invasion

The Sahel is characterized by major invasions of insect pests such as the yellow desert locust (*Schistocerca gregaria*) and fall armyworm (*Spodoptera frugiperda*). These outbreaks pose a major threat for farm households and undermine larger efforts to strengthen food systems [29]. Locusts are notoriously difficult to control once large swarms accumulate and spread over expansive areas. Following favorable rains, vegetation is sufficient for multiple generations of locust to spread across agricultural landscapes, devouring everything in their path. Early warning and preventative control are keys to stopping locust populations from reaching epidemic proportions. Spraying with chemical insecticides controls desert locust but to be most effective, insecticides must be applied directly onto migrating swarms. Spraying interventions for smaller areas can be performed by teams on foot with knapsacks, whereas for larger areas there is need for vehicle mounted nebulizers or specialized spray planes.

The invasion of fall armyworm across cereal croplands throughout Africa, including the Sahel, also represents a major threat to food security [30]. TAAT offers a rapid response kit consisting of a custom-built cargo tuktuk, power sprayers, safety equipment, commercially recommended pesticides, farmer information, and communication materials [5]. Early control of armyworm is also achieved through maize seed treatment with Syngenta's FORTENZA DUO, offering protection to maize crops up to 4 weeks after germination. Authorities in countries worst affected by fall armyworm are encouraging all maize seed producers to treat their seed with this product.

3.4.2 Overcoming striga infestation

Striga is a parasitic weed-attacking cereal and other grass and invading cropland of the Sahel. The damage inflicted by striga begins underground where its roots enter the host, feeding on its nutrients and moisture and releasing toxins into the plant causing twisted, discolored, and stunted growth [31]. After feeding below ground for 4–5 weeks, a fast-maturing shoot emerges that produces attractive spikes of violet (*Striga hermonthica*) or red (*Striga asiatica*) flowers that mature into capsules containing abundant, tiny, long-lived seeds. Parasitism greatly reduces crop yields. Striga attacks millet and sorghum, but these crops show some tolerance to its effects; maize is more severely affected. Farmers respond to striga by hand weeding and, less often, burning affected fields, but the efficacy of these practices remains questionable considering the large numbers of tiny seed that a single, mature plant produces and returns to the soil.

The agricultural community has responded by developing several new approaches to striga control. These approaches involve crop resistance to systemic herbicides, striga-tolerant cereal varieties, and striga suppression by nonhosts and trap cropping [32]. Farmers must become aware that striga infestation is a solvable problem and gain experience in the use of breakthrough technologies. Local and national authorities must fully recognize the threat posed by striga and prioritize efforts to overcome it within rural development agendas. By attacking this plant parasite through a combination of approaches, it is now a solvable problem and offers an important element of comprehensive rural development packages wherever this parasitic weed occurs.

3.4.3 Transition to agroforesty

Great potential for agricultural transformation exists through the conversion of open-field cropping to agroforestry parkland [33]. These parklands appear as well-spaced trees that protect the soil and contribute to soil fertility renewal. Because of these benefits, the crops that grow near or below these trees often perform better than those in an open field. Parklands also sequester significantly greater carbon stocks than open croplands in a way that mitigates emissions of greenhouse gasses. These increased carbon stocks may be 20 or 40 MT C per ha greater than that retained by open cropland and hold potential to sequester carbon into deeper soil horizons [34]. The agroforestry parklands that appear in the cultivated drylands are often the result of clearing trees rather than planting them, and this creates difficulty in carbon accounting, but when open cropland is purposefully transitioned to agroforestry parkland, the carbon gains are clear and attributable to the efforts from tree planting and protection [5].

Afforestation of open croplands is best practiced at the community level because of the demand for quality tree seedlings, the need to plant them at scale, and the collective responsibility to protect them until these trees are well established. Transitioning from degrading open cropland to productive agroforestry parkland should be considered within agricultural development efforts as sound from both the food security and climate action perspectives, noting that success also involves capacity development at the community and extension advisory levels.

