Wheat Technology Toolkit Catalogue

TAAT Clearinghouse

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Front cover photos: Furrow irrigated raised bed cultivation system (left). Effect of heat-tolerance on wheat resilience (right). Photographic credits: Agrinatura (https://agrinatura-eu.eu/news/an-old-new-business-opportunity-for-africa-durum-wheat/) and Ni et al. (DOI: 10.1016/j.cj.2017.09.005)

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TAAT offers to become your broker of modernizing agricultural technologies!

Purpose and Introduction

This catalogue describes a series of technologies related to the modernization of wheat production in Africa. It is based on the combined efforts of the Project Platform for Agricultural Solutions (ProPAS), an information portal, and the Technologies for African Agricultural Transformation, a large collaborative program that is deploying agricultural solutions across the continent. Both activities are addressing the imperative to better connect proven technologies to those who need them, but each undertakes this goal in a very different manner. Wheat is one of TAAT's priority commodities because of its huge importance to food and nutritional security, and the need for reduced flour imports to Africa. It is also targeted as an agro-industrial crop for processing and trading on world markets. During its compilation, ProPAS has accumulated several technologies that specifically address this commodity and we have compiled them into a "technology toolkit" designed to advance understanding and encourage adoption and investment into the proven agricultural solutions that advance this crop. This is one of several catalogues that are produced as a joint ProPAS-TAAT activity. For more information on the featured technologies or other solutions toward transformative impact on agriculture in Sub-Saharan

Africa, contact Dr. Innocent Musabyimana at i.musabyimana@cgiar.org or visit the TAAT internet site www.taatafrica.org.

About ProPAS. The Product Platform for Agricultural Solutions (ProPAS) provides a mechanism to compile and access innovations, management technologies and products needed for Africa's agricultural transformation. The platform provides two pathways: it permits users to enter their proven and promising solutions into a database, and then encourages others to sort through its options to reveal the suite of opportunities that can assist their agricultural objectives. ProPAS results from the recognized need by the International Institute of Tropical Agriculture (IITA) to more systematically compile and access the full range of agricultural solutions available to modernize and transform African agriculture. Its overall goal is to accelerate the process of agricultural transformation in Africa. Many solutions are available to improve and modernize Africa's food systems but those who could benefit from them most are often unaware of the best options at hand. In addition, more solutions are in the research and development pipeline that are best advanced through wider exposure and validation. Solution profiles are compiled and released in a systematic manner that involves submission by technology holders, entry into a user-friendly software platform, and use by an expanding base of clients. A small committee of agricultural experts oversees this process, but recognizes that its strength is through open-ended access to a marketplace of solutions. ProPAS is therefore managed through a three-phase process that involves solution submission, database management, and client access.

About TAAT. The Technologies for African Agricultural Transformation (TAAT) is a program led by the International Institute of Tropical Agriculture (IITA) that has pioneered new approaches to the deployment of proven technologies to African farmers. TAAT arose as a common effort of IITA and the African Development Bank (AfDB); and is an important component of the latter's Feed Africa Strategy. TAAT is organized around "Compacts" that represent priorities in terms of achieving Africa's potential in achieving food security and advancing its role in global agricultural trade. Nine of these Compacts relate to specific priority value chains of rice, wheat, maize, sorghum and millet, cassava, sweet potato, bean, fish, and small livestock. Weaknesses in the production of commodities are viewed as responsible for Africa's food insecurity, need for excessive importation of food, and unrealized expansion of Africa's food exports. Together these Compacts design interventions in collaboration with national programs to introduce technologies and management innovations that are designed to meet targets for agricultural development. In many cases, these targets are addressed through the implementation of projects resulting from sovereign country loans.

The TAAT Top 100 Technologies. The Clearinghouse developed a database of the Top 100 Technologies that are transforming African agriculture. It is based upon the approaches of the TAAT Commodity Compacts but also includes those from the CGIAR Collaborative Research Programs that are recently described as ready for next user. These technologies are divided between those involving improved genetics and plant and animal breeding (23%), those based upon the distribution of digital information (3%), production input products of proven efficacy (21%), crop and animal management technologies of utility within agricultural extension messaging and campaigns (27%) and the availability of appropriately designed labour-saving equipment (26%). These technologies have a direct role towards the achievement of the Sustainable Development Goals in relationship to farm productivity, food security and hunger reduction, improved household nutrition and diets, economic growth, climate-smart innovation and improved human equity. These technologies form the basis for selecting entries into ProPAS, including those advancing wheat.

The Top 10 Wheat Technologies. This catalogue presents ten technologies that serve to modernize and transform production and processing of wheat in Africa. These technologies include: 1) heat and drought tolerant varieties with high grain yield and grain qlulaity that achieve food security and human health, 2) rust resistant varieties to avoid devastating outbreaks and yield losses, 3) Hessian fly resistant varieties for decreasing insect buildup and crop damage, 4) irrigated production in heat prone regions for expanding cultivation and stengthening resilience, 5) furrow irrigated raised bed cultivation systems that improve water use and reduce costs, 6) conservation tillage and surface mulching of soils for water, nutrient, carbon conservation and weed management, 7) integrated biological, physical and chemical strategies to sustainably control insect, disease and weed pests, 8) combine harvesters and fleet management that offer access to mechanized agriculture, 9) hermetic storage of grain to reduce post-harvest losses and increase storability, 10) flour milling and systems for high quality products that can access premium markets.

Technology 1. Heat and Drought Tolerant Varieties

Impact of heat stress on sensitive (left) and tolerant wheat varieties (right)

Summary. Heat and drought stress are two major constraints to wheat production in Sub-Saharan Africa. For example, in Sudan temperatures often exceed 41°C and this severely undermines the flowering and grain-filling stages of wheat, leading to low national average of only 2 tons/ha, and in some cases crop failure. The increasing occurrence of extreme heat and drought due to climate change is making this situation even worse. More precisely, a 1°C rise in average temperature is known to decrease the productivity of wheat by 3-10%, and when 4°C warmer the crop's productivity drops by 34%. The International Center for Agriculture Research in the Dry Areas (ICARDA), in partnership with National Agricultural Research Systems, has developed a series of heat-tolerant wheat varieties that were released across countries in the Sahelian zone. These improved lines of wheat can withstand temperatures that are 4°C higher than normal which offers real advantage at critical times during the growing season. Higher and more stable yields over successive growing seasons are achieved by farmers that cultivate heat-tolerant wheat varieties, reaping up to 6 tons/ha. Expansion of the area planted to newly released lines of wheat that withstand heat stress has led to the replacement of low-yielding and less-adapted genotypes, and significant increases of wheat production across the Sahel over the past few years. For more information about this technology please contact Dr. Zewdie Bishaw from ICARDA by email at z.bishaw@cgiar.org.

Technical Description. Breeding for heat-stress tolerance in wheat varieties is achieved through conventional methods, including multi-location screening, shuttle breeding, double haploids, marker-assisted selection and key location phenotyping. The key mechanisms against heat and drought stress of improved lines are early maturity (within 90 days), adjustments to canopy structure and thermostability of physiological processes. Farmers in Sudan who use these newly developed wheat varieties, together with best agronomic practices, have managed to increase wheat grain harvests from 2.5 tons/ha to 5 tons/ha. Drought resistant varieties were developed that achieve 75% of their yield potential with less than 200 mm of moisture and heat stress, whereas common non-improved varieties show a 50% yield loss under those extreme conditions. Various other improved traits can be stacked in lines of wheat that possess heat stress tolerance, including high water use efficiency and tolerance to diseases and pests like yellow and stem rust (see Technology 2). Before heat tolerant varieties can be released, there is need for participatory testing so that its agronomic and nutritional characteristics match the preference of farmers, industry and consumers.

Uses. Wheat varieties that can withstand heat and drought stress offer large benefits for production in all growing areas of Sub-Saharan Africa because extreme temperatures and reduced precipitation occur widely and more frequently due to climate change. This suitability includes rain-fed systems cultivated during summer months in Ethiopia, Eritrea, Kenya, Uganda, Rwanda, Burundi, Tanzania and South Africa, as well as irrigated systems cultivated in the dry winter months across lowlands from Zambia, Zimbabwe, Malawi, Madagascar, Mozambique, Nigeria, Senegal, Mali and Sudan. Owing to the trait of heat tolerance, it is also possible for farmers to grow wheat crops in non-traditional locations such as dryland regions in the Sahel characterized by temperatures of 30-40°C and rainfall below 250mm, turning marginal wheat lands into suitable ones.

Composition. Since 2013, more than 30 climate resilient wheat varieties that combine high yield potential, grain quality, and heat and drought tolerance have been released by ICARDA across several countries in Sub-Saharan Africa. This collection of lines is characterized by an early harvest maturity (90-100 days), morphological and physiological protection mechanisms against extreme temperature and low rainfall, and good bread-making quality (14-15% protein content). Resistance to yellow and stem rust diseases that are common across Eastern and Southern Africa (see Technology 2) is possessed by a series of heat and drought tolerant varieties that were developed through conventional breeding techniques.

Application. Seed multiplication of heat and drought tolerant wheat varieties can be done by private companies, and commercial and small-scale farmers themselves. The process is the same as for other cultivars and involves 3-4 growing cycles starting from breeder seed using the "ear-to-row" method practiced by agricultural research centers. In a first step, basic seed is produced that is inspected for true-to-type traits. The basic seed is then planted again to produce certified seeds for distribution and sales. Farmers can use their own seed for maintaining a stock of planting material over the next few seasons but must guard against genetic drift. Heat and drought tolerant wheat varieties are cultivated on farmer fields using the same planting density and mineral fertilizer input as other improved cultivars based upon local conditions. Accompanying practices such as reduced tillage, raised bed planting, soil fertility management, integrated pest management and efficient irrigation systems featured in this catalogue allow for these improved varieties to achieve their yield potential.

Commercialization and Start-up Requirements. Quality seed is of high genetic purity and free from other crop seeds, weeds and foreign material. Farmers obtain improved, certified seed from seed companies and then can recycle that seed for few seasons. Seed of heat and drought tolerant wheat varieties is produced by private seed companies and large-scale commercial farmers in several African countries. National programs offer access to this improved technology in many places where the multiplication and delivery has not yet been commercialized. Rapid and widespread uptake of newly developed heat and drought tolerant wheat varieties requires: 1) Identifying high yielding lines with stress resistance that are adapted to local growing conditions and fulfill preferences of farmers and markets, 2) Providing basic seed and capacity building to private seed companies and public seed enterprises to ensure accelerated production of high-quality certified seed, 3) Enacting stable agricultural and trade policy frameworks that make wheat production cost-effective and attractive for farmers, and 4) Reinforcing information, marketing, transportation and value-add infrastructures within growing areas that improve linkages among farmers, processors and consumers.

Production Costs. Labor requirements for seed multiplication of wheat are low since the crop is self-pollinating and doesn't need elaborate field operations. For the production of certified seed, a normal or slightly lower planting rate of 50-75 kg/ha is used as it increases the number of harvested seeds per planted seed and protects seed quality. The cost of seed is about US $35 to $45 per ha including treatment with fungicide. Cultivating wheat for seed or food necessitates input of mineral nitrogen, phosphorus and potassium fertilizers which costs US $45 to $155 per ha, and spraying with herbicides and insecticide which cost US $37 to $105 per ha.