3.4.4 Improved range management

Raising livestock is a critical enterprise across the Sahel but overgrazing has resulted in extensive land degradation [35]. Cattle, sheep, and goats are regarded as assets among pastoralists living in areas too dry for reliable farming, and strategies are available to improve the grazing and forages that these lands provide. Water harvesting technologies presented in this paper may be practiced on noncultivated lands planted with improved grasses and browse species, particularly near watering holes where animals are likely to concentrate during the dry season. Stover and stubble of cereal fields are grazed following the harvest of millet, sorghum, and maize, and these lands are then fertilized by the manure that is deposited. While this system is robust as long as rotational intervals are of sufficient length, these systems begin to degrade if cropping becomes to frequent. One means to strengthen the crop-livestock system is to improve these rotational pastures using either annual or perennial grasses. These grasses not only provide feed for livestock, but they provide ground cover that resists wind and water erosion.

Improved rangeland management falls into four general categories that are best applied in packages. Agronomic measures are associated with annual crops in a rotational sequence and are impermanent and of short duration. Vegetative measures involve the use of perennial grasses, shrubs, or trees and are of longer-term duration. Structural measures reduce erosion and capture water and may result in a permanent change in landscape. Management measures involve a fundamental change in land use and may be directed through policy intervention [35]. Improved rangeland management is best conducted at the community level where lands are collectively managed. This participation reduces the risks of conflicts between farming and livestock that often lead to larger social misunderstandings.

3.4.5 Local production and use of biogas

This technology refers to the production of combustible gas within small-scale digesters at the household level. It is based on the utilization of plant and animal residues as organic wastes that are decomposed in anaerobic tanks, forming methane and a digested slurry byproduct useful as an organic fertilizer and soil amendment [36]. Gasses rise and collect through an outlet for burning as cooking fuel and the sediments sink into sludge for later collection. Gasses may be produced in a variety of vessels located above- or belowground. These reactors may be fashioned from metal tanks, built from concrete, or purchased as complete units. Attraction to this technology is growing across the Sahel because of its socioeconomic and environmental benefits, and it has a proven ability to improve the lives of rural households that would otherwise burn wood and charcoal, or cook using purchased kerosene [5]. The diversification of energy supply creates economic opportunity to those who build and equip these digesters, and it reduces local air pollution and deforestation due to firewood collection and charcoal making, and increases sequestration of carbon into soils amended with the digested organic sludge. Carbon sequestration is also achieved by the substitution of renewable energy production from methane as compared to reliance upon fossil fuels. Biogas generation is best considered among a suite of rural development options that are designed to educate stakeholders and supply the hardware and infrastructure it requires [37].

4. Impacts from technology deployment

Table 2 presents findings for millet and sorghum from the TAAT Program in seven countries of the Sahel [18]. ICRISAT coordinated this effort based on the delivery of "technology toolkits" through national programs. Millet and sorghum yields were improved by 133% and 140%, respectively, and reached nearly 84,000 households

Parameter	Millet	Sorghum	Units
Average increased productivity	1.00	1.75	MT dw increase ha^{-1}
Yield improvement over baseline	133%	140%	MT increase/MT baseline
Number of technology adopters	12,403	71,217	Households adopting technologies
Innovation coverage	23,765	100,098	Total ha
Total increased production	23,765	175,172	MT on harvest weight basis
Total increase value	4,515,361	37,662,005	Value of increased production in US$
Average adoption area	1.92	1.41	ha $household^{-1}$
Increased food supply	1.92	2.46	MT hh^{-1} yr^{-1}
Increased revenue per household	$364	$529	Total return US$ hh^{-1} yr^{-1}

Table 2.
Benefits from adopting improved technologies for millet and sorghum in the Sahel between 2018 and 2020.

managing about 124,000 ha and leading to the increased production of 199,000 MT of grain worth US $42 million. Individual households greatly benefited in terms of food security, and the average increase income from participating in the technology delivery effort was about US $504 (calculated as a weighted average from **Table 2**). Activities involved 16 partnerships and delivered 1391 MT of improved certified seed. The right technologies taken to scale can deliver benefits to partnering farming communities that rely upon millet and sorghum as a staple crop.

Investment in TAAT technologies results in economic gain across a wider selection of commodities as well. **Table 3** provides information on the increased yields of five cereal crops (rice, wheat, maize, sorghum, and millet), increased cost of production and economic returns to that investment. The average increased productivity was 1.3 MT ha^{-1} worth US $333 resulting from $136 increased investment, mostly as fertilizers. This results in an average increased value of US $197, ranging from $85 (for millet) and $299 for rice. Note that except for rice, these crops were grown under rainfed conditions. The partial benefit to cost ratio ranges between 1.8:1 (for millet) and 3.2:1 (for maize), suggesting that economic returns are solid but not spectacular.

Table 4 shows projections of carbon sequestration resulting from TAAT interventions to cereal production including system gains, values, and household contributions. These projections are based on reports of increased yield, coverage, numbers of adopters (see **Table 2**), and assumptions concerning biomass, moisture content, Harvest Index, crop carbon content, CO_2e:crop C ratio, planning horizons, and the price of CO_2e. This approximation allows for the estimation of realizable gains of CO_2e associated with increased biomass and residual benefits in terms of CO_2e gain per ha and as total average gain per project-year and household [18]. Realizable gains were achieved based on increased focus upon climate-smart field practices and products within the technology toolkits employed by participating farmers and development projects. This approach results in estimated CO_2e gains averaging 4.4 MT ha^{-1} across these five cereals and a total of 2.1 million MT of CO_2e per year worth about US $65 million. When the number of adopters is considered, this amounts to per capita emissions reductions of 1.5 MT CO_2e per household per year, similar to the targets established by Branca et al. [38] and Lipper et al. [39]. This analysis is incomplete, as it does not take into account carbon losses from other farming practices; rather it focuses on peak seasonal increases.

The feasibility of organizing small-scale African farmers into a force devoted to carbon sequestration is an exciting opportunity, but one that does not greatly benefit individual climate-smart practitioners from the standpoint of direct financial benefit as their gains are worth only $16 household per year at current prices of CO_2e. The

Commodity	Units	Rice	Wheat	Maize	Sorghum	Millet	Mean (± SEM)
Increased productivity	MT ha^{-1}	1.2	1.9	0.7	1.7	1.0	1.31 ± 0.19
Increased fertilizer cost	US $ ha^{-1}	91	200	69	146	103	122 ± 20
Total increased cost	US $ ha^{-1}	153	203	73	148	105	136 ± 19
Increased crop value	US $ ha^{-1}	452	418	231	376	190	333 ± 44
Increased partial net return	US $ ha^{-1}	299	215	158	229	85	197 ± 30
Partial benefit: cost ratio	US $ US $$^{-1}$	2.95	2.06	3.17	2.55	1.81	2.51 ± 0.22

Table 3.
Economic returns to technology investment in cereals based on TAAT toolkit packages (2018–2020).

TAAT commodity compact	Increased system CO_2e	Annual increased CO_2e[1]	Value of annual increase in CO_2e[2]	Annual reduction per adopter[3]
	($MT\ ha^{-1}$)	$MT\ y^{-1}$	$\$\ y^{-1} \times 10^6$	$MT\ CO_2e\ y^{-1}$
Rice	1.06	186,882	4.1	0.08
Wheat	2.92	1,753,606	38.6	1.9
Maize	3.1	869.284	19.1	1.5
Millet	5.71	22,611	0.5	1.8
Sorghum	9.27	154,668	3.4	2.2
Total (*mean*)	*4.41*	2,118,636	65.7	*1.50*

[1]*Mean weighted by coverage from* **Table 2***, ± standard error of the mean.*
[2]*Based on US $22 per MT CO_2e.*
[3]*Based on the annual increase of CO_2e and overall mean weighted by beneficiary households from* **Table 2**.

Table 4.
Estimated carbon offsets from the adoption of TAAT technologies by African cereal producers (based on [18]).

benefits of climate-smart technologies are perhaps better advanced in terms of improved livelihood and agricultural resource quality and then factored in terms of realizing national commitments at the landscape level; rather than presented to farmers as an income generating opportunity.

5. A transformational model

The TAAT Clearinghouse is developing a conceptual and mathematical model useful in understanding and managing agricultural transformation in Africa. This model has both qualitative and quantitative features.