Customer Segmentation and Potential Profitability. The deployment of heat and drought tolerant wheat varieties involves a diverse customer base, including small-scale and commercial producers, national systems, private seed companies and food processors. Major gains in yields and resilience can be made by cultivating heat and drought tolerant wheat varieties that offer large opportunities for increasing the incomes of commercial and small-scale farmers, in part through expansion of wheat production areas. It is estimated that a ten-fold rise of the cultivated area with heat tolerant wheat in Africa will create more than 200,000 new jobs and double the income of farmers. In Senegal alone, countrywide scaling of the newly developed high-yielding climate-resilient wheat varieties could yield up to 600,000 ton of additional food that would generate roughly US $180 million in additional revenue for farmers without affecting the production of other crops.

Licensing Requirements. The production of basic seed and certified seed for heat and drought tolerant wheat varieties to sell to farmers is subject to standards and procedures as part of licensing schemes and national plant protection regulations. Private and cooperative enterprises wishing to multiply seed materials for these improved wheat varieties can do so by entering into a technology transfer agreement with breeding centers. Heat and drought tolerant wheat varieties are available as Regional Public Goods from ICARDA.

Technology 2. Yellow Rust and Stem Rust Resistant Wheat Varieties

Yellow rust (left) and stem rust (right)

Summary. Yellow rust and stem rust are destructive diseases in major wheat production zones of Sub-Saharan Africa. Infections by these fungal pathogens lead to yield losses of 50-90% and may destroy entire wheat crops within only a few weeks. Rust diseases quickly spread as their spores are carried by wind, resulting in massive losses as occurred with the highly virulent African strain of stem rust Ug99. There is a rapid emergence of new strains over time. Rusts can infect native grasses that make it difficult to eradicate from agricultural landscapes. Use of wheat varieties that are resistant to yellow and stem rust prevents disease outbreak and enhances yields across breadbasket areas. The International Center for Agricultural Research in the Dryland Areas and the International Maize and Wheat Improvement Center, together with national partners have established expansive networks for developing and multiplying rust resistant lines in major wheat production zones that allow proactive and cost-effective disease control. Further details on this solution can be obtained from Dr. Zewdie Bishaw of ICARDA by email at z.bishaw@cgiar.org.

Technical Description. Resistance to yellow rust and stem rust in wheat is expressed from the seedling through adult stages of the growing cycle. Seedling resistance often originates from a single gene but may be restricted to just one strain of the pathogen. Adult plant resistance arises from multiple genes and usually offers protection against multiple rust strains. These resistance mechanisms are then combined resulting in disease resistant varieties. Breeding for rust resistance in wheat is performed through conventional methods by crossing lines into new cultivars and screening their performance under field conditions. A shuttle breeding approach is employed by international centers for developing rust resistant wheat with varieties across Mexico, Kenya, Morocco and Lebanon, allowing selection for multiple desired resistance traits. National testing, release and accelerated seed multiplication ensures that these varieties reach farmers quickly. Generally, resistance to rust by wheat is effective for five years after which a new varieties are required to counter new variants of the diseases.

Uses. Yellow rust and stem rust diseases have spread in all major wheat growing zones of Eastern and Southern Africa. Cooler night temperatures (<15°C), heavy dew and intermittent rain allow rusts to infect and damage wheat crops. Different races of yellow rust and stem rust occur in specific areas of Africa from Egypt to South Africa. One strain alone, Ug99 (TTKSK), occurs across Kenya, Ethiopia, Sudan, Eritrea, Mozambique, Zimbabwe, Tanzania and South Africa. Because of the genetic diversity of these diseases, resistance of wheat varieties is developed for particular sets of geographic conditions.

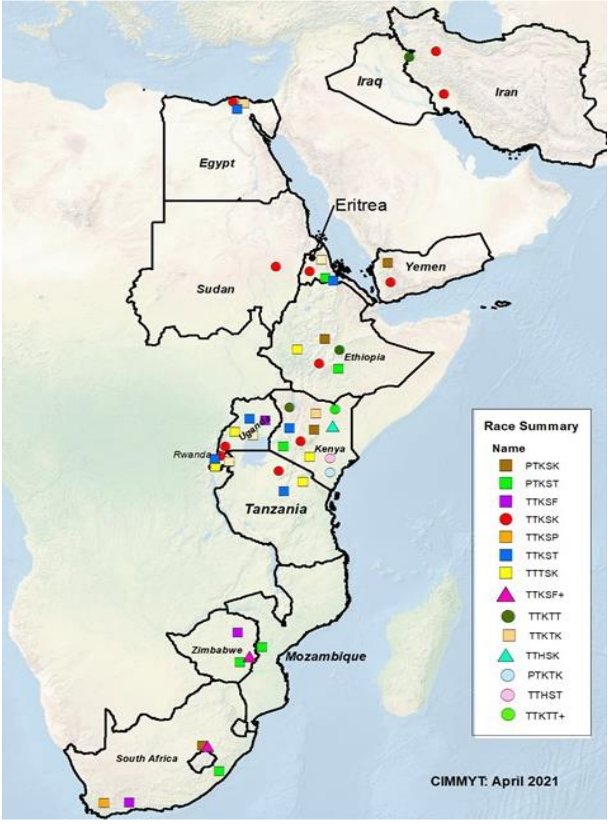
Composition. There are rust resistant wheat varieties that withstand one specific strain of a rust species and others that are immune to a collection of strains, species and types. More than 80 rust disease resistance genes are known and selected ones are expressed in resistant wheat varieties that are available to farmers in Sub-Saharan Africa. In Ethiopia a total of 22 bread varieties were released that withstand yellow and stem rust (e.g. Kababa, Shorima, Ogolcho, Wane, Hidasie). A number of wheat varieties that are resistant to Ug99 stem rust have been developed and introduced across East-Africa over the past couple of years as a response to the devastating outbreak. The available wheat varieties that withstand rust diseases are characterized by a medium to high yield potential, and have good baking quality. Disease resistance is often lost because of the high rate of mutation of the fungus causing the productive lifespan of a new variety to be rather short and requiring continuous development and deployment of new varieties.

Impact of yellow rust on wheat varieties that are sensitive (right) and resistant (left)

Application. Seed multiplication of rust resistant wheat is done after the varieties undergo verification and adaptation trials, requiring about one year for farmers to access the new technology. In case of severe outbreaks, it is possible to perform accelerated seed multiplication alongside field testing of new varieties during both main- and off-seasons, allowing farmers to access resistant germplasm in less than a year time from its release. Seed multiplication of rust resistant wheat involves 2 stages. First, early-generation or basic seed is produced by agricultural research centers, and in a second step this is passed on to private seed companies, public seed enterprises, farmer cooperative unions, farmer seed producer associations and model farmers for multiplying large volumes of certified seed. Wheat varieties that are resistant to yellow rust and stem rust are grown with the same planting density and mineral fertilizer input as other improved wheat cultivars, following local recommendations. To realize the full yield potential and strengthen drought resilience of the crop additional measures need to be taken. Fungicide spraying may also be required in some cases to ensure season-long protection of the crop.

Commercialization and Start-up Requirements. Rust resistant wheat varieties are produced by private companies and large commercial farmers in several African countries, whereas access to them is provided through national programs elsewhere. The following actions have to be undertaken for wheat farmers to enter into this improved seed technology: 1) Identify rust resistant varieties through fast-track field testing and release, 2) Demonstrate rust resistant varieties to farmers, 3) Establish seed multiplication for accelerated scaling out the technology, and 4) Strengthen the capacity of national systems for disease monitoring, varietal selection and seed multiplication and distribution.

Production Costs. Stringent selection procedures applied during screening of varieties in nurseries and yield trials reduce the costs and time for breeding rust resistant wheat varieties. Multiplying seed of rust resistant wheat bears the same costs as susceptible varieties, and labor requirements to produce quality seed are relatively low because the crop is self-pollinating. Total operational costs for farmers in Ethiopia to grow rust resistant wheat have been shown to reach US $440 per hectare, whereas for susceptible varieties it is US $422 per hectare. This includes the cost of seed for rust resistant at US $37 per hectare, labor costs for land preparation, sowing, fertilizer application, weeding, harvesting, and threshing at US $265 per hectare, costs of fertilizers, pesticide and herbicide at US $101 per hectare, and costs for land and equipment rental, fuel and marketing at US $36 per hectare.



Distribution of Ug99 rusts in Africa and Middle East (Source: RustTracker.org)

Customer Segmentation and Potential Profitability. The multiplication and cultivation of yellow rust and stem rust resistant wheat varieties serves a diverse customer base, including national programs, small-scale and commercial producers, private and public seed companies and food processors. Controlling yellow rust and stem rust in wheat production through use of genetic resistance is more effective than chemical control with fungicides, offering substantial economic advantage to farmers. Growing wheat that withstands rust diseases reduces or entirely avoids the need for spraying chemical fungicides and is thus better for the environment and biodiversity. A study across four wheat growing areas of Ethiopia over 3 seasons found that rust resistant varieties achieved an average grain yield of 4.1 ton/ha whereas susceptible varieties produced only 2.9 ton/ha. In another wheat production zone of Ethiopia households adopting rust-resistant varieties have been shown to obtain 351 - 455 kg/ha more wheat yield than non-adopters. The higher grain yields that are realized by rust resistant wheat reduces the cost of production to US $110 per ton as compared to US $136 per ton for susceptible varieties. Cultivating wheat that withstands rusts ensures greater incomes for farmers since yields and profit margins are higher during years with low or severe levels of disease pressure. The genetic protection of wheat crops to rust outbreaks is a business in itself and permits many African countries to become self-sufficient and reduce expensive imports.

Licensing Requirements. Varying standards and procedures for multiplying rust resistant wheat varieties are specified by different national regulatory authorities. A technology transfer agreement must be signed with breeding centers before private and cooperative enterprises can produce and sell basic and certified seeds from rust resistant wheat varieties. Improved lines of wheat that withstand rust are developed and released as Regional Public Goods by ICARDA and International Maize and Wheat Improvement Center (CIMMYT) and are transferred without royalties.

Technology 3. Hessian Fly Resistant Wheat Varieties

Hessian fly adult (left) and larvae and damage to wheat (right)

Summary. Production of wheat in North Africa and elsewhere, including some parts of Sub-Saharan Africa, is threatened by infestations of the Hessian fly (*Mayetiola destructor*), also called gall midge. This insect pest has spread across many major breadbasket areas, causing substantial losses. Damage to wheat crops is attributed to larvae from eggs deposited in grooves on the upper side of leaves. Larvae have the ability to form hardened gall structures that offer protection from natural enemies and other control agents. On seedlings of wheat, the larvae feed on the growth apex (crown), while at later growth stages of the crop larvae establish feeding sites beneath the leaf sheath. Planting wheat varieties that possess a natural defense mechanism against the Hessian fly larvae is the most effective control method and farmers can avoid severe damage by growing these resistant varieties. Crop surveillance and extension messaging ensures the best use of these varieties. For more information about this technology please contact Dr. Zewdie Bishaw from ICARDA by email at z.bishaw@cgiar.org.

Technical Description. Resistance of wheat to the Hessian fly originates from a naturally occurring trait that activates a biochemical defense response to larvae feeding on the leaf and stem. More than 26 resistance genes have been identified in wheat that is now incorporated into local, high-yielding varieties. Common breeding techniques such as phenotyping and backcrossing are used in the development of wheat varieties that withstand Hessian fly attack. Molecular markers associated with resistance genes for the insect pest allow fast-tracking of varietal selection, reducing the cost and time for the development and release of new varieties. Hessian fly populations can overcome resistance in wheat over time because variants of the pest emerge through genetic mutation and environmental pressure, so the effectiveness of released varieties must be monitored to avoid pest outbreak.