5.1 Transformational realms

These realms are based on the roles and responsibilities of three interacting driving sectors: policy, markets, and farmers. It assumes that policies drive public works and rural development programs, markets determine the scope and appeal of commercial products and related investments, and farmers undertake individual and local collective actions. When these roles are depicted along three triangular coordinates, a conceptual model emerges that contains different transformational realms, many of them widely recognized. Grassroots actions occur where farmers dominate adoption processes (**Figure 1**), commerce is conducted where businesses buy and sell agricultural technologies, and government-led parastatal operations exist where government controls agricultural opportunities and trade. Other familiar blended realms exist including agricultural extension, public-private partnerships, and farmer-commercial alliances (e.g. out-grower networks). At the center of these activities, we identify complex alliances, where all three drivers meet on equal terms to pioneer progressive change. Each of these seven realms is briefly described.

5.1.1 Grassroots actions

Grassroots actions (*upper center*) are localized in scope and conducted by farmers and their communities as opposed to being guided by those in more centralized

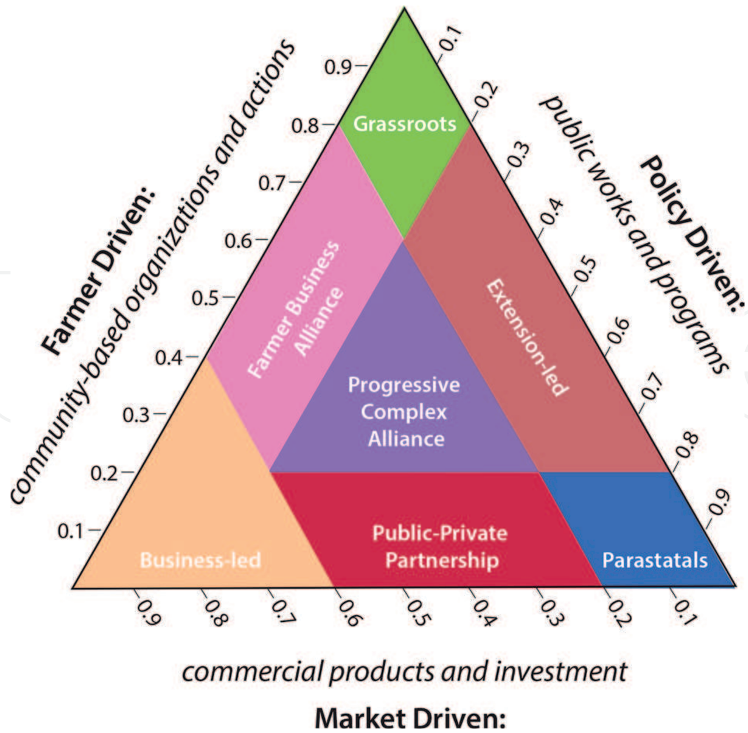

Figure 1.
Rural development realms resulting from policy-, market-, and farmer-driven interests.

positions of power. Farmers belonging to grassroots organizations rely on individual and collective action to effect desired local change and often receive guidance from local agrodealers and extensionists.

5.1.2 Business-led development

Business-led development (*lower left*) incorporates a range of strategies aiming to establish markets and provide economic opportunities that drive rural growth and employment opportunities. In more advanced settings, the private sector plays the lead role in research and development as well, translating breakthrough technologies into useful products and services.

5.1.3 Farmer-business alliances

Farmer-business alliances (*center left*) allow small-scale producers to transition into commercial agriculture by providing information, inputs, and markets, usually based on a focus commodity. This alliance can operate as out-grower schemes and is further advanced through digital services and e-commerce platforms. The "farm to fork" approach relies upon such alliances.

5.1.4 Public-private partnership

Public-private partnership (*center bottom*) is an agreement between the public and private sectors for the purpose of accelerated delivery of products or services beyond the reach of either. In some cases, it increases the efficiency of public services, and in others it is intended as an accelerated pathway to privatization. It may be based on contracts where government assigns some of its responsibilities to a private partner and often involves joint investment under terms attractive to business.

5.1.5 Agricultural extension

Agricultural extension (*center right*) applies new knowledge to agricultural practices through farmer education and advisory services, leading into increased productivity and improved livelihood. It relies on farm visits, group interactions (e.g. demonstrations and field days), and mass information campaigns and is increasingly reliant on digital devices and linkage to education systems. The effectiveness of current extension systems in Africa is often questioned.

5.1.6 Parastatals

Parastatals (*lower right*) are organizations operating under political authority, often as a state-capitalistic form of agricultural production. They are often criticized for being inefficient, corrupt, and for underpaying producers but at the same time have a proven ability to transfer modern farming techniques and new commodities to small-scale producers. Parastatals are increasingly targeted for privatization through public-private partnership.