Uses. The dispersal of the Hessian fly in Sub-Saharan Africa has not been mapped in detail but the occurrence of this insect pest has been confirmed in wheat production zones of Eritrea, Ethiopia, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Sudan, Tanzania, Zambia and Zimbabwe. During the rainy seasons in tropical climates there is a large risk for severe infestations of the insect pest because egg hatching and survival of larvae are favored by higher temperatures and moisture. Genetic resistance to Hessian fly attacks is a suitable approach for protecting wheat crops in all African growing areas since the technology can be embedded into elite lines with a high yield potential and adaptations to other environmental stresses.

Composition. Wheat varieties resistant to Hessian fly are available in Morocco, Egypt, Algeria, Syria and South Africa, as well as some countries in Sub-Saharan Africa. Globally, more than 200 common wheat and durum wheat varieties were developed that withstand attacks from this insect pest that offer good bread-making quality. There are ongoing efforts by breeders to incorporate resistance genes into wheat cultivars that are commonly grown in the breadbasket regions on the continent.

Performance of wheat varieties sensitive (left) and resistant (right) to Hessian fly

Application. The multiplication of seed for Hessian fly resistance follows the same procedures as for other improved cultivars and takes 2 to 4 growing cycles. In a first stage, early-generation of basic seed is produced by agricultural research centers, and in a later stage this is passed on to seed producers for multiplying large volumes of certified seed. In-field techniques, such as the ear-to-row method where best-performing ears are selected and replanted in single lines can be used by farmers to maintain stocks of planting material. Planting density and mineral fertilizer input for cultivation of Hessian fly resistant wheat varieties follows the same local recommendations as non-resistant varieties. Complementary practices include adherence to planting schedules, destruction of reservoir hosts and use of insecticides. Hessian fly control in farming systems is most effective when accompanied by pest surveillance and extension support.

Commercialization and Start-up Requirements. Hessian fly resistant varieties are multiplied and sold by large-scale commercial farmers in several countries, whereas access to them is provided through national programs. Bringing this seed technology to wheat farmers in major wheat growing areas of Africa requires a set of actions: 1) Identify Hessian fly resistant wheat varieties through laboratory and field testing, 2) Demonstrate the benefits of resistance to the insect pest, 3) Engage national systems, farmer associations and private companies in seed multiplication of resistant wheat varieties, and 4) Enhance the capacity for pest surveillance, varietal selection and seed distribution in major wheat production areas.

Production Costs. Multiplying high-quality seed of Hessian fly resistant wheat varieties has the same costs as more susceptible varieties, and because the crop is self-pollinating there are relatively low labor costs for additional field operations. The price tag of certified seed for wheat that withstands the insect pest ranges between US $35 and $43 per hectare. Coordination within the wheat farming community is required since devastating outbreaks can only be averted if a sufficient portion of cropland (50% to 80%) is cultivated with resistant varieties. The surveillance of pest outbreak and distribution also bears a cost that must be covered by local or national authorities and incorporated into development projects and extension work plans. When resistance to Hessian fly attack is widespread, farmers reduce their insecticide usage, resulting in positive effects on the environment and non-targeted organisms, including build-up of natural predators.

Customer Segmentation and Potential Profitability. The multiplication and cultivation of Hessian fly resistant wheat varieties serves a diverse customer base, including national programs, small-scale and commercial producers, private seed companies and food processors. Resistance to Hessian fly attack in wheat is a financially attractive solution to farmers as it results in stable production that justifies investment in certified seed. Cultivating resistant wheat in a fly-free situation has no negative effect on grain and forage yields. Lines with a natural defense against the insect pest released in Morocco have a yield potential of 5.5 to 7.1 ton/ha, and protects from 79% to 100% of the crop. Extensive monitoring of resistant varieties in the wheat belt of Northern America found that an additional 130 to 210 kg grain per hectare is harvested for every 10% less infestation by Hessian fly larvae, and the same likely holds for Sub-Saharan Africa. The economic benefit for production of forages that is results from resistance in wheat offers producers an additional US $105 per hectare.

Licensing Requirements. Certified seed of Hessian fly resistant wheat varieties can be produced and sold by private and cooperative businesses after signing a technology transfer agreement with breeding centers that are responsible for their development. Licensing schemes and national regulators apply different standards and procedures for multiplying seed from improved wheat varieties. Hessian fly resistant wheat varieties are developed and released as Regional Public Goods by the International Center for Agriculture Research in the Dry Areas (ICRARDA) and International Maize and Wheat Improvement Center (CIMMYT) and no royalties must be paid by seed producers.

Technology 4. Expanded Production of Irrigated Wheat

Water delivery to borders of planting basins

Summary. Grain yields of wheat strongly decrease when the crop is exposed to high temperatures during its growth cycle and this occurs frequently during the rainy seasons when wheat is traditionally cultivated in Sub-Saharan Africa. Higher temperatures are more frequent as a result of global climate change, and this is unlikely to change in the near-future. Growing wheat during the cool season in African dryland belts, referred to as "winter" production, avoids adverse effects of heat stress and allows production of two or more crops in a year. The limited amounts of precipitation that are received during the dry season requires that irrigation systems be in place. Several different irrigation options are available for wheat including flood, furrow and overhead systems. Investments in irrigation and accompanying water delivery are profitable in the mid-term because off-season production generally results in higher wheat yields. This way the innovation builds a food value chain that is resilient to climate shocks and expands the cultivation of wheat across non-traditional growing areas. The success of irrigated wheat production in several breadbasket regions of Africa is advancing self-sufficiency and reducing expensive importation. Further details on this solution can be obtained from Dr. Zewdie Bishaw of ICARDA by email at z.bishaw@cgiar.org.

Irrigated wheat field in El Gezira, Sudan

Technical Description. Farmers in Africa traditionally cultivate wheat during the wet season because adequate rainfall is received without investment in irrigation. However, high mean diurnal temperatures of 33-36°C and extreme heat events with temperatures above 45°C may occur during the growing season that acutely reduce the performance of wheat, even for improved varieties bred to withstand heat stress (see Technology 1). By cultivating wheat in the cooler, dry season, the risk of heat-related yield loss is reduced as temperature spikes above 35°C are uncommon. To compensate the lack of rainfall during the dry season, wheat crops must be provided between 300 to 500 mm of water through irrigation. The advantageous growing conditions under irrigation also lower the risks of pests and diseases. Irrigated winter production of wheat also enables farmers to practice crop rotation, particularly with legumes that serve to protect soil quality.

Uses. Large potential for irrigated production of wheat in the dry sub-humid and semi-arid belts exists across the Sahel, Horn of Africa and Southern Africa because these areas face high temperatures during their growing seasons. Similar advantage exists among wheat farmers in East Africa between the bimodal rainy seasons. Strategic planning and deployment of irrigated wheat production during the cool seasons of Africa's breadbasket areas is of great importance to achieve wheat self-sufficiency under rapidly warming conditions and more frequent heat.

Composition. Winter production of wheat in Africa can be performed with spring bread varieties if 450 mm of water is supplied through irrigation and rainfall, whereas spring durum cultivars require only 250 mm. Heat-tolerant wheat varieties can be used in years when elevated temperatures and heat waves are predicted to occur during the cold season, while common spring wheat cultivars may be grown under normal weather conditions. The type of irrigation that farmers employ depends on the available water sources and topographic position of fields. In broad terms, they have a choice between passive gravity-based systems that divert rivers via canals and dams, or active levitation systems that draw from surface and underground reservoirs through water pumping systems. Overhead water delivery requires higher water pressures, while furrows and floods may be supplied through gravitational flow.

Application. The window for growing wheat during the dry season of African drylands may be rather narrow since cooler temperatures last only 2-3 months and because of delays in cultivation and harvesting before and following the rainy season. In that case, it is necessary to use early maturing wheat varieties with production cycles of 90 to 100 days. Seed must be planted into moist beds using water from dams or nearby rivers. Soils are ploughed and leveled by hand, animal or tractor at which stage farmyard manure or other organic resources should also be incorporated. Seed is planted in lines to allow effective control of weeds and more even distribution of water.

Commercialization and Start-up Requirements. Irrigated dry season production of wheat is practiced by commercial wheat farmers in all major growing areas of Sub-Saharan Africa. Varieties are available for growing in this time of year. With irrigation and the new heat tolerant varieties (see Technology 1), wheat production may be greatly expanded across Africa if the following conditions are met: 1) Educate farmers and investors about the advantages and costs of crop irrigation, 2) Provide access to quality seed of improved varieties, affordable irrigation systems and technical advisory services on their use, 3) Link producers with markets and food processors through prices allowing fair profits and 4) Consider wheat value chains within public sector water infrastructure development projects.

Production Costs. The main expenses for winter production of wheat in dryland farming systems include the installation and maintenance of irrigation systems, the purchase of improved seed, mineral fertilizers, animal manure and chemical control agents, and the labor for land preparation, planting, weed management and harvesting. Farmers may also incur costs for the construction of reservoirs to store water as well as payment of water use fees. The prices of irrigation water and water use efficiency determine the profitability of irrigation. Dry season production near the Nile River in Sudan cost of US $373 per hectare, with 19% going to irrigation. Infrastructure investments to constructing dams, reservoirs and pumping stations are covered as public sector agricultural investments through development projects and then recovered as user fees over time, so it is important that farmers buy into their services.

Customer Segmentation and Potential Profitability. Irrigated wheat production must be made attractive to wheat farmers. Irrigated production of wheat in the dry lowlands and midlands of Africa provides grain yields of 4 to 6 ton/ha, while rainfed production often yields only 3 to 4 ton/ha during favorable years and less than 2 ton/ha during drought and heat spells. Cultivating wheat in the dry, cool season under irrigation can replace the traditional unproductive fallow period on 7.2 million ha of rice paddies across West African countries. The technique also makes it possible to expand wheat production into untapped irrigable land, with a potential of 330,000 hectare along the Senegal and Niger River in Mali, and 108,000 hectare in Mauritania alone. Irrigated winter production of wheat in Senegal could displace the US $55 million annual durum imports and growing wheat in the fallow period of all rice paddies in the country would allow it to meet the national demand and export wheat to neighboring countries at favorable prices.

Licensing Requirements. In some cases, farmers enjoy traditional water rights and may develop their own unlicensed small-scale irrigation schemes. In other cases, access to irrigation water is regulated and requires licenses and the payment of fees, even by farmers living alongside surface waters. Approval from national and local regulatory agencies must often be obtained for extracting water from rivers or groundwater. Irrigation equipment and supplies often enter countries duty-free to encourage investment in agriculture. Techniques for irrigated production of wheat are a Regional Public Good, and ICARDA and the International Water Management Institute have responsibility of developing and disseminating knowhow about appropriate irrigation systems.

Technology 5. Furrow Irrigation of Raised Wheat Beds

Irrigated raised beds of wheat prior to emergence (left) and mid-crop (right)

Summary. Irrigating wheat crops across drylands and dry seasons of Sub-Saharan Africa is vital to realize higher yields, strengthen drought resilience and expand production into new areas. The limited supply of freshwater for agriculture, and cost of extraction, storage and delivery pose major challenges, so available resources must be developed in the best way possible. Furrow irrigated, raised bed cultivation is a highly efficient technique that ensures farmers efficient water use. Planting beds and irrigation furrows are relatively easy to construct with locally available tools and can be maintained over several growing seasons. With the availability of suitable machinery such as raised bed makers and planters, wheat can be seeded in line at the same time as forming the beds. The savings in water achieved by this technique offset the increased cost of production and reduces pressure on dryland agricultural resources. Also, bed planting of wheat not only saves water but improves fertilizer use efficiency and grain yield. For more information about this technology please contact Dr. Zewdie Bishaw from ICARDA by email at z.bishaw@cgiar.org.

Technical Description. This irrigation technique consists of forming raised beds of soil that are 40-130 cm wide and 10-15 cm in height separated by irrigation furrows that are 20-50 cm wide. It is important that beds and furrows run along slope contour. Crops are planted on top of the beds and water is fed to the furrows, which ensures fields are irrigated evenly and that soils maintain ideal moisture conditions. Water use efficiency is improved by about 25% as the wetted area of the field is small and the planting area is high compared to the conventional flood irrigation. These engineered bed surfaces also promote the collection and infiltration of rainwater, decreasing soil erosion and irrigation water needs. Raised beds draw water through capillary forces and evapotranspiration, preventing damage from water logging. Unlike in the case of surface flood irrigation, furrow irrigation allows farmers to apply water and fertilizers on wheat crops when grain heads are forming without the risk excess leaching. With proper scheduling, this practice of wheat cultivation can maintain optimal soil moisture and nutrient availability throughout the season, ensuring high grain yields and returns on investment.

Uses. Cultivating wheat on furrow irrigated raised beds is suitable where conventional flat planting with flood irrigation is performed, and where freshwater resources are limited, or where water lifting is expensive. The technique offers major advantages where frequent droughts occur because small amounts of water can be applied to compensate for short-term rainfall deficits. It is possible to practice raised bed and irrigation furrows on soils with a loamy or clayey texture, but less so in sandy soils unless delivery systems are piped or lined with plastic. In pure sands furrow irrigation is not possible. Slopes should be less than 3% otherwise the strong flow of water can breach the beds and cause erosion. Furrow irrigation is not appropriate where underground sodium deposits are present since the wetting of soil will cause salts to be drawn into the root zone, resulting in salinization.

Establishing raised beds, furrows and planting rows in a single pass over a tilled and level field

Composition. The dimensions of planting beds and irrigation furrows are determined by soil texture, rainfall conditions, groundwater levels, irrigation water quality, space between wheels of a tractor and requirements of accompanying or rotational crops. In sandy soils water infiltrates rapidly so the furrow length must be shorter for water to reach the downward end of the field. In clay soils the infiltration rate is slow so the furrows should be longer and slightly wider for slowing water flow. Multiple rows of wheat are planted on top of the raised beds and the row spacing can range from 12 to 18 cm without reducing yields. This raised bed furrow system is also suitable for rotating crops like rice, cotton or soybean.

Application. Before forming raised beds and irrigation furrows, land is surveyed to determine the slope and direction of water flow. On fields with a less than 0.5% gradient, the furrow runs down slope, and when greater than 0.5% it needs to run along slope contours. Soils are prepared by clearing rocks and tree trunks, tilling to a depth of 20 cm and harrowing to break up large clumps. A distribution channel is installed at the higher end of a field and a collection bund and drainage channel established at the lower end. In this way, slope is kept at a minimum allowing even spread and infiltration of water. Soil in the furrows is placed on the raised bed with a hand hoe or tractor-mounted plough, and then leveled with a harrow. These beds can be maintained as a permanent feature, and even placed into conservation tillage (see Technology 6). Farmers should apply chemical fertilizers, manure or crop residues at recommended rates maintaining high yields. Weeds growing in the furrows must be removed manually or mechanically, and those in between the crop can be controlled by spraying a suitable herbicide. Weed infestation is further reduced by planting wheat cultivars with early vigor that rapidly cover the soil surface.

Commercialization and Start-up Requirements. All equipment for engineering soil surfaces and supplying irrigation water is readily available in most African countries. The improved irrigation technique can be part of an extension message delivered through national projects. Private service providers may be contracted for mechanized construction of beds and furrows and installation of irrigation systems. This system is advanced through four steps: 1) Value chain actors understand the benefits of the technique on grain yields, water use and climate adaptation, 2) Advisory and machinery is available for the construction of engineered soil surfaces and water supply systems, 3) Financial support for the improved irrigation technique is offered in the form of loans or subsidies, and 4) Secured markets are in place to ensure that higher yields result in greater profits.

Production Costs. Farmers performing traditional flood irrigation can adopt the improved technique at no additional cost to infrastructure or machinery, but installing the beds and furrows requires significantly more labor. The total cost of labor and inputs for irrigated raised bed cultivation is just under US $300 per hectare. After that, raised beds need to be reconstructed within three growing seasons, thus attracting a recurrent cost. Sheet plastic used to make permanent raised beds costs an additional US $360 per hectare, whereas organic mulches vary in price depending on the nutrient quality and sourcing distance. The costs of crop mulches are weighed against their alternative value as hay. Installing beds, furrows and distribution channels is less expensive than the infrastructure for sprinkler and drip irrigation systems. Between US $100 to $250 per hectare is typically spend on water from planting to harvesting of wheat under this improved technique, depending on fees for water extraction.

Customer Segmentation and Potential Profitability. Deployment of raised bed furrow irrigation techniques involves small-scale, cooperative and commercial wheat producers, agricultural extension agencies and private service providers. In mid-altitude highland wheat farming systems of Ethiopia, raised bed furrow irrigation consumes 28% less water and yields 27% more grains compared to traditional flatbed planting and blanket flooding methods. The combined use of improved varieties, inorganic fertilizers and furrow irrigation by farmers in Sudan results in 2.3 ton/ha more grain than traditional systems. Raised bed systems reduce the seed rate by about 30% without yield loss. On permanent beds, the production cost of wheat and rice rotations can be decreased by up to 25% over conventional technique.

Licensing Requirements. The construction of beds, furrow and feed-in channels does not need approval in most African countries. Licenses for installing irrigation equipment and extracting water from rivers or groundwater need to be obtained from national and local regulatory agencies. Furrow irrigated raised bed cultivation techniques for wheat is a Regional Public Good, and ICARDA has the responsibility of developing and disseminating knowhow about it.

Technology 6. Wheat in Conservation Agriculture

Summary. Declining soil fertility and increasing water stress are major challenges to wheat production in the cultivated drylands of Sub-Saharan Africa. Farmers often rely excessively on tillage for managing weeds and return limited amounts of organic residues to soils, leading to soil degradation and low soil organic matter contents. Conservation agriculture (CA) involves a set of soil and crop management practices that offer major advantages for wheat production in dryland farming systems. The strategy has a low implementation cost, saves on fertilizer, labor and irrigation, and provides reliable yields and profits under both favorable and poor rainfall. Adopting CA also enriches soil biodiversity, mitigates emissions and sequesters carbon which benefits the environment and climate. Further details on this solution can be obtained from Dr. Zewdie Bishaw of ICARDA by email at z.bishaw@cgiar.org.

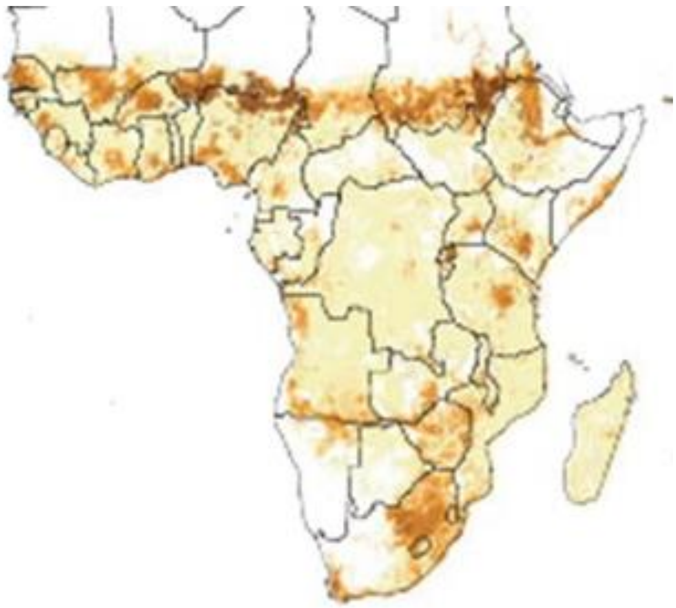
Technical Description. Conservation agriculture combines three principles: 1) minimal soil disturbance by no or reduced tillage, 2) retention of crop residues on the soil surface, and 3) proper crop rotation. The strategy has proven to enhance soil quality, water use efficiency and yield stability, and diminish expenditures on inputs, energy and time in dryland wheat farming. Practicing CA benefits several key processes that influence soil aggregate formation, water infiltration, nutrient availability, acidification, salinization and canopy temperature regulation. Farmlands that are minimally disturbed, covered by a mulch and seasonally rotated show less drought and heat stress on crops then those that are subject to regular and intensive tillage. Soil drying and weed growth are slowed down under CA practices helping farmers save on irrigation water and herbicide application. Rotating wheat with legumes or other crops offers advantages for improving soil nutrient supply, and pest and disease build-up. In the first two or three years of CA there may be small or slightly negative impacts on yield compared to conventional systems, yet over time consistent higher productivity is achieved as soil quality improves.

Later ripening and better grain filling of wheat due to water conservation in no-till system (middle)

Uses. The principles of CA are applicable to wheat farming systems with a range of soil types and water regimes. Reduction in soil erosion and improvements of water use efficiency that are realized by minimal tillage and surface mulching are advantageous to both rainfed and irrigated production. The soil and crop management practices are fully compatible with raised bed planting and furrow irrigation (see Technology 5). CA systems allow wheat farming to be expanded into non-traditional growing areas where the availability of water resources and native properties of soils are inadequate for raising the crop under conventional practices, as is the case for large areas in the dryland belts of the Sahel, East and Southern Africa.

Composition. CA practices greatly vary depending on local management recommendations, agro-ecological characteristics and farmer objectives. Zero tillage means that soils are never ploughed but this is only possible on farmlands that do not suffer from acute compaction, crusting and erosion. Reduced tillage involves less frequent plowing at intervals of 2-5 years, and/or is restricted to bed rather than the whole field. Permanent cover of soil surfaces by crop residues may be complimented by rotational cover crops. In general, there is need to cover at least 30% of soil surfaces before crop yields become increased under CA. Rotational crops include rice, cotton, soybean and cowpea depending on farmer preference, market opportunity and management of pests and diseases.

Application. Practicing CA requires suitable field equipment, retaining some portion of previous season crop residue and timely weed and fertilizer management. Different types of no-till seeders include manually or animal power devices and small to large tractor drawn attachments are available. The spacing between rows and plants is often the same as conventional systems. Recommended rates of inorganic fertilizer and animal manure are applied prior to planting, and fertilizers later applied as topdressing. Fields must be weed-free before planting, often by applying non-selective herbicides at least 1-2 weeks before planting. Weeds pose a major challenge to CA but under proper management and as time passes the seed bank of weeds is steadily diminished.