5.1.7 Progressive complex alliances

Progressive complex alliances (*center triangle*) represent a difficult to achieve form of stakeholder partnership that effectively balances the interests of rural communities and the private and public sectors. In many cases, the loans from development banks are focused on combined actions involving these stakeholders through their combined participation and investment, although formula for success remains ambiguous as it involves complex, knowledge-rich problem-solving across competing interests and site-specific settings.

5.2 Sector interactions

Successful partnership within rural development programs striving for agricultural transformation, particularly within the realm of progressive complex alliances, requires effective communications between sectors (**Figure 2**). Between farming communities and the public sector, these communications involve advocacy on behalf of agricultural producers and their workers, and effective response from agricultural extension services. This dual mechanism ensures that public investment in advisory services is demand-driven. Unfortunately, rural communities often find it difficult to express their needs, and those that do so on their behalf may behave opportunistically. At the same time, public agricultural extension services are too often understaffed and under-resourced, yet it is this communication that can lead to more efficient performance by extension specialists and project designers.

Communication between farming communities and the private sector is more direct. Businesses stream input products through agrodealer networks to farming communities and later purchase their surpluses through buyers. Accompanying these input products is information about them that is intended to achieve or maintain various competitive advantages. Farmer feedback on the availability, efficacy, and affordability of these input products is mainly felt in terms of seasonal purchases. At the same time, businesses seek direct feedback from potential customers to guide their selection of product lines and advertising campaigns. One difficulty in this dual mechanism is the inability of poorer farmers to purchase the full suite of

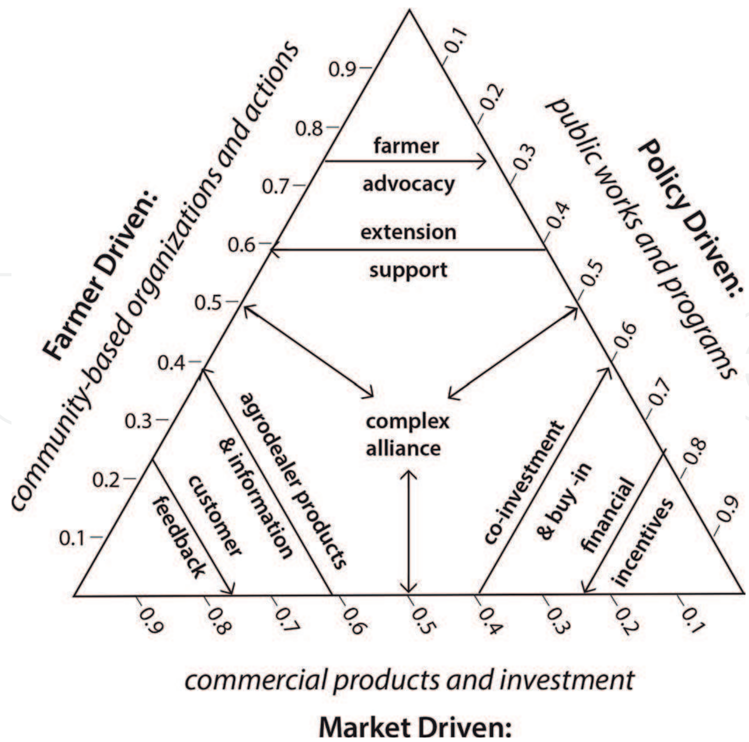

Figure 2.
Key interactions between the public, private, and farming sectors that relate to the design and implementation of rural development projects.

recommended input products proven to maximize their production. There is also the risk that unless accompanying technologies are properly bundled, the returns to any one technology may be disappointing. This communication mechanism can lead to alliances between farmers and businesses in terms of bulk purchase of production inputs and better coordinated marketing of produce.

Interactions between the private and public sector are focused on regulatory approval of products and steering financial incentives, often in ways designed to maximize profits or taxation and that often bypass farming communities. Nonetheless, the opportunities for co-investment into modernizing technologies through these dealings are enormous and can lead to the formulation of needed public-private partnerships that indirectly benefit farmers. One risk of this dialog, however, is where haphazard or opportunistic privatization may result in parastatal inefficiencies being replaced with private sector excesses.