Potential suitability of CA in Sub-Saharan Africa, darker shaded areas have larger benefits (Source: Prestele et al. 2018)

Commercialization and Start-up Requirements. Machinery for direct seeding of wheat crops are widely marketed in Africa, mostly as imported equipment. Commonly available herbicide and pesticide products are important in CA systems. The techniques for minimal tillage, surface mulching and crop rotation are disseminated through extension messages and within farmer groups. Wheat farmers in major production zones of Sub-Saharan Africa may readily implement CA principles by: 1) Creating awareness on CA as a management strategy and its benefits in terms of investment, productivity and soil quality over time, 2) Equipment for direct seeding and fertilizer inputs are accessible to farmers at affordable prices from local dealers and service providers, 3) Agro-ecosystem services like reduced erosion, water conservation and soil carbon storage are rewarded in the form of discounts or credits, and 4) Strong linkages with food manufacturing industries are established that guarantee stable and fair markets.

Production Costs. No-tillage or minimum tillage saves land preparation cost for farmers as compared to intensive plowing, whereas use of herbicide to kill weeds before seeding incur additional expenses, and to a large extent these are offsetting in the short-term but result in savings over time. Retaining some crop residue as surface mulch reduces the availability of hay for animal feed, but this can be compensated by higher yield and biomass production under improved management. The three-year average total production cost for wheat-chickpea rotation under CA in Morocco is US $740 ha^{-1} compared to US $838 ha^{-1} for a conventional tillage system. CA practices with zero tillage and soil residue retention in Tunisia have shown to increase yield by 15% and water use efficiency by 18% while steadily accumulating soil organic carbon.

Customer Segmentation and Potential Profitability. The techniques of conservation agriculture are appealing to commercial wheat farmers in Sub-Saharan Africa. The adoption of CA in wheat-chickpea rotations in the Moroccan drylands increases yields by 22%, rainfall water use efficiency by 21% and incomes by 20%, as compared to the conventional tillage system. In Mexico, profits from wheat production are demonstrated to increase by US $923 ha^{-1} under CA management instead of intensive tillage. At the same time, minimal tillage and mulch application were found to increase soil organic carbon levels by 63% at 0 to 5 cm depth and 32% at 5 to 30 cm depth. The time saved to prepare lands under CA allows for flexibility in planting date based upon weather conditions, adding to climate resilience. Maintaining residues on soil surfaces reduces erosion by water and wind, protecting soil as a farm resource. CA principles offer major opportunities to adapt wheat farming in African drylands but flexibility is needed to pass these benefits to small-scale farmers.

Licensing Requirements. Implementation of minimal tillage, surface mulching and rotational cropping in wheat-based farming does not require approval. Use of irrigation under CA management requires licenses from national and local regulatory agencies for installing equipment and extracting water from surface and groundwater (see Technology 4). The techniques for CA in wheat farming are a Regional Public Good, and ICARDA leads its development and dissemination in Sub-Saharan Africa.

Planting tools and techniques for no-tillage and minimal tillage

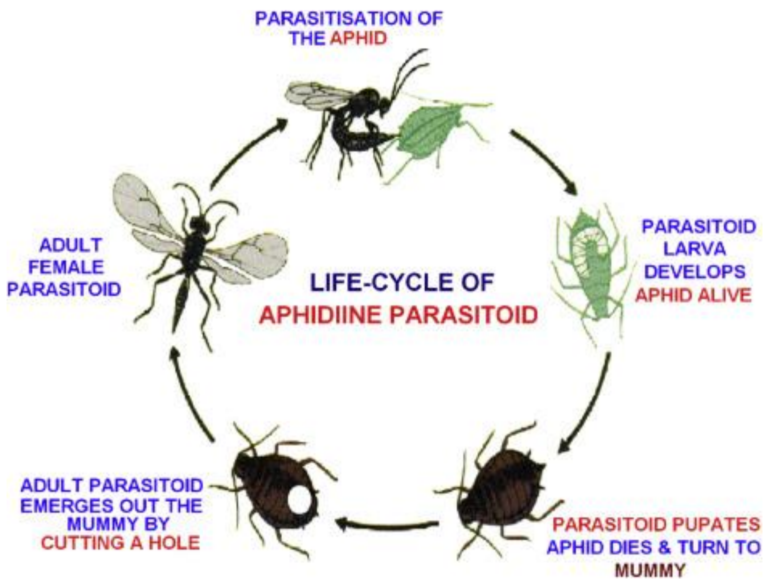
Technology 7. Integrated Management of Insects, Diseases and Weeds

Summary. Pests and diseases are managed through breeding resistant varieties and integrated crop management. Wheat farmers in Sub-Saharan Africa commonly apply agrichemicals to prevent losses from weeds, diseases and insect pests. Over time, however, this imposes a selective pressure on these organisms that leads to resistance to these chemicals. Modifying the use of a chemical agent or changing to another type of substance provides short-term relief but does not avoid the emergence of resistant biotypes in the future. Frequent application of broad-spectrum pesticides on farms distorts the control of harmful insects, diseases and weeds due to the loss of organisms that are their natural enemies. Integrated Pest Management (IPM) and other related practices reduces reliance upon agrichemicals by employing diverse biological and agronomic methods offering lasting crop protection, and do not pose dangers for food safety and the environment. For more information about this technology please contact Dr. Zewdie Bishaw from ICARDA by email at z.bishaw@cgiar.org.

'Fish hook' deformation of heads (right) caused by wheat aphid, compared to a normal wheat head (left)

Technical Description. IPM harnesses natural control mechanisms for pests resulting in minimal use chemical pesticides. The primary focus is maintaining a well-balanced population of beneficial and harmful organisms based upon their lifecycles and interactions with the environment. Strategies involve carefully selected mixes of biological, mechanical and cultural techniques that are tailored to local conditions. A wide range of biological measures are available that target pests. Release of natural predators and enemies, or sterile insects reduce pest populations to a lower steady state but require caution to ensure no detrimental effect to the larger ecosystem. Mechanical interventions involve equipment to scare away birds or rodents or picking pests off plants. Cultural measures avoid that pest build-up and include practices such as precision sowing, shifting planting dates, removing waste or diseased plants, wildflower strips and pest-resistant varieties. IPM interventions can suppress multiple pests at the same time as is the case for aphids which transmit yellow rust and stem rust in wheat crops. Wheat can be infested with both grassy and broadleaf weeds, reducing yields by competition for moisture, light and nutrients. Weeds also interfere with harvest and lower grain quality. An effective weed control in wheat considers all aspects of the cropping system, including tillage practices, crop rotation and herbicide application. Insects directly cause injury by feeding, and thus predispose plants to disease. Integrated disease management include use of disease resistant wheat varieties, chemical seed treatment, fungicide sprays and reliance upon crop rotation.

Uses. Effective IPM strategies are available for many important pests of wheat crops in Sub-Saharan Africa, including insects like aphids, mites, maggots and cutworms, diseases like rusts, bacterial blights, root and crown rots, and weeds like wild oats, annual ryegrass, nut grass and chickweed. The principles of IPM can be universally implemented in rainfed and irrigated systems, lowland valleys or highland plateaus, and dry sub-humid and semi-arid climates. Mechanical and cultural techniques match a very broad set of agronomic and environmental conditions and can be easily modified within local contexts. Biological techniques suit a narrow range of geographies defined by the physiological traits of beneficial organisms and composition of native communities.



Predation of wasps on aphids
(Source: Singh et al. 2016)

Composition. Releases of beneficial organisms follow two approaches; 'inoculative' where a limited number are introduced and populations build over time, or 'inundative' where mass rearing takes place and large numbers are dispersed. The inoculative technique is suitable for long-term intervention, whereas the inundative technique immediately results in suppression of pests. Reproduction and survival of natural predators and enemies can be enhanced by providing alternative hosts or favorable nesting and feeding sites. The sterile insect method effectively decreases reproduction rates of pest by releasing infertile males that rival fertile males and cause unsuccessful breeding. A key cultural technique for controlling aphids in wheat crops is to shift the time of planting when conditions for not favorable for rapid multiplication of the pest. Rotating wheat with rice, chickpea, pea, cotton and other crops is the cornerstone of integrated weed management. Increasing crop density and decreasing row spacing is effective to suppress the growth of weeds and their seed banks. Mass trapping techniques that use pheromones or other substances are appropriate for controlling whiteflies and thrips in wheat crops. IPM strategies minimize the application rate of chemical substances to control pests by methods such as seed coating and applying pre-emergent herbicides.

Application. Implementing IPM strategies begins with identifying the type and number of harmful and beneficial organisms on a farm and establishing critical thresholds in the community structure when economic injury take place. Monitoring pests is performed with simple tools such as traps and magnifying glasses, or with advanced high-resolution cameras fitted onto drones that allow rapid surveillance of large areas. Inspection of weeds is performed between emergence and tillering stages when annual broadleaf weeds are in early vegetative stages and later after the harvest. Insect and disease surveys are carried out simultaneously and must be repeated at different growth stages of crop development. Software tools offer an easy means for data gathering and analysis which allows tracking of pests and their enemies. Once the threshold for populations of harmful and beneficial organisms is established, then biological, mechanical and cultural measures are prescribed.

Commercialization and Start-up Requirements. IPM techniques for wheat are offered as part of public and private extension messaging. Wheat farmers transition to IPM after: 1) Identifying the full range of pests to anticipate and the beneficial organisms that help to keep the community balanced, 2) Defining appropriate strategies by observing effects in fields as compared to conventional practice, 3) Understanding the benefits for pest control and production costs in the short- and long-term, and 4) Securing access reared predators and enemies of pest organisms, bio-pesticides and related advisory services. Planned release of natural enemies may be incorporated into larger development projects.

Production Costs. Detailed surveillance of pests and their natural enemies for implementing IPM strategies requires substantial labor and is best conducted by specialists working with communities of wheat farmers. Rearing colonies of parasitoid wasps requires inexpensive equipment; planned release of proven control agents requires only US $5,000 to install and a further US $6,000 per year to operate. Seed coating is also inexpensive depending upon the price and dose of the needed agrichemical. Use of pre-emergence herbicides requires US $25 to $35 per hectare for the weed control product, and hiring sprayers and labor to treat crops. A full IPM package that includes raised fertilizer rates, precision herbicide application and seed treatment costs about US $515 per hectare. Adopting the bundled technologies of genetics and crop management can boost average productivity to 3.5 to 4.8 tons per hectare, resulting in increased income ranging between US $585 to $1,311 per hectare per season.

Wildflower strips in wheat field for increasing populations of natural enemies

Customer Segmentation and Potential Profitability. Biological, mechanical and cultural techniques are intended for small-scale and commercial farmers, with products, equipment and use advisory being delivered by agro-input suppliers, local service providers and extension advisors. Proactively managing the use of synthetic pesticide agents by implementing green-based control measures avoids outbreaks and production losses when pests become resistant. In central Asia, an IPM package for wheat reduced beetle damage by 17-33%, rust infestation to less than 10%, and increased grain yields by 30-70% as compared to the farmer practice. This particular set of measures showed a profit of US $35 ha^{-1}, whilst net losses or small profits are made under the farmer practice. Removal of parasitoid wasps from stands of winter wheat crops in Germany has been shown to increase aphid populations by 70% and cause major grain yield loss. The expansion of wheat across Africa should be accompanied by similar integrated control strategies.

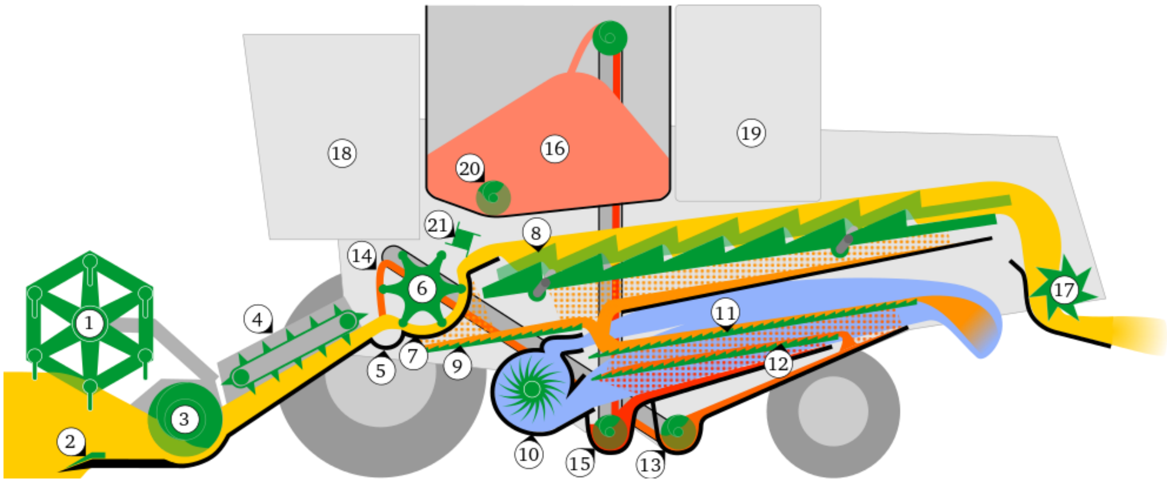
Licensing Requirements. Permits from national plant health agencies are needed for the rearing and release of biocontrol agents for wheat and other crops. Countries in Sub-Saharan Africa have specific regulations in place for compliance and use of pesticides for agriculture which have to be obtained by agro-input companies supplying local markets. Biological, mechanical and cultural measures included under IPM strategies are offered as a Regional Public Good. ICARDA and International Centre for Insect and Pest Ecology are responsible for development and dissemination of the technologies.

Technology 8. Combine Harvesters and Fleet Management

Combine harvester operating in Sudan

Summary. A combine harvester is a type of modern agricultural machinery that performs multiple harvesting operations, combining reaping, threshing and winnowing into a single process. Combine harvesters are available in a broad range of sizes, from small units that can handle a few hectares per day to very large units for major operations that harvest several hectares per hour. Some of these harvesters can be used for multiple crops such as wheat, maize, rice, soybean, barley, sunflower, allowing services to different farms. Careful selection and efficient management of combine harvesters is key to optimize performance and minimize costs and it is possible to design a fleet by considering the technical and technological parameters of the machines. Tools exist that characterize the best composition of a combine harvester fleet based on the field sizes, crop rotations and harvesting timeframes. Combine harvesters substantially reduce grain losses during harvest and the costs of labor and also make it possible to expand production in areas where there is a shortage of workers. For more information about this technology please contact Dr. Zewdie Bishaw from ICARDA by email at z.bishaw@cgiar.org.

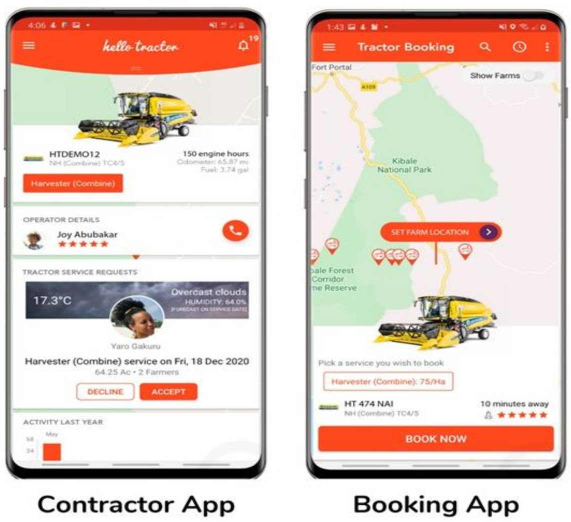
Technical Description. Wheat crops are gathered by a slowly rotating reel and cutter at the front of combine harvesters while passing through the field. The cut parts are carried by a conveyor that feeds into the threshing drum consisting of grooved rasp bars and a concave grate. By friction the rasp bars pull the crop through concaved grates that separate the grain from straw. Long pieces of straw cannot pass through the grate and float over it onto the "straw walkers" that lead to a chopper at the back of the combine where it exits onto the field. In most modern combines, the grain head is transported by a set of augers to the shoe which contains the chaffer, sieves and fan that separate chaff and grain. The lightweight chaff is blown away and also ejected from the back of the combine. An auger at the bottom of the sieves moves the clean grain into the tank from which it can be transferred to carts pulled by tractors that drive alongside the combine. A variable transmission fitted on combine harvesters allows the ground speed to be changed while maintaining a constant engine and threshing speed. The capacity of combine harvesters depends on their size, configuration and threshing speed. Large units with a cutting width of 4 m or more have a harvested weight performance of 15 to 25 ton per hour, and harvested area performance of 4 - 5.5 hectare per hour. Smaller "mini" combine units with a cutting width of 1.2 m have a harvested area performance of 3 to 6 hectare per day.



Schematic overview of a combine harvester: 1) reel, 2) cutter, 3) header auger, 4) grain conveyor, 5) stone trap, 6) threshing drum, 7) concave grate, 8) straw walker, 9) grain pan, 10) fan, 11) top sieve, 12) bottom sieve, 13) tailings conveyor, 14) re-threshing of tailings, 15) grain auger, 16) grain tank, 17) straw chopper, 18) driver's cabin, 19) engine, 20) unloading auger, and 21) impeller

Uses. Combine harvesters can be deployed in all commercial wheat growing areas of Sub-Saharan Africa as it is possible to select the right size, configuration and performance for farms with different sizes, planting density and micro-topography. Power thresholds of combine engines allow use of different machinery across different types of landscapes. Hydraulic hillside leveling systems are fitted on some combine harvesters allowing the machine to be operated on croplands with a steep slope without large amounts of accompanying grain loss. Fleet management systems are available as mobile and web application, and have extended offline capability for the various modules that can operate in remote rural areas. The digital tools for service contracting and performance tracking can be used anywhere since they have the ability to roam different telecom networks.

Composition. The head of a combine harvester can be adjusted to a required performance and crop type. Rigid headers are used for cereals whereas flexible headers that move over contours and ridges can be used for other crops. When moving between fields the header is removed and towed behind the harvester so it fits with roadways. Tires fitted to most combines can operate on a broad range of terrains whereas some have rubber tracks that put less pressure on the soil and can easily move over wet fields in lowland areas. Besides the combine harvester, there is need for separate tractor carts or trucks to collect expelled grain and transport it to storage and processing facilities. Fleet management



Digital applications for fleet management and contract services by Hello Tractor systems embed sensor technology for collecting intelligence on the internal workings and performance of combine harvesters. Multiple telematics solutions are integrated for optimizing the deployment of combine harvester fleets such as GPS tracking, fuel management, driver management, maintenance and servicing, fraud prevention and customer booking; which are operated via an easy-to-use dashboard that can be accessed via smart phones.

Application. Combine harvesters can be operated by a single person trained on the workings of electronic control panels and the mechanical parts inside the machine. Operators ensure that the equipment is used properly and is well maintained. The height of crops, land slope and other features of a field must be surveyed in consultation with farmers for determining the best approach to avoid grain loss, excessive fuel usage, poor maneuverability and damage to irrigation furrows (see Technology 5). Through mechanized contracting platforms, owners of combine harvesters can offer services directly to farmers, or may work through booking agents that aggregate demand within farming communities. Farmers who seek contract mechanization services may request, schedule and prepay for them through mobile applications connecting them with equipment owners or booking agents. Once a job is completed, the balance of payment is settled through the digital system. Equipment owners and investors receive detailed reports about service performance which allows them to improve business models and access financing for new equipment in the future.

Commercialization and Start-up Requirements. Many combine harvester manufacturers or certified retailers are selling small to large combine harvesters across commercial wheat production zones of Sub-Saharan Africa (see Technology 1) but few or insufficient combine fleets exist in areas targeted for expanded wheat production. Growing numbers of service companies and private owners provide the mechanized harvesting equipment for rental to farmers through digital contracting platforms. The following steps must be taken for expanding the use of combine harvesters and fleet management tools in wheat growing areas of Africa: 1) Raise awareness with farmers about the benefits of using mechanized equipment to improve harvest efficiency, 2) Provide financial incentives for purchasing combine harvesters and initiating smart service delivery, 3) Develop networks of equipment owners, trained operators and booking agents as consolidated contracting platforms, and 4) Monitor the performance of harvesters, operators and booking agents to optimize equipment movement, maximize profits and reduce fraud. Development projects to advance wheat production in Africa should consider offering harvesting services to farmers.

Production Costs. The capital investment for combine harvesters varies according to size, configuration and performance. Small units that have a header width of 1.1 meter and no grain tank are more affordable with prices starting from US $12,000. Large combine harvesters with a cutting width of 10 meters and a grain tank of 5,000 liter cost US $300,000 to $500,000. The CLAAS Lexion 670 with a cutting width of up to 12 m has fixed costs for the equipment of US $32 to $51 per hour, with variable costs of US $67 per hour, half of which is paid to labor, 40% to fuel and 10% to maintenance. Harvesting cost for this unit ranges from US $25 to $33 per hectare, or US $4.7 to $9.2 per ton of grain (depending on field productivity. For a smaller New Holland CX 8080 with a cutting width of 3.7 m, total harvesting cost is between US $56 and $63 per hectare. Digital applications that help manage contracted use of agricultural power equipment can be downloaded for free by equipment owners, farmers and investors. Aside from the capital for equipment acquisition, owners must also invest in smart mobile devices and their installation by accredited technicians so that critical information about its performance can be regularly collected.

Customer Segmentation. There is a diverse market for modern combine harvesters in wheat growing areas of Sub-Sahara Africa. Larger- and smaller-sized units are fit for agricultural service companies and commercial wheat farmers who operate on holdings of one hundred hectares or more. Smaller units can be operated collectively by larger associations of farmers who produce a few hectares each. Satisfying increased demand for harvesting services from wheat farms is a business investment opportunity in itself.

New Holland CX 8080 with 3.7 m cutting width (above) and CLAAS Lexion Combine 670 with a 12 m cutting width (below)

Potential Profitability. Farmers receive several advantages from contracting mechanized combine harvesters as opposed to traditional systems operated by hand or animal-traction. Costs of cutting, threshing, straw disposal, winnowing and overall grain losses during harvest are substantially reduced by the single automated process. Cleaner grain is collected by better separation of weeds seeds and chaff. Saving in labor make it possible to cultivate larger areas of land and to prepare fields for the next season in a shorter time. At the same time, farmers' returns depend on total yield, the ratio of grain to straw and the market price for grain. The use of fleet management tools and optimization models minimize running costs and increases efficiencies crucial for further investment in this capital-intensive equipment. Use of advanced financial analytics alleviates risks of inappropriate deployment and breakage of power equipment which increases confidence in further investment in mechanization. Contracting platforms for agricultural equipment offer farmers wider options for service provision and make digital agricultural services more competitive as well.