Clearly, the optimal situation is where tripartite communication leads to the design and successful implementation of rural development projects that engage and benefit all three parties: rural communities, the private sector, and government (**Figure 2**). These complex alliances require problem-solving with clear agreement of which difficulties exist, how to merge possible solutions within everyone's best interests, and how different options most appealing to those different interests may be blended or pursued simultaneously. From the programmatic perspective, it is also important to establish how resulting activities may be accurately and continuously monitored within the context of contingencies and corrective adjustment. This level of communication as it relates to the deployment of modernizing agricultural technologies in Africa has proven to be no easy matter.

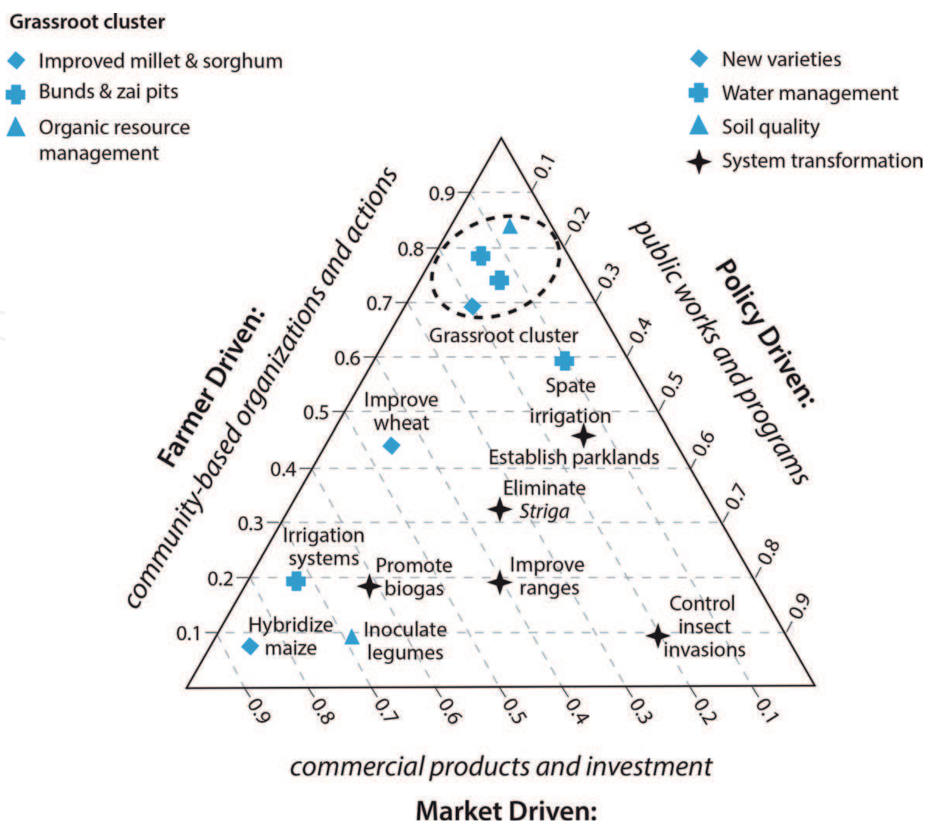

Figure 3.
Selected climate-smart technologies important to the Sahel as positioned within the Agricultural Transformation Triangle.

5.3 An example from the Sahel

Technologies may be positioned within the agricultural transformation triangle assuming that the relative importance of the three different drivers can be assigned (**Figure 3**). This positioning is based on the relative importance of each driver in the deployment of technologies and development outcomes, recognizing that all of them must ultimately be acceptable to rural households to become widely adopted, whether as technology customers or management practitioners. This approach, applied to the 17 technologies appearing in **Table 1**, results in clusters of technologies including those that are mainly achieved through grassroots efforts (upper center), or by private sector investment (lower left). Note that the positioning of new cereal varieties depends largely on whether they are hybridized or open pollinated, as the latter allows for community-based and farmers-own seed production. Also note that systems-level changes (e.g. containment of insect invasions, elimination of *Striga*, agroforestry parkland establishment) require greater involvement of the public sector. One advantage of this approach is that technologies appearing in different clusters and within realms (see **Figure 1**) can be considered mutual objectives within a program's operational framework.