Licensing Requirements. The intellectual property of combine harvesters is owned by manufacturers, whereas digital applications for management and contracting of a fleet, such as Hello Tractor, are free of commercial licenses and royalties. Understandings related to modernize harvesting operations are developed as a Public Good by TAAT and its partners and warrants replication throughout Africa.

Technology 9. Hermetic Bags for Safe Storage of Grains

Design of a hermetic storage bag

Summary. Large post-harvest losses of wheat and other dried foods occur across Sub-Sahara Africa because of improper storage conditions. To avoid this risk, grains are often sold immediately after harvest when prices are at their lowest. The hermetic storage technology for grains overcomes this constraint by using sealed bags that exclude air and moisture, creating an environment that is non-conducive to pests of stored grains. The bags preserve the quality of grains and obstruct the entry of insects and microbial organisms through depletion of oxygen levels and accumulation of carbon dioxide. These conditions prevent damage by insects like beetles, weevils, moths, mites and borers, and inhibit the development of fungi that contaminate the grain. In addition, taste and color characteristics of the food product are retained. This simple and inexpensive storage technology makes it possible for farmers to improve the year-round supply of food and income. Further details on this solution can be obtained from Dr. Zewdie Bishaw of ICARDA by email at z.bishaw@cgiar.org.

Technical Description. Hermetic bags are air-tight, preventing oxygen and moisture from affecting grain stored within them. A multi-layer technology is used to modify the environment and restrict gas exchange with the outside atmosphere. Under this system, farmers can store grains for up to two years while retaining their palatability and cooking quality. This ensures that farmers have enough to eat in between harvests and can sell their produce when the price is more favorable. Grain quality is conserved through the regulation of moisture inside the bag and inhibits fungal growth that may lead to build-up of carcinogenic mycotoxins. The cooking time of grains preserved in hermetically sealed bags is the same as freshly dried ones whereas loss of moisture in traditional storage techniques may double the amount of time and energy required for food preparation.

Uses. Storage of grains is particularly susceptible to damage by insects and microorganisms under hot and humid weather conditions that promote the introduction and multiplication of pests. Losses of more than 25% in storage are common because current storage techniques of farmers, traders and food manufacturers do not provide ample safeguards against pests. Hermetic storage bags compliment the operations and infrastructure of producers, buyers and processors, and the slightly higher cost of these bags is offset by the ability to reuse them for several years. This grain preservation technology is especially suitable in regions where the road networks are poor and where markets and processing industries are located far away, as is the case across many locations intended for greatly expanded wheat production across Africa.

Different brands of hermetic grain storage bags are available from agrodealers

Composition. Hermetic storage bags have several protective layers with two separate inner liners made of high-density polyethylene with a thickness of 0.8 mm and a standard polypropylene woven bag on the outside. A sealed environment is created by the inner bags that have very low permeability of gasses and are water repellent, allowing it to maintain stable moisture levels in stored grains under both dry and humid conditions of outside air. The outer bag provides strength to withstand handling given the weight of the grains it contains. A series of hermetic storage bags are marketed by different brands including the Purdue Improved Crop Storage (PICS), ZeroFly Storage Bags, Elite Storage Bags, GrainPro Storage Bags, and AgroZ Storage Bags.

Application. Threshed grains are dried to appropriate moisture level and then placed into high-density polyethylene bags with a capacity of 50 kg or 100 kg. The first bag is filled completely, but with a 20-30 cm void and tied securely. The second bag’s neck, surrounding the inner bag containing harvest is also tied securely. Finally, these two bags are placed in a third woven nylon or polypropylene bag. With the third bag tied securely, the container can be handled without bursting the inner bags and is readily accepted by grain buyers and handlers. An alternative method is to fold both liners together and twist tie them together, an approach that considerably reduces time spent on bag sealing. The hermetic bagging process can be performed entirely by hand or fitted into automated fill and seal machines. Wheat grain can be stored for up to 2 years with this preservation technology. Rats, mice and other rodents are able to chew through the different layers, breaking the hermetic protective environment, and thus must be kept away from stored grains.

Commercialization and Start-up Requirements. Hermetic bags are becoming widely available across Sub-Saharan Africa. To date, the storage technology has been introduced, piloted, adopted and now commercialized in countries not limited to Kenya, Ghana, Uganda, Ethiopia, Southern Sudan, Niger and Burkina Faso through various programs and interventions. The adoption of this safe storage technology can be scaled through the following steps: 1) Sensitize commercial and small-scale growers and processors on the benefits of the hermetic technology for preserving harvested grain, 2) Build capacity on how to fill and seal bags, and how to manufacture them from raw materials, 3) Provide lines of financial support to manufacture purchase hermetic bags and mechanized fill and seal technology, and 4) Convince agrodealers and other retailers to offer hermetic bags as a product and display them prominently.

Production Costs, Customer Segmentation and Potential Profitability. The raw material and labor to manufacture hermetic grain storage bags with three layers costs between US

$1.00 to $1.50 per piece, and are sold at US $2.00 to $3.00 by suppliers. High-density tube plastic and fully automated sealers needed to make the inner liners are available on most local markets across the continent. The use of hermetic bags for safe storage of wheat and other grains is readily scalable to millions of small-scale and commercial wheat farmers through manufacturing industry and retail businesses, as demonstrated by its success to date. Post-harvest losses can be reduced by up to 90% when using the preservation technology, protecting the food supply of producers and improving the supply and prices of local produce. Indeed, rapid growth in the manufacturing and sales of hermetic bags has occurred over the past 12 years through multiple private businesses. For example, roughly 20 million units were distributed across Sub-Sahara Africa in 2019 protecting about 1.5 million tons of produce, not including the reuse of these bags.

Licensing Requirements. Hermetic storage bags are becoming increasingly available through commercial channels. Designs and manufacturing techniques of hermetic bags are more often protected by trade secrets than patent although manufacturers and suppliers may require licenses to produce and distribute these bags. Knowledge on the composition, application and effectiveness of hermetic bags for storage of dry grain is readily available over the internet. The commercialization and dissemination of the wheat storage technology is led by ICARDA and CIMMYT as a Regional Public Good.

Technology 10. Flour Milling Systems

Summary. Farmers, producer associations and traders can quickly add value to wheat by milling it into flour used to make a variety of processed food products such as bread, biscuits, cakes, porridges and pasta. At the same time, techniques for producing wheat flour must meet industry quality standards and preferences of consumers. Small- to large-sized milling and blending systems are available from local and international manufacturers that allow production of premium wheat flour close to production areas. The advantages of processing wheat into flour are the reduction in transport costs from farms to factories and the longer shelf life that result in better access and supply to markets, food processors and manufacturers. Building capacity of rural communities for milling and blending of wheat flour boosts output, value addition and competitiveness of local processors, and allows African wheat farmers better access to markets. Further details on this solution can be obtained from Dr. Zewdie Bishaw of ICARDA by email at z.bishaw@cgiar.org.

A small-sized mill for wheat flour production

Technical Description. Producing wheat flour may be considered a business art that begins with selecting the right factory location, followed by procuring the right wheat variety at the right price, followed by cleaning and milling in the right way. Locations for processing should

Evolution of local flour milling: traditional African grindstone (left), ancient Roman stone mill (center left), modern home stone mill (center right), small-scale electric mill (right)

be close to major growing areas that can provide a reliable supply of quality grains, and have convenient transportation routes for easy delivery of raw and shipping of final products. In selecting the wheat varieties for blending, it is important to take the hardness into consideration because it strongly affects annealing strategies of heat treatment to relax starch structures. Blending procedures must also be conducted in accordance with the gluten, sedimentation and index values that determine flour quality, and are closely monitored by food manufacturers. Another purpose of annealing ensures the optimum moisture level for milling and to enhance flours wetting ability. Modern milling equipment ensure that a very high proportion of flour is obtained by sequential crushing of the grain leading to size reduction of the flour by steel rollers.

Uses. Flour milling and blending technologies for wheat improve African food self-sufficiency and promote business development in rural communities. Small-scale equipment is relatively simple to install but require reliable sources of electricity. Solar power is an option as this technology is particularly advantageous in more remote locations. Milled wheat flour presents opportunities to improve existing supply chains and open up trade in new areas since it renders large savings on importation and transportation costs.

Composition. There is a wide range of equipment for processing wheat based on size, shape and density of grains. A typical air-screen cleaner consists of four screens that are located beneath a hopper. Grader machines that sort out impurities based on width and thickness are comprised of cylindrical screens that are horizontally positioned and have round perforations. Separators that select grains by length, density or gravity use angular sieves and forced air which can be adjusted according to specific needs. An abrasive grain mill has a feed-in hopper, roller table for grinding, rotary sieve for bran separation, and a conveyor belt.

Application. Before establishing a flour milling enterprise, there is need for market research to identify viable business models. One must be sure about location, supply and market so investments are not made at the wrong place. Next one needs to perform a comprehensive analysis of the investment needs for capital equipment, staff wages and other fixed and variable costs. Based upon this information, one can identify finance mechanisms and approach investors. Once funding is secured, then equipment for cleaning, annealing and milling must be purchased and assembled into a flour processing line. Reliable supply of electricity is very important and backup systems should be in place. There is need for continuous quality assurance of the flour to ensure product compliance with market standards on gluten content, sedimentation and index values.

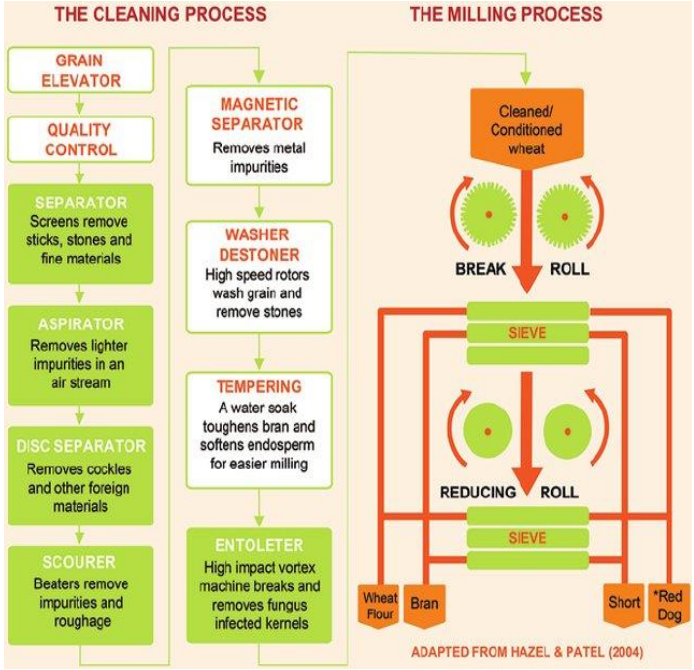


Diagram of typical steps in wheat cleaning and milling. Green boxes indicate where reduction of mycotoxins take place (Source: Bianchini et al. 2015)

Commercialization and Start-up Requirements. Equipment setups for cleaning, annealing, blending and milling of wheat are available from manufacturers and retailers in many African countries, though some equipment must be imported or modified. The following steps are needed for enterprise development around wheat flour milling and blending, and widespread replication thereof: 1) Raise awareness with farmers, agri-food companies and investors on the economic benefits of the technology, 2) Formulate appropriate product standards, packaging sizes and prices based on consumer demand, 3) Identify profitable, durable and equitable strategies for taking wheat flour products to local, regional and international markets, 4) Establish reliable supply of high quality grain to processing plants through nucleus farming or sub-contracting, 5) Set up equipment and production lines that make efficient use of energy and labor, and 6) Train operators and workers on safety and quality adherence throughout the manufacturing process.