6. Investment volumes

Substantial if not ample investment in the agriculture of the Sahel occurs (**Table 5**). Researchers at the Policy Analysis and Research Group at of Evans

IFI annualized investment	Sahel	All sub-Saharan Africa	Percentage (%)
In smallholder agriculture	$590,213,920	$3,408,245,800	17.3
In rural infrastructure and commercialization	$92,362,308	$2,834,768,443	3.3
In agriculture as a sector	$682,576,228	$6,243,014,242	10.9
Into all development	$3,393,963,264	$28,331,013,684	12.0
Population (2019)	111,121,173	1,045,204,638	10.6
Per capita investment	$30.54	$27.11	112.7
Cultivated lands (ha)	41,883,700	226,540,000	18.5
Per ha investment	$16.30	$27.56	59.1

[1]*Evans School of Public Policy and Governance (EPAR), University of Washington (Project #411).*

Table 5.
Annual investment in African agriculture and natural resource management by three major International Financial Institutions: The African Development Bank, The World Bank, and the International Fund for Agricultural Development (based on EPAR[1]).

School of Public Policy and Governance (University of Washington) recently compiled data from three major International Financial Institutions (The World Bank, the African Development Bank, and the International Fund for Agricultural Development) to provide insights into the "Investment Landscape" in Africa [40]. The database contains all investments in 46 sub-Saharan African countries from the three IFIs as of May 2021 and includes "active" or "implementation" projects, loans, grants, or other financial investments [40]. To make funding by country more comparable, investments were annualized by dividing the total financial commitment per project by the number of years of implementation. Codes were applied that allowed summation for Sahelian countries including Burkina Faso, Chad, Mali, Mauritania, Niger, Senegal, and South Sudan, but not those with a small portion falling within the Sahel (e.g. Benin, Cameroon, and Nigeria). Annual investment in agricultural development across all of sub-Saharan Africa totaled US $6.24 billion in 2019, with 11% of it (=$0.68 billion) directed to the Sahel. This amount is proportionate in terms of population (±0.3%) and represents 20.1% of total IFI investment. Considering the importance of agriculture in the Sahel, this percentage seems somewhat low.

Overall, the per capita annual investment from the three IFS in the Sahel zone is about $30. What can be done with this resource and how may it best be leveraged toward greater benefit? **Table 3** suggests that the cost of modernizing Sahelian farming is about $136 per ha, so these funds are only sufficient for improved production on only 0.22 ha on a household basis. This intervention results in an additional 288 kg food production and revenues worth $73. These modest gains can lead to substantial improvement in lives. If 50% of the funds earmarked to smallholder agriculture in the Sahel (about $295 million, calculated from **Table 5**) was directed to the delivery of TAAT cereal technologies, this is sufficient to "jump start" improved production across 2.17 million ha (calculated from **Tables 3** and **5**) resulting in 2.8 million additional tons of cereal and profits of over $560 million per year from improved agriculture. A similar analysis may be performed based on funds directed to cultivated lands rather than households (**Table 5**). About $16.30 per ha is invested by IFIs in the Sahel, considerably less than the average across sub-Saharan Africa. This level of investment is sufficient to modernize production on 0.34 ha, producing about 445 kg of additional cereal, leading to a huge improvement in food security (calculated from **Tables 3** and **5**).

These same gains would lead to an estimated additional 3.3 million MT of sequestered CO_2e across the Sahel worth $71 million (calculated from **Table 4**), assuming that buyers for that offset due to climate adaptation can be found. One complication, however, is that the costs of directly quantifying carbon offsets on a smallholder farm may well be greater than the value of those offsets themselves ($33 calculated from **Table 4**). Clearly, potential exists for combined agricultural development and climate action given the current level of development investment, and the challenge is to better realize these gains so that even more investment will follow.