Production Costs. The prices of wheat at the factory gate are a major determinant of the economic viability of a milling enterprise. Exact costs of a flour milling depend on the geographic location, size of operation and equipment selection. In general, 60% of the capital investment that is required to set up a processing plant goes into equipment, while the rest to construction and marketing. A small flour mill that is manually refilled with an output capacity of 300 - 500 kg flour per hour costs around US $3,500. The base price for a fully automatic wheat flour mill with a capacity of 30 ton flour per day is about US $38,000. Operating a flour mill requires skilled labor to ensure that production runs smoothly and equipment is properly maintained and a manager to keep track of expenses, supply and sales. Mechanical inspection by a professional technician and replacement of high-wear parts ensures continuity of operations.

Customer Segmentation and Potential Profitability. Wheat flour milling and blending systems are applicable to industrial flour processors and food manufacturers, and may be modified to suit the needs of more localized processors and community-based activities. It also requires that consumers accept the products resulting from blended flours. High-performance cleaning systems for wheat ensure very low percentages of non-millable material that would otherwise reduce milling efficiency and revenues. In general, a 1% reduction in non-millable fraction provides an additional US $3 per tonne of flour. Modern

Flour milling products: whole wheat (left), milled flour (center) and wheat bran (right)

equipment for annealing and milling wheat grain achieve maximal recovery of flour at 80-82% and 18-20% bran, whereas traditional manual techniques and older milling systems recover only 65-70% flour. Better annealing and milling realized from modern equipment improves flour quality and market price with a 2% increase of water absorption translating into a premium of up to US $9.20 per ton. Altogether the effect of running at higher efficiency versus lower milling efficiency provides additional net profit of about US $30 per ton of flour.

Licensing Requirements. Obtaining a license from regulators and registering your factory is important to the success of a flour milling business. This involves periodic inspection to assure that quality standards are met. Techniques for production of wheat flour are a public good, and ICARDA and other organizations, including national Bureau of Standards, are actively involved in disseminating this information across Sub-Saharan Africa.

Increased wheat productivity, expansion of its production area and adoption of modern milling technologies can transform Africa from a massive wheat importer to a competitive flour exporter. Join TAAT to realize this opportunity!

TAAT is Your Technology Broker of Choice

TAAT offers its services toward the advancement of modernized agriculture. It brokers a wide range of needed technologies and bundles them through a process of co-design into winning solutions. It recognizes that modernized agriculture will serve as the main engine for economic growth in Africa's cultivated drylands. This change is intended to achieve not only food and nutritional security but also to meet obligations under climate agreements allowing collaborative efforts to better combine global, national and community-level interests. The Technologies for African Agricultural Transformation Program (TAAT) operates from a unique perspective to mobilize innovative solutions through better partnering that includes honest technology brokerage and effective, scalable skills development through five key mechanisms.

- ☑ **Unique understanding:** Expertise is offered in the areas of site characterization and problem identification.
- ☑ **Innovative solutions:** Leadership is provided in technology brokerage and solution bundling based upon a dynamic portfolio of candidate technologies.
- ☑ **Better partnering:** Assistance is offered in the better co-design and management of projects prompting agricultural transformation.
- ☑ **Replicable approaches**: Assistance is available to advance skill sets in technology brokerage and project management through customized Training of Trainers.
- ☑ **Honest brokerage:** An independent capacity for impact assessment and constructive learning is achieved through standardized monitoring and evaluation.

These partnership mechanisms are applied to the technologies featured in this catalogue as follows:

1. **Improved Varieties of Wheat.** The latest progress in breeding for heat and drought tolerance, rust and insect resistance, as well as nutritive biofortification is transferred by TAAT to national authorities for testing and approval. Alternatively, the direct release of imported varieties to farmers can be arranged for rapidly responding to food insecurity and newly emerging pests. We also provide support in building awareness among stakeholders about the benefits of improved varieties, and their suitability for particular growing areas. *These services are arranged by TAAT with its partner ICARDA.*
2. **Sustainable and Resilient Production Systems.** TAAT recognizes that small-scale and commercial producers look at multiple factors at the same time rather than just one individual component when considering change to farming practice. For this reason, this catalogue includes approaches such as dryland production, raised bed furrow irrigation, minimal tillage and surface mulching, and integrated pest management, as well as opportunities for greater reliance upon mechanization. All of these techniques are intended to cut across individual wheat farming enterprises and assist African producers to modernize their systems as a whole. Advice is also offered as to how these solutions are best bundled to increase economic yields and product quality, and overcome climate impacts. *TAAT and its partners from ICARDA, the International Water Management Institute and the International Fertilizer Development Center offer expertise in transforming wheat production systems.*
3. **Farm Mechanization and Service Contracting.** Increasing access and use of power equipment for labour-intensive field operations is crucial to reduce costs of production and increase the area on which farmers can grow wheat. Featured in this catalogue is

the combine harvester technology that allows farmers to improve work rates and reduce grain losses in field, and digital applications for fleet management and service contracting that help optimize equipment selection and contracting. *TAAT and its partner ICARDA are prepared to assist national programs in the scaling of mechanized equipment and models for rental and collective purchases in small-scale and commercial enterprises.*

4. **Market-Oriented Value Addition.** Agriculture, food, nutrition and commerce are now unified into the common perspective of farming systems after having been fragmented into individual disciplines for many years. It is thus extremely important that efforts to increase crop yields are coupled with deployment of processing technologies so domestic markets can compete with imports of premium grade food. For this purpose, TAAT is championing innovations that enable rural communities to manufacture top-quality, shelf-stable ingredients for human food (i.e., hermetic storage and localized milling) without the need for large capital investments. Expertise and hands-on training about value-added technologies is offered which focus on its synergies with production, resilience, gender and markets. *The TAAT Clearinghouse with its partner ICARDA is ready to assist in the design of national programs to augment market-oriented value addition together with development banks including the African Development Bank.*

Be assured that TAAT is prepared to partner with development investors, national projects and the private sector in a demand-driven manner; always in the spirit of participation toward the co-design and collaborative implementation of solutions that advance the modernization of African agriculture.

Heat tolerant wheat and its accompanying toolkit technologies can transform the food security and agricultural economies of Africa’s Sahel. Join TAAT to realize this opportunity!

Conclusions

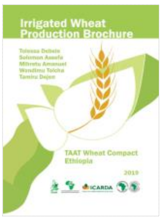
This toolkit catalogue provides a wide variety of options for modernizing wheat production in Africa. It identifies improved varieties that are high yielding and resistant to adverse weather, viruses and insects, along with practices for expanding production, enhancing irrigation water use, and conserving soils and residues, as well as chemical, cultural and mechanical techniques for pest control in fields to address challenges on production, nutrition and resilience of food system. The toolkit also features solutions linked to harvesting and value addition which reduce losses in field and storage, and increase the quality and profit margins of processed end-products. With this set of proven technologies it is possible for wheat growing communities in Africa to access the high-end of the value chain and global marketplace, which can boost incomes of farmer households and commercial agribusinesses alike.

This catalogue was prepared with a variety of users in mind whether they be producers, agents of agricultural development or private sector investors. Farmers can use many of these catalogue items as production guidelines. Those from the public sector can utilize the catalogue as a whole and design agricultural projects involving maize around its toolkit of modernizing technologies. Members of the private sector, including seed producers, input manufacturers, processors and investors also benefit from the contents of this catalogue. Indeed, the Technologies for African Agricultural Transformation Program's Clearinghouse welcomes feedback on its content

Note that this catalogue was developed in part to support the Programme for Integrated Development and Adaptation to Climate Change in the Niger Basin (PIDACC). PIDACC is funded by the African Development Bank 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, Cote D'Ivoire, Guinea, Mali, Niger, Nigeria, and Chad. Discussions started in September 2020 and led to the selection of 25 technologies related to wheat, rice, maize and soil and water management. TAAT is producing technology catalogues, organizing training events, and assisting in Monitoring and Evaluation. Expanding wheat production using the heat tolerant varieties described in Technology 1 and accompanying technologies described throughout this catalogue have a very important role in PIDACC.

Of particular interest to PIDACC are: 1) High-yielding, heat-tolerant and disease-resistant wheat varieties adapted to non-traditional growing areas of the Sahel that have traits for pest and disease resistance, early maturity, higher yield, and desirable milling and flour characteristics; 2) Integrated soil fertility and crop management packages that stabilize wheat productivity through good agricultural practices and protects the agricultural and environmental resource base; 3) Seed system innovations that accelerate seed delivery to farmers in sufficient quantity and quality while providing opportunity for both private and public sector engagement; 4) Integrated pest management systems that are deployed in conjunction with extension campaigns and agrodealer networks, including approaches that offer long-term advantages against weeds and grain pests; and 5) Mechanized tools that are locally produced and low cost, and that allow for more efficient land preparation and planting, better irrigation systems, and improved grain yield. Indeed, farmers that 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.

Information Sources



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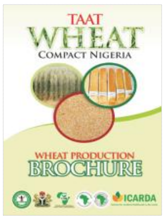

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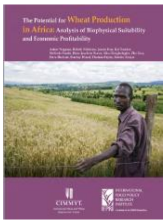

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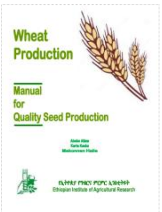

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Acknowledgements

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Please note a map and diagrams were borrowed from sources other than TAAT and its partners. These are R. Prestele *et al.* 2018. A spatially explicit representation of conservation agriculture for application in global change studies. Global Change Biology 24 (on page 18); R. Singh and G. Singh. 2016. Aphids and Their Biocontrol. Academic Press (on page 21); and A. Bianchini et al. 2015. DON Occurrence in Grains: A North American Perspective. Cereal Foods World 60 (on page 31). Some photographs were also discovered over the internet offering products described or recommended in this catalogue.

Technologies for African Agricultural Transformation (TAAT) and its Clearinghouse Office

The development objective of TAAT is to rapidly expand access of smallholder farmers to high yielding agricultural technologies that improve their food production, assure food security and raise rural incomes. This goal is achieved by delivering regional public goods for rapidly scaling up agricultural technologies across similar agro-ecological zones. This result is achieved through three principal mechanisms; 1) creating an enabling environment for technology adoption by farmers, 2) facilitating effective delivery of these technologies to farmers through a structured Regional Technology Delivery Infrastructure and 3) raising agricultural production and productivity through strategic interventions that include improved crop varieties and animal breeds, accompanying good management practices and vigorous farmer outreach campaigns at the Regional Member Country level. The important roles of sound policies, empowering women and youth, strengthening extension systems and engaging with the private sector is implicit within this strategy. The Clearinghouse is the body within TAAT that decides which technologies should be disseminated. Moreover, it is tasked with the responsibility to guide the deployment of proven agricultural technologies to scale in a commercially sustainable fashion through the establishment of partnerships that provide access to expertise required to design, implement, and monitor the progress of technology dissemination campaigns. In this way, the Clearinghouse is essentially an agricultural transformation incubation platform, aimed at facilitating partnerships and strengthening national agricultural development programs to reach millions of farmers with appropriate agricultural technologies.

Dr. Innocent Musabyimana, Head of the TAAT Clearinghouse

Back cover photos: Combine harvester with hill levelling system at work on a steeply sloping field. Photographic credit: Don Murray.

Wheat Technology Toolkit Catalogue

In collaboration with