7. Conclusions

Modernizing technologies literally bring scientific breakthroughs to life in ways that reduce risks and better manage cause-to-effect relationships. Technology transfer determines how this modernization occurs as a process involving a wide assortment of stakeholders from government, the private sector, financial institutions, and research, civil, and educational institutions [41]. This process intends to work on behalf of both the holders of technologies and those who stand to benefit from them most. In the case of climate action through the deployment of agricultural technologies, these users are primarily land managers directed toward larger global needs through practical self-interest, mainly acquisition of more secure harvests and greater protection of farm resources. Policies may set the stage for change, but ultimately environmental gains are achieved through combinations of purchased inputs and improved management practice, with each category representing a different type of technology holder. Input delivery is largely the concern of the private sector in terms of commercial distribution; and management practices are influenced by agricultural service providers, including public extension. Change is quickest when the two work in conjunction, and this forms both a challenge and opportunity to the design of rural development projects.

Two large regional programs of the African Development Bank are well positioned to benefit from the technologies and deployment approaches described in this chapter, The Programme for Integrated Development and Adaptation to Climate Change in the Niger Basin (PIDACC [6]) and The Horn of Africa Project. PIDACC is funded through the Niger River Authority and TAAT is one of its funded partners. It covers nine countries in the Niger River Basin: Benin, Burkina Faso, Cameroon, Chad, Cote D'Ivoire, Guinea, Mali, Niger, and Nigeria. Its activities include climate-smart technologies related to rice, maize, wheat, as well as soil and water management applied at the field, household, and landscape levels. It operates under the premise that farmers who adopt and exchange improved crop varieties, proactively manage pest outbreaks, better utilize water resources, and maintain soil fertility are in a much stronger position to secure food and income for their families and protect their agricultural resource base.

Horn of Africa is an AfDB regional project at an advanced stage of preparation. Its partner countries will deploy proven, climate-smart agriculture technologies across Djibouti, Ethiopia, Kenya, Somalia, South Sudan, and Sudan from 2022 to 2028. The objective of the project is to build resilient food and nutrition insecurity and climate change response, engage women and youth, and reinforce peace and security across the Horn of Africa. Specifically, it aims to (1) improve agro-sylvo-pastoral productivity, (2) increase incomes from that production, and (3) enhance the adaptive capacity of the populations to better prepare for and manage climate risks. Clearly, the right technologies, including those featured in this chapter, are required to achieve these goals. AfDB is also leveraging co-financing from major climate funds in ways that can impact upon UNFCCC Nationally Determined Commitments.

There is a strong relationship between dryland soil and water management technologies available to small-scale farmers and the need for climate action in the Sahel and elsewhere [19]. Within the context of risk reduction, many of the technologies appearing in this chapter are intended to adapt to climate extremes, particularly higher temperatures, moderate drought, and erratic and intense rainfall. These adaptive technologies are particularly important at the field and household level. Farmers that better capture rainfall or protect their cropland soils from wind and water erosion are better able to feed their families. The same is true for communities that adopt and exchange improved seed of open pollinated cereals such as millet and sorghum. In this way, adaptation to climate extremes offers a “drawdown” of greenhouse gasses that are accumulating in the atmosphere.

The most direct mitigative effects are to increase standing biomass and to manage that biomass in ways that become sequestered into soil organic matter and woody biomass. This is readily feasible using improved soil and water management practices across large areas of land over sufficient times to realize these gains. In general, about 50% of increased productivity is carbon and a small proportion of that enters the soil as residues for longer-term retention. One means to greatly increase standing biomass is to move from rainfed to irrigated agriculture, and another is to rehabilitate lands that are degraded and overgrazed. It is possible to combine adaptive and mitigative technologies as when bunds intended to capture water and reduce erosion are planted with perennial vegetation. Also, the same contour structures used to protect croplands may be constructed in adjacent rangeland to assist in the re-establishment of native vegetation. At the same time, carbon gains in rangelands must be weighed against the increased livestock carrying capacity and the methane they release through digestion.

Substantial opportunity for carbon gains across landscapes exists through the steady transition from open-field cultivation to managed parklands, often through the introduction of economically useful trees. The agroforestry techniques to achieve this transition are well described. Re-vegetation has a transnational dimension through the ambitious Great Green Wall for the Sahel and Sahara Initiative to act as a barrier to further desertification [42]. Another proactive mitigation response occurs through bio-digestion in terms of fossil fuel replacement. One huge advantage of mitigation over adaptation is that quantified carbon gains may then be offered for sale and traded with polluters as a condition of their continued emissions. Another is that they can be applied to the Nationally Determined Contributions of countries within climate agreements [43]. Ultimately, rural development projects and climate actions must be viewed as one and the same.

